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NASA Ames Research Center Human Performance Modeling Predictions of Surface Operations Behavior Using Air MIDAS

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Executive Summary

The San Jose State University Human Performance Modeling Team (Team HAIL) undertook this research into human error performance prediction in 5 stages from the development of domain expertise, familiarization with prior simulations, human error process definition and modeling to model implementation and test. We report on that process and progress here.

Phase One of this project required the Air MIDAS development team to gain a complete understanding of the environment that was going to be modeled. In gaining this understanding, the Air MIDAS team gathered information from the Human Error Modeling (HEM) organizing team and generated an understanding of the operational environment surrounding the Taxiway Navigation and Situation Awareness (T-NASA) environment and Chicago O'Hare Airport. The information provided came from a human-in-the-loop (HITL) simulation that was completed in FY 2000. This information was used to assist in identifying the operational world within which the modeled agents performed, thus the operational world that we were tasked to represent in our model. The operational environment was used to identify situations where human error behavior was likely to emerge and developed a series of rules to guide the responses of the agents in the simulation in response to the various environmental conditions. A human performance modeling structure was created that would be generalizable across situations in the simulation responses that we modeled. The requirement arises because multiple agents may not have the same precise operational environment, thus cannot rely on deterministic programming in a domain specific or "tailored to" an environment to cause the requisite behaviors. The domain specific models do not provide behaviors that emerge as a function of the environmental situations and agent contexts. The ability for a human performance model to generalize is critical for the acceptability of the model across domains and is one of the principle motivations guiding our model development effort.

Phase Two of this project required us to gain an understanding about human error and examine some of the causes behind human performance and some of the pre-cursors to human error causality. A background, literature review paper on human error and system performance and included as part of the deliverable to NASA Ames Research Center. This information served to guide human performance modeling and assists in creating an accurate understanding of human-system performance.

Phase Three required the Air MIDAS team decided upon a theoretical paradigm to guide the model development process. Through our research on human error, a theoretical paradigm developed by Erik Hollnagel (1993) was identified was determined to be an appropriate. The model identified by the Air MIDAS team was the Contextual Control Model (CoCoM). Through comprehensive review of various human error processes, the Air MIDAS team became more convinced that the CoCoM could be implemented within the Air Man-machine Design and Analysis System. The theory and the modeling approach share control mechanisms that are based on resource constraints and their interaction with the context of action in the simulation. This match permitted translation of the theory's control mechanism to code a fairly straightforward process. Phase Four of this project required the Air MIDAS team to develop an analytic model of operator performance. Three agents were determined to be principally involved in the

operations of the surface operations, the Captain, the First Officer, and an Air Traffic Controller Agent (ground and local controller combined into one agent). Vulnerability points in the operation among these three agents were identified. Team Air MIDAS then needed to link the analytic model with erroneous performance of the operators from the HITL data. This analytic model was implemented in Air MIDAS and required incorporating the activities and procedures that were to be performed by the multiple operators in the operational environment provided.

During the analytic model development process, it was noted that the interaction of the multiple agents was a key point of safety vulnerability. Given this insight, we developed procedures that attempted to reproduce the information and communication sensitivities we noted in our analysis.

Phase Five of this project was to create an operable HPM. Using its constituent sub-models, the Air MIDAS software was set to run in the baseline operations condition of the HITL T-NASA simulation. This baseline condition was expected to generate predictions on human workload and time to complete various procedures. The environmental triggers, a key component in the emergent human performance model, were coded in the Air MIDAS environment. Environment triggers (e.g., turns, signs, ATC calls) elicited the baseline behaviors that were predictive of human performance in current day operations. This served to identify risk factors that increase the probability of error or that could mitigate the error. We encoded working memory decay rate and capacity, and timing of information availability to the operators in the simulation. Error rates, performance times and workload were output from the human performance model. These predicted that errors do occur as a result of increasing decay rates and reducing memory capacity, while changes in the data patterns occur as result of changes to the time of information availability to the crew members in the simulation.

NASA Ames Research Center Human Performance Modeling Of Surface Operations

NASA research efforts have focussed on creating dynamic models of human performance and, more recently, on anticipating human error that has significant system-level impact. The development of a valid model of human error behavior applied to surface operations was undertaken based on information that was provided by NASA Ames Research Center's Human Error Modeling Program (Foyle, Andre, McCann, Wenzel, Begault, D. & Battiste, V., 1996; Hooey, Foyle and Andre, 2000) and from a detailed analysis of existing literature on the etiology of human error (Appendix A). The previously validated (Pisanich and Corker, 1995; Corker & Pisanich, 1995; Corker, Gore, Fleming & Lane, 2000) software tool, Air MIDAS was used to generate predictions of human operator performance using technologies designed to improve surface operations safety. The effect of the change in information available and the resultant potential for human error due to the uncoordinated mental representations among virtual operators in the system is of interest here.

An integrated representation of the humans operating in the environment was therefore required. This integrated representation modeled a critical point in the operating environment, ramp navigation and gate-approach. The Chicago O'Hare Airport (ORD) was used in a full mission human-in-the-loop (HITL) simulation was generated in a HOOTL model and it was expected that this HITL simulation data would be compared with the HOOTL predictive simulation data that was collected during the current modeling effort. Generated human performance predictions of the baseline conditions set the stage for comparisons to human performance when technological introductions are made. In order to generate a sufficiently valid model of error predictions, we represented the equipment (physical aircraft), the crew-station and external environment at varying levels of fidelity depending on the importance of the information for updating the operator's world. The control modes in Air MIDAS that have the potential to be sensitive to manipulations include memory errors and their effect on the simulated crew's internal representation, termed updateable world representation (UWR). Three types of error mechanisms were represented.

- The first error type, declarative memory errors, included errors that occurred when virtual operators 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 cause multiple competing behaviors to occur concurrently and invoke the procedure scheduler (dropped tasks = memory loss).
- The second error type, memory load errors, occurred as a result of information competing for 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 not written down to a location from an actively available list from which the operator was able to visually encode the information (for example a taxi clearance).
- The third type of error, UWR discrepancy errors, occurred when there was a worldview inconsistency between two virtual operators. This error occurred

when one virtual operator erroneously "thought" a different virtual operator had received information. This UWR discrepancy was a possible cause of and a response to the occurrence of an error.

The errors represented above were created by increasing the number of items in working memory (WM) and by increasing information transfers through active procedures. Each type of error emerged as a result of the scenario requirements and demands placed on the virtual operators and each type of error was not created deterministically.

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. We accomplished this by building a representation, of pilot-pilot interaction, of ATC-pilot interaction, and of the airport surface environment. A set of realistic landing procedures was modeled including: environmental monitoring, changing radio frequency, contacting ATC and listening to clearance, writing down the 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 (the rules guiding the behavior of the operator) to be invoked. The NASA ARC 1999 full mission simulation experiment involving an augmented system to aid in the surface operations during low visibility conditions called the Taxiway Navigation and Situation Awareness (T-NASA) system was used. The T-NASA simulation took place at Chicago O'Hare Airport (ORD). One operational environment from a series of scenarios utilized in the HITL T-NASA simulation was selected as the environment to model in Air MIDAS

Scenario details.

The model scenario commenced when the ground sent the taxi clearance information to the flight crew. The selected environment was Route NH3 of ORD (see Hooey, Foyle & Andre, 2000 for a review of the operating environment). Route NH3 possessed a complex taxiway geometry that served to increase the UWR of the virtual operators. This route also required extensive communication among the agents in the simulation.

Human error modeling system vulnerabilities.

Two human error vulnerabilities in surface operations were modeled - UWR error, and memory errors. 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 3). It was determined that modeling the three agents, the Tower Air Traffic Controller (ATC), the first officer (FO) and the Captain (CA) would provide a realistic modeling environment and exercise some of the multiple crew coordination mechanisms within Air MIDAS.

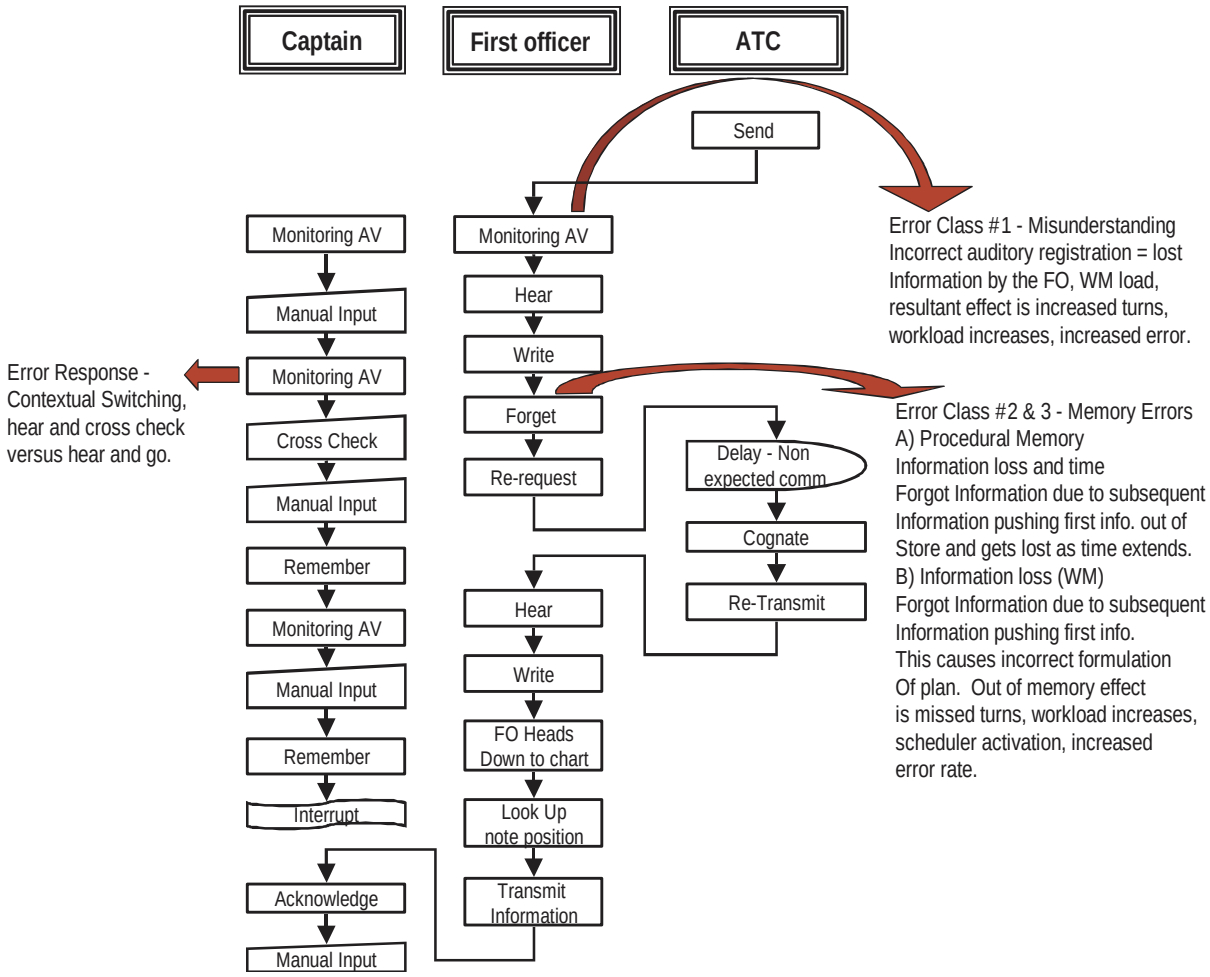

Figure 1. Overview of the scenario considerations guiding the development of human error within Air MIDAS.

The three agents outlined in Table 1 were used by the Air MIDAS environment to trigger the onset of erroneous performance by the operators.

Table 1. Procedural coding considerations for the three agents in the HAIL HEM simulation.

Captain	First Officer	ATC (Tower&Ground)
Based on the turn-off instruction, the Captain might have expectations regarding their taxi route, which might influence his/her decisions later i.e. confirmation bias, heuristic—same for FO	*Before all of this (in the air), the FO was supposed to refer to the taxi chart to gain an awareness of where the expected turn-off was situated in relation to the airport configuration*	
While navigating turn-off	Do: (order depends on time, A/C positioning i.e. whether still approaching HS bar or not or whether ATC responded yet)	
❑ Keeps navigating or is waiting on HS bar by now ❑ Listens to taxi route clearance (depending on load)	❑ Contacts Tower of clearing runway and location ❑ Switches frequency to Ground ❑ Contacts Ground regarding clearing runway and location ❑ Waits for a clearance	❑ Tower ATC gives frequency for Ground ATC ❑ Ground ATC gives taxi route when ready (*this message might be given right away or it might take them longer)*
❑ Keeps navigating or is at HS bar by now ❑ Listens to taxi route clearance (depending on load)	❑ Writes down taxi route ❑ Reads back taxi route to Ground	❑ Ground ATC might acknowledge the confirmation, but might not
❑ If already stopped, may start on taxi route *while* discussing with FO (*this would mean that the Cptn heard the first route instructions and thought s/he knew how to start off—was probably under time pressure to do so)*	❑ Discusses taxi route with Captain	
❑ Visually reference chart if unsure/lack of local and/or global awareness	❑ Visually references chart	

As demonstrated in Table 1, three agents were represented along with their procedures, the Captain (CA), the First Officer (FO) and the Air Traffic Controller (ATC). The high level static procedural representation are noted in this Table and were used as the basis for coding the procedural representations required by Air MIDAS noted

in Figure 2 below.

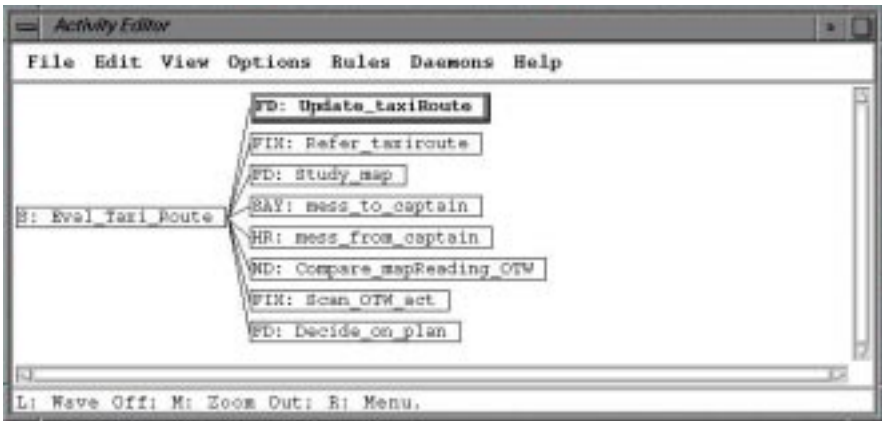

Figure 2. Air MIDAS screen snapshot of the activity procedural editor representation of the "Evaluate Taxi Route Procedure".

Figure 2 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 3. The occurrence of the two activities demonstrated here are designed to serve as exemplars of the code within the Air MIDAS software tool.

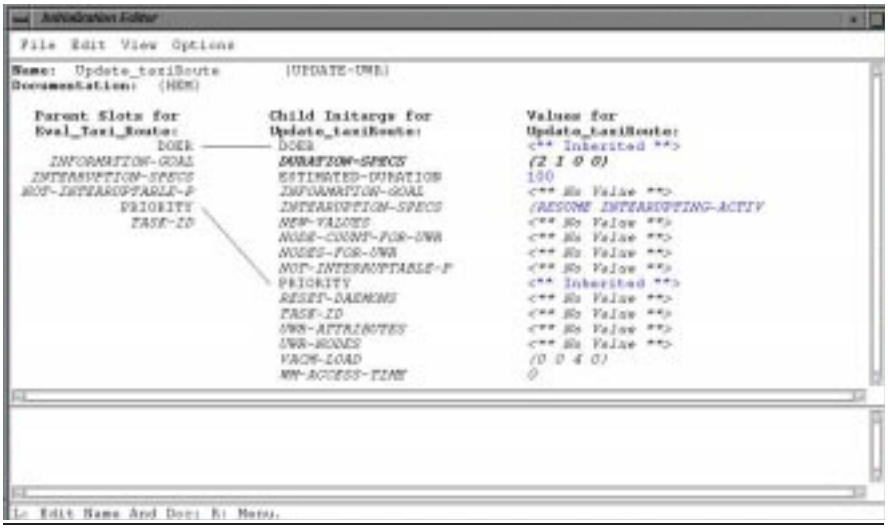

Figure 3. Air MIDAS screen snapshot of the sub-leaf activity "update_taxi_route".

Dependent and Independent Variables.

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 set at either 12 seconds or 24 seconds and the memory capacity was either 5 elements or 10 elements. The decay rates were representative of operator performance in complex environments (Baddley, 1992; Smith & Corker, 1993). The decay rates and the memory capacity were not counterbalanced. A second set of manipulations included the time that the Air Traffic

Controller received the navigation information - 24 seconds, 50 seconds and 80 seconds. The memory manipulations were counterbalanced with the time that the ATC received the navigation information. Each simulation scenario was run 10 times.

Results

Two types of results were generated from this simulation, those associated with the structures internal to the model (rules/heuristics to guide behavior) and those related to the predictions generated from the HOOTL simulation. The metrics of interest in this results section include the virtual operator's performance times, the workload measures, and the number of errors created in traveling the surface operations environment (reflected by missed turns). 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.

Heuristics Created

A number of rules that were created to guide the performance of the model in this simulation need to be outlined as they will be referred to throughout the results section.

Behavioral Heuristic # 1

Operating Under Uncertainty. Crewmember performs a "crosscheck".

Behavioral Heuristic # 2

Operating Under Time Pressure. Crewmember enacts "direct to goal" behavior.

Behavioral Heuristic # 3

Operating Under Uncertainty Combined with Time Pressure. Crewmember does not perform "cross check" and enacts "direct to goal" behavior.

Cognitive Heuristic # 1

Primacy effect. Information entering into the crewmembers Updateable World Representation will be pushed out of memory by subsequent information entering the UWR if it exceeds the critical 7 +/- 2 memory limit (Miller, 1956).

Cognitive Heuristic # 2

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

Human Performance Metrics

Three human performance metrics were of interest. The first was related to the occurrence of errors, the second was related to the performance times surrounding the occurrence of the errors, and the third was related to the workload that was faced by the virtual operators 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.

Error Rate

The error that was predicted from the human performance model in the current experiment occurred at one of two locations along the airport surface of Chicago ORD's Route NH3. Figure 4 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 following the aircraft turn from the runway. This error occurred due to the excessive head down time that was required of the first officer. An error on the first turn resulted in executing the "Direct to Gate" Heuristic. This error emerged as a result of the capacity limit within the virtual operator.

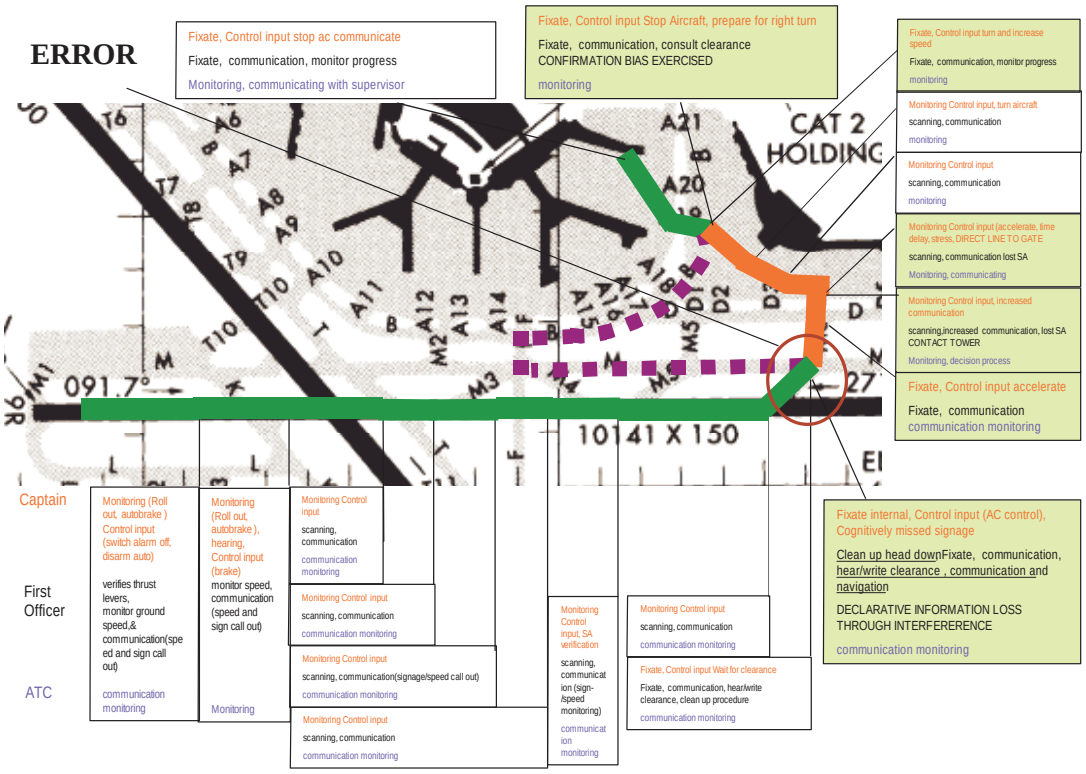

Figure 4. Air MIDAS Error at Turn #1 (Circled). Operator continued traveling straight but should have turned left onto the cleared route (dotted line). Error invoked direct line to gate heuristic as the operator recognized that they were lost. A representation of the activities coded and completed along the environmental timeline is included in this graphic.

Figure 5 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 the memory capacity of the virtual operator in the simulation. This error emerged due to a 'no recall' procedure.

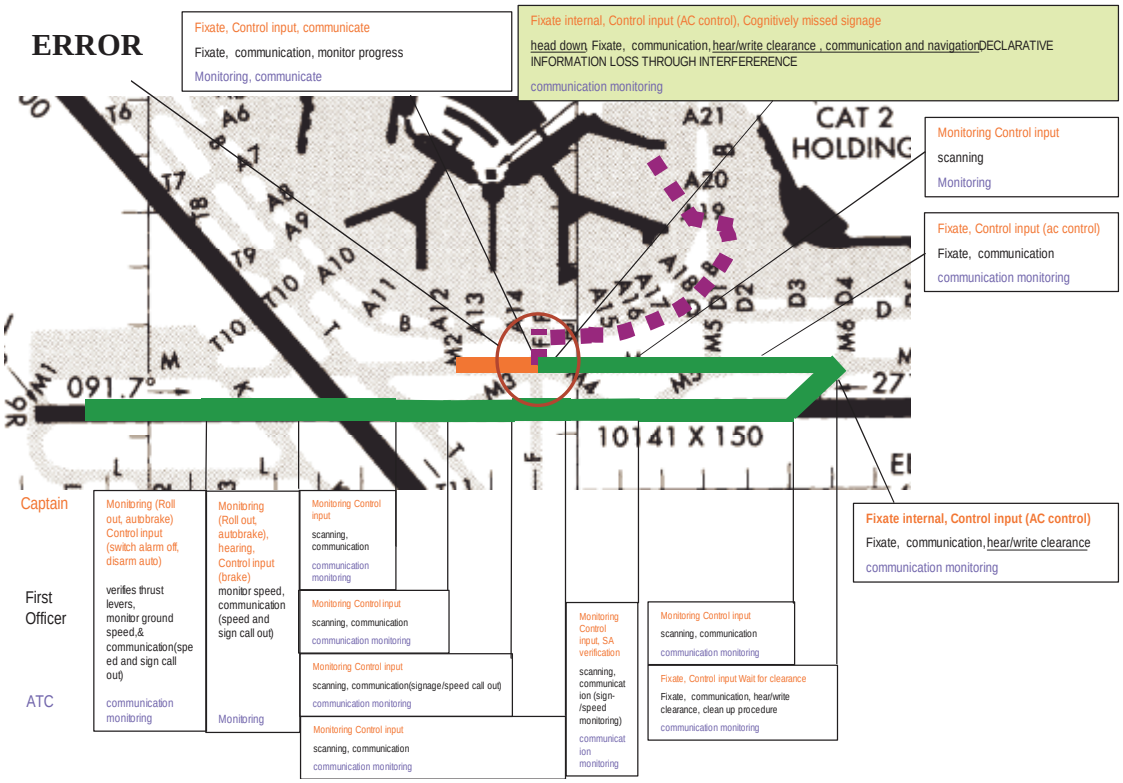

Figure 5. Air MIDAS Error at Turn #2 (Circled). Operator correctly made a left turn onto Mike and traveled along taxiway Mike to Foxtrot. Virtual Operator made error at Foxtrot as they did not stay on the cleared route (dotted line). Error resulted in simulation termination. A representation of the activities coded and completed along the environmental timeline is included in this graphic.

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 operator performance. The presentation of these results assumes that the virtual operator is engaging in activities in an unaided condition (no environmental cueing mechanisms). As demonstrated in Figure 6, the probability of recalling 25% of the information that was provided to the virtual operator when operating in condition 120 with a capacity of 5 elements, would be at 12 seconds after the information was received by the virtual operator (algorithm #1 – solid line). The probability of recalling 25% of the information that was provided to the virtual operator when operating in condition 240 with a capacity of 10 elements, would be at 24 seconds after the information was received by the virtual operator (algorithm #2 – dashed line). These algorithms affected the virtual operator performance differentially.

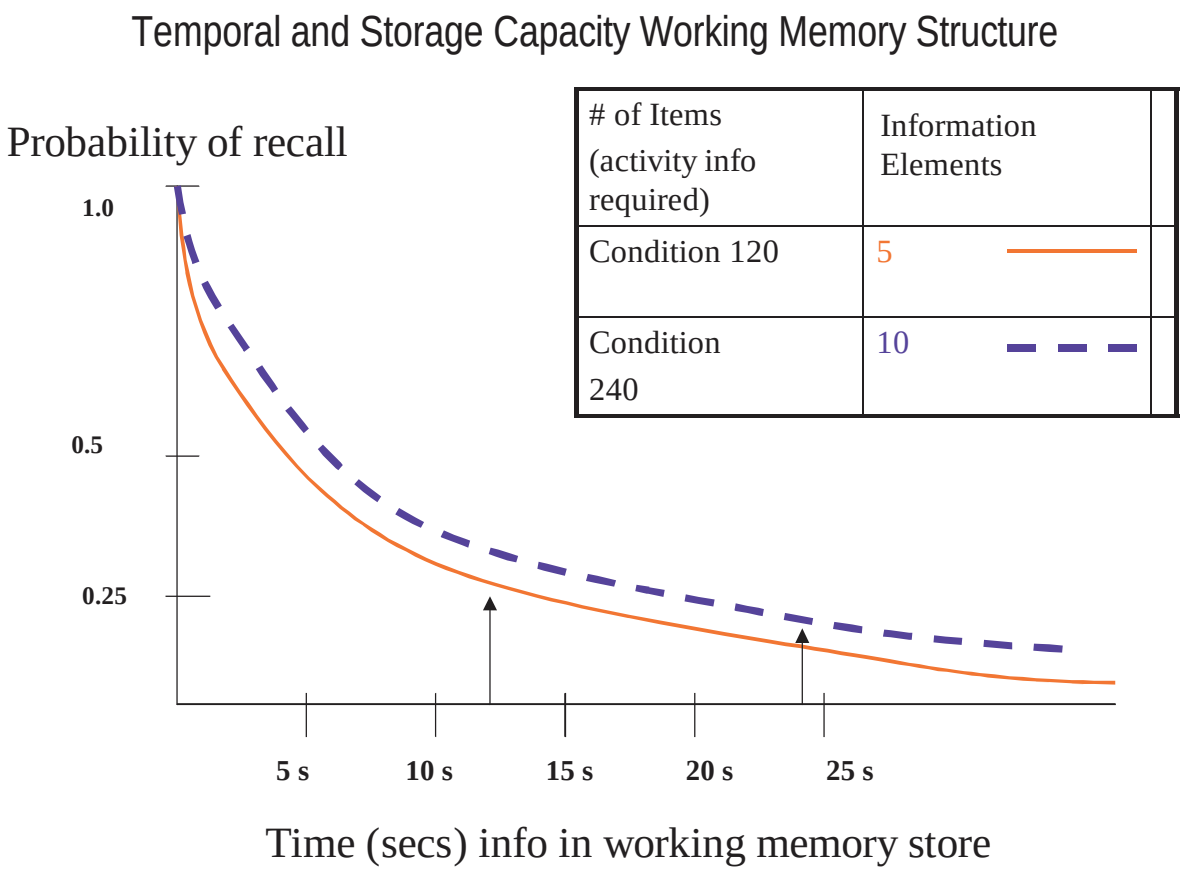

Figure 6. Temporal and storage capacity of Air MIDAS' working memory structure.

Figure 6 demonstrates that the performance of the virtual operator was affected by increasing the time delay between the receipt of the information and the performance of a goal behavior (turning on the airport surface). This is demonstrated by the increase in the time required for the cognitive structure of the operator to possess a probability of recall of 25%. This algorithm was used to assist in emerging the errors from the Air MIDAS model that is reflected through the performance output.

Performance Output –Errors Generated

The performance output of interest 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 – two memory decay and memory capacity rates, and the three times associated with receiving the air traffic control information. A total of ten seed-generated, Poisson distribution runs were completed for each of the experimental manipulations made in the simulation for a total of 60 runs. These data can be found in Figure 7.

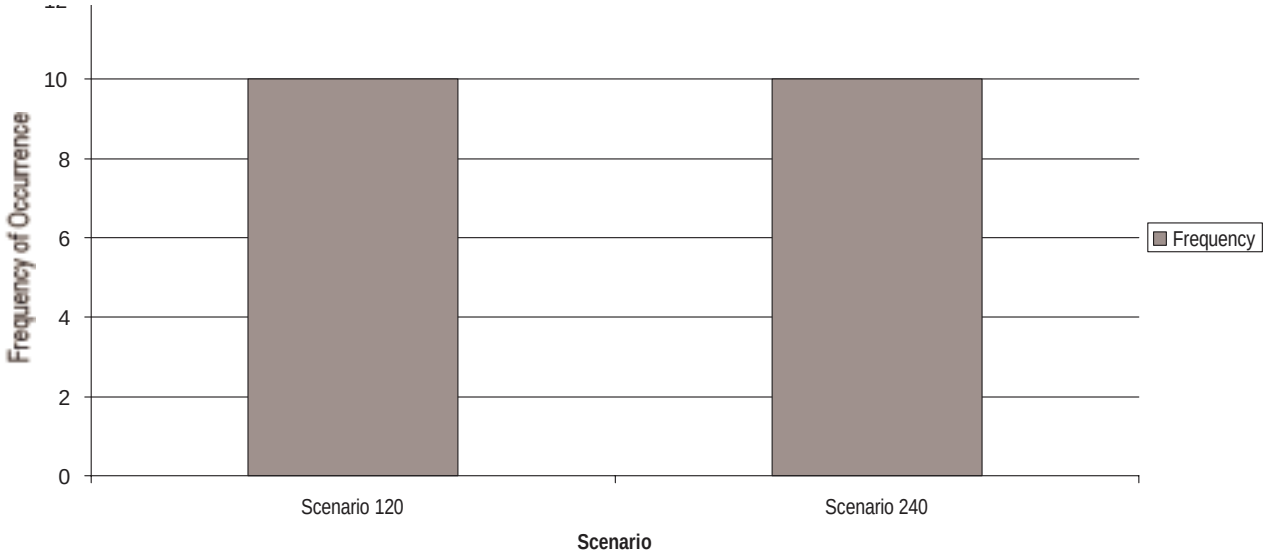

Figure 7. Frequency of heuristic being called as a function of the scenario manipulations.

Figure 7 demonstrates that 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, 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.

The output shown in Figure 8 demonstrates that the human performance model did not predict any difference in performance at the 12 second decay rate and the 5 element level (scenario 120) but that differences were found between the heuristics invoked in the 24 second decay rate, 10 element memory capacity (Scenario 240). This indicates that performance was better if information arrived later in the scenario (approaching the 5000 tick mark of the simulation).

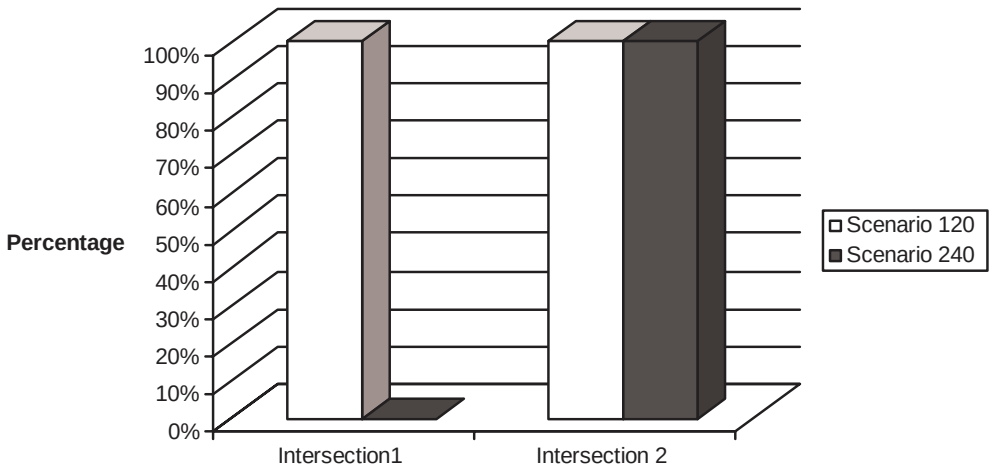

Figure 8. Percentage of time the heuristic was invoked as a function of time in the scenario (5000 Ticks).

The output shown in Figure 9 demonstrates that the human performance model again did not predict any difference in performance at the 12 second decay rate and the 5 element level (scenario 120) but that differences were found between the heuristics invoked in the 24 second decay rate, 10 element memory capacity (Scenario 240). This result indicates that performance was better if information arrived later in the scenario (this time approaching the 8000 tick mark of the simulation). It is of significance that there is no difference between the 5000 and the 8000 millisecond times so the structure responsible for the occurrence of the error must be accessed somewhere between the 2400 and 5000 millisecond time period.

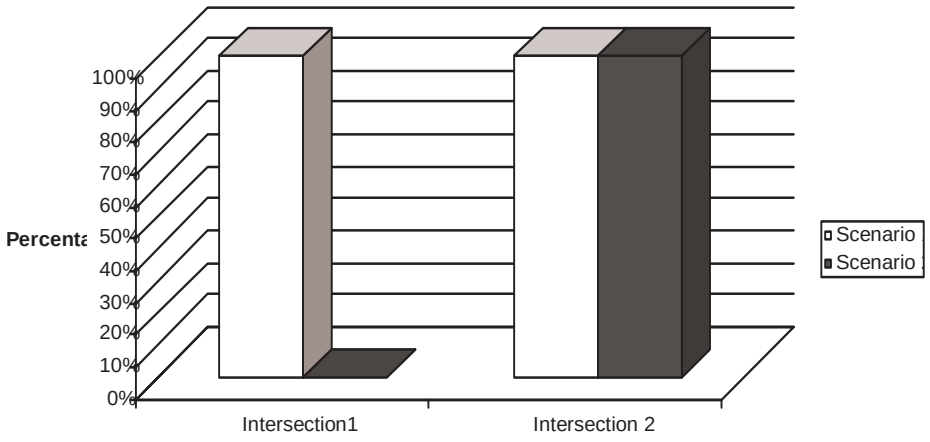

Figure 9. Percentage of time the heuristic was invoked as a function of time in the scenario (8000 Ticks).

Performance Output - Information Receipt Time and Scheduled Activities

The data that was collected was viewed from the perspective of the flight deck. Figures 8 and 9 indicate that there was a difference between the experimental manipulation of memory load (memory decay and memory capacity rates) and the time that the virtual operator received the navigation information. At the intersection # 1 for the memory decay rate of 12 seconds and the memory capacity of 5 elements condition, there was a complete degradation of memory as there was a 100% error rate. At the intersection # 1 for the memory decay rate of 24 seconds and the memory capacity of 10 elements condition, there was no degradation of memory as there was a 100% successful completion rate. At intersection # 2 however there was a 100% error rate for both of the memory conditions. This differential effect from intersection #1 performance indicates that there was some effect on the memory decay rate and memory capacity on the performance of the virtual operators in the simulated environment modeled of the time that information was presented (made available) to the operator.

An examination of the status of the activities by scenario was completed to identify the active structures when the errors occurred in the simulation. Figure 10 demonstrates that there was no difference in activities completed, aborted, and resumed between conditions. Under each of the manipulations, the operators were faced with a similar set of tasks to complete and did in fact complete 41 of the required navigation tasks. Virtual operators also aborted 7 tasks and resumed 7 tasks. This result would presumably be affected with the incorporation of the third rule set of intra-cockpit communication.

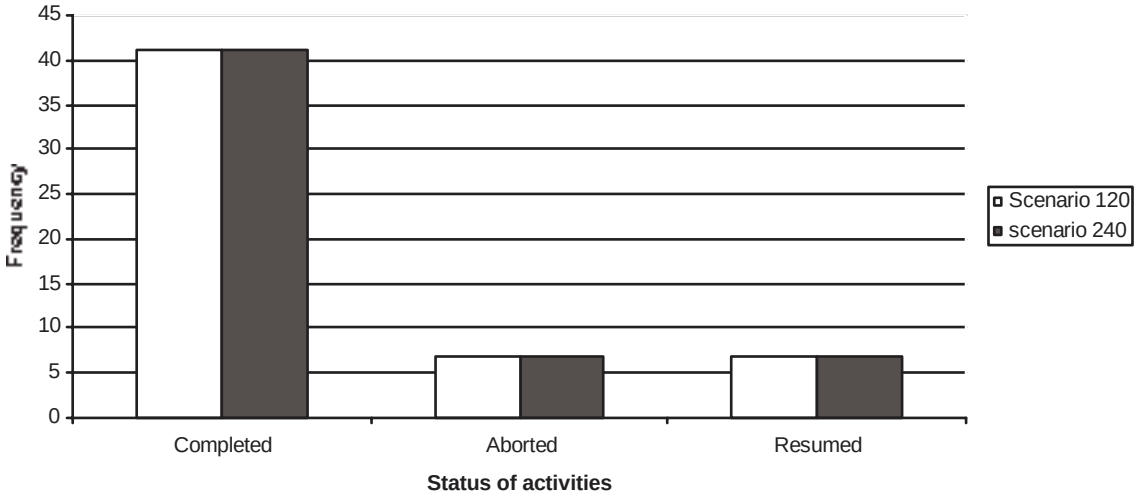

Figure 10. Activity status across scenarios. “Completed” indicates frequency of tasks that were completed during the scenario, “aborted” indicates the number of aborted tasks during the scenario and “resumed” indicates the number of aborted tasks that were restarted.

Performance Output - Workload

A workload output from the HOOTL HPM was obtained in the current experiment. Figure 11 demonstrates the visual, auditory, cognitive, and psychomotor loads comprised the measures of workload output from the HPM. These output measures were based on the manipulations that were made in the experiment – two memory decay

and memory capacity rates, and three times associated with receiving the air traffic control information. Ten, Poisson distribution runs were completed for each of the experimental manipulations made in the simulation for a total of 60 runs.

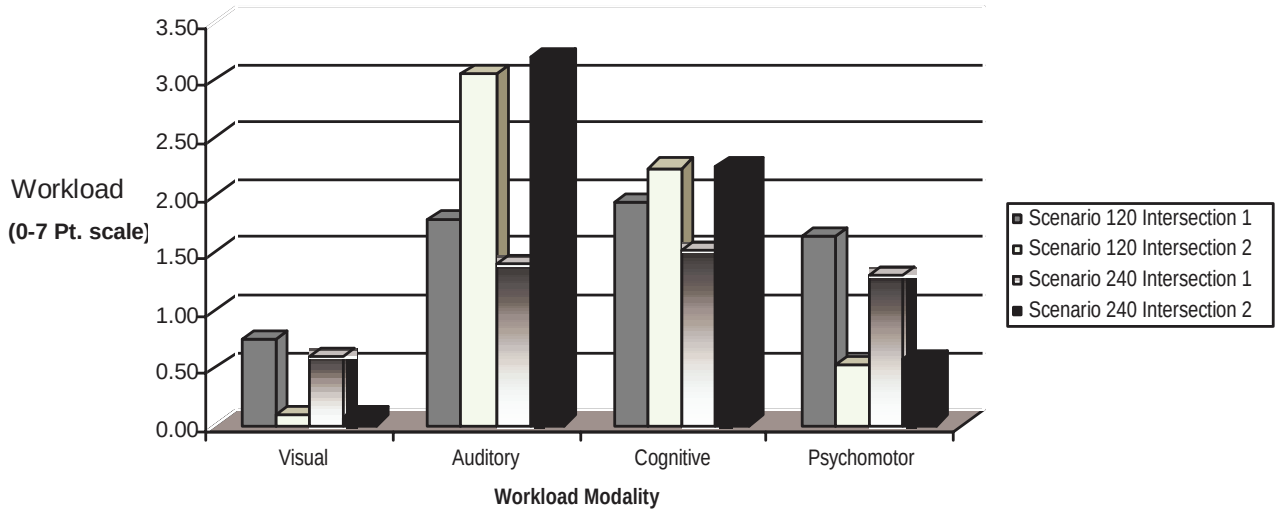

Figure 11. Predicted load levels within components that comprise workload by experimental condition.

Figure 11 demonstrates that the virtual operators' 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 at intersection #1 (Error Pattern #1), in a consistent pattern across memory conditions (scenario 120 and scenario 240). An increase in cognitive demands was found to be associated with the second intersection (Error Pattern #2) – this was an expected finding as the flight crew will be relying more on their memory for the accurate directions as opposed to using information immediately available within their cognitive store. It can be seen that the auditory and cognitive demands were greatest at intersection #2 (Error Pattern #2). The auditory increase for intersection #2 (Error Pattern #2) was due to increased communication between the flight crew operators as they needed to refresh their memory store as time extended from the receipt of information to the time that performance was required. When this cognitive representation is considered with the performance characteristics, it is interesting to note that the flight crew operators forgot their navigation instructions when they relied solely on the cognitive structure embedded within Air MIDAS. Psychomotor demands were greatest at intersection #1 (Error Pattern #1). This occurred because the operators made physical inputs to slow the aircraft from the runway speed to taxiway speed followed by receipt of information from ATC.

Discussion

The findings from this simulation demonstrate that the modeling software structure as represented by Air MIDAS provides predictions of operator performance in a pre-specified operational environment and predicts the likelihood of erroneous performance during baseline surface operations at Chicago O'Hare Airport. The Air MIDAS output is useful for identifying risk factors that increase the probability of error

and is useful for providing some insight into mitigation strategies when errors occur. Air MIDAS does not however predict error rates.

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 emerge from Air MIDAS demonstrate that internal structures within Air MIDAS are sensitive to assumed psychological capacities and scenario demands. Procedural interruptions occur when operators are faced with procedures that compete for procedural memory resources. These resources decay across time and become lost if time extends beyond an acceptable upper time boundary (decrements by the WM decay rate on each tick of the Air MIDAS simulation).

The procedural errors, manifested by incorrect turns, are consistent with the HITL surface operations simulation that found evidence of errors occurring because operators omitted or substituted parts of a required taxi clearance to get to the gate, a procedural memory error (Hooey et al., 2000). The use of the HOOTL HPM provides the ability to create scenarios with psychological and environmental demands that impact the virtual operator. The HPM predicts performance effects based on modifying the information presentation to the virtual operator. This provides the model developers and the system designers with some insight into the causes of the human performance limitations. It is with this information that the system designers can then suggest design alternatives to maximize human performance with complex systems

It can be inferred from the procedural errors that Air MIDAS is predicting, that the world representations of the virtual operators in the system are misaligned. This misalignment can cause the occurrence of a negotiation between operators in order to realign the world representations of the virtual operators. The representation within Air MIDAS of a communication agent enables the recognition of auditory information to update the world representation through the visuo-spatial scratchpad that is contained within Air MIDAS. This process will be a critical component that will be examined in upcoming human performance models examining the behavioral predictions associated with Synthetic Vision Systems (SVS) as virtual operators interact within system constraints using augmented/assistive technologies (automation).

A second type of behavioral prediction emerges from the Air MIDAS. This emergent error occurs as a result of two interacting mechanisms within Air MIDAS' structure - the "forgetting" mechanism and the forgetting heuristic mechanism within the model. As this effort predicts, the model loading factors appear to have an impact on the performance of the forgetting mechanism and on invoking the rule guiding the response to the forgetting function. This demonstrates that the computational mechanisms within the Air MIDAS software are attempting to replicate the operations of humans when humans are faced with a forgotten piece of information. When there are a number of items occupying WM, one item in WM is shifted out of the limited capacity store by the subsequent information from the pilot or from the controller communication. The

respective agent loses information from the "active" list, or the series of active procedures scheduled to occur, if it is not written down. Given that the human operator is characterized as a limited capacity store, items within this memory structure fall out of memory if not rehearsed. Rehearsal can occur by mentally recalling the required information bits, or when this is not available relying on some external visual aid like a list or a dynamic presentation of information consistent with the T-NASA system. The importance of this finding is that the model world is predicting consistent patterns of responses to the HITL data that found evidence of this error type and suggested that demands may be too high and causing pilots to forget part or all of the clearance (Hooey et al., 2000). This error type is indicative of a Working Memory (WM) Load Error that can be assisted by a change in the manner in which information is provided to the operators in the simulation as WM Load Errors occur as a result of information competing for WM space. The output from this effort demonstrates that this aspect of complex interactive performance (due to the multiplicity of mechanisms impacting performance) is one that can be examined through the use of a predictive human performance model.

There is evidence to suggest that information availability and information immediacy impact the performance of the virtual operators in the simulated environment programmed in this simulation. Information availability refers to the accessibility of information when the operator determines a need for the information to complete the goal behavior. The HPM predicts that operators perform better when the virtual operator receives navigation information later in the scenario. Given that the HPM predicts that the operators are predicted to perform differently depending on the time of the receipt of information, it can be inferred that a system that provides a differential time to clearance from the ATC can impact Flight Crew performance in the HPM. This suggests that in the current modeling environment, a system such as T-NASA (which enables information immediacy) can impact the performance of the virtual operator. The interaction and the inter-related nature of the system elements can also be examined successfully using a HPM like Air MIDAS. Information immediacy is one of the motivating factors for the SVS currently under development at NASA Langley and NASA Ames Research Centers.

As indicated above, the HPM predicts that virtual operators perform better when the virtual operator receives navigation information later in the scenario. In examining system performance when considering implementation of automation to assist the human operator complete the goal behaviors, a concern regarding the workload levels of the human operator arises. Recalling that implementation of automation in the current modeling environment is represented by availability of information. A prediction is generated indicating that there is a potential for increases in auditory and cognitive demands as time in the scenario increases (as the virtual operator approached the second turn). This suggests that providing the human operator with a selectable information format allows for more efficient performance as the operator is able to "call" for the required information when they determine the information need for completing the goal behavior. This selectable element is important for design considerations being created in the Synthetic Vision Systems whose concept is currently under development at NASA. The primary and the secondary effects of such display technologies can use some of the generative functions created in the ORD Baseline scenario discussed in this report.

The potential for memory errors to emerge can be tested in occupational environments to measure worker task and procedural completion, and to examine the effect that various performance modifiers (e.g. automation, training, re-design) has on assisting the successful and safe performance of the National Airspace System. Many options exist to assist an operator's memory to complete complex tasks – electronic checklists, placement of equipment, cross checks with other operators in the operating environment, or other automated reminding mechanisms. System vulnerabilities in the NAS environment can therefore be successfully modeled and procedural re-design or job re-design performance can be examined through the use of the HOOTL human performance model to predict the effect the re-design may have on operator performance (increased efficiency and increased safety). The HOOTL prediction can provide valuable insight earlier and more efficiently (in terms of time and costs) into specific job related demands and the effect that procedural changes will have on job completion.

CONCLUSION

This report documents the advances in computational cognitive modeling tools that attempt to create dynamic computational models of human performance to represent some portion of the causes of human error. The identification of mechanisms involved in the creation of error will certainly lead to a better understanding of the concepts associated with safety underlying human performance, and will lead to more solid computational predictive tools of human performance, especially in the increasingly complex and automated work environment. This computational analysis methodology permits a closer link between the job, the use of the automation and the human performer complete with their physical and cognitive abilities. This coupling 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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Appendix A - Background Information on Human Error

National Aeronautics and Space Administration (NASA) has recently undertaken a series of projects aimed at developing dynamic models of human behavior focussing on human error. Quantifying human error in a manual control representation is a task that can be modeled quite simply by control input-output mechanisms exemplified by the servo mechanisms developed in the mid 1940's (Craik, 1947). The identification of the underlying reasons for the error exhibited by human performance, however is much more difficult. The reasons for inaccurate human performance could be the result of inadequate design of the physical work environment or could be due to the human cognitive component. Many theories exist on human error causality and all have some merit as they attempt to quantify the measurement of human error. The first step in gaining an understanding of the human error mechanisms is to establish a definition of the components that make up human error. These central components can be exercised in a computational paradigm to examine the performance characteristics associated with the emergence of inaccurate human behavior. An explanation of the conceptualization of inaccurate human performance, human error, is warranted as there is certainly value in understanding the conceptualization that other researchers have taken in the search for accurate examination of human error.

Human Error

Mechanistic era.

Human error has traditionally been studied in an incidental or somewhat reactive fashion. During the initial portions of the 20th Century there had not been a concerted effort to understand the root causes of erroneous behavior, rather the effort was to identify that errors had occurred. The initial studies examining human error began in the late 1920's and early 1930's. These initial studies examined a set of over 1000 individuals who performed incorrectly on a series of performance metrics that were designed from common everyday mechanistic behaviors (Spearman, 1928). The general studies that were completed throughout this initial phase included control input-output kinds of studies examining incorrect physical performance of various goal-related tasks. These control input-output studies lead to the mechanistic definition of human error that scoped human error in terms of incorrect physical task performance due to some physical cause. This series of studies lead to an initial definition of human error that has since evolved from the purely mechanistic view (simply being the output of incorrect physical performance) to one recognizing cognitive factors behind human error (in the 1950's onwards) to being the result of an interaction between the physical and cognitive worlds (the current thought). Hollnagel (1993***)*** defines human error as being situations or events where undesirable consequences occur and where the cause can be attributed in whole or in part to human action. More recently however, Hollnagel (2000) has augmented the concept of human error to include the contextual component behind human action and human cognition as opposed to solely speaking about incorrect human actions.

Serial approach era

The development of the modern definition of human error has grown from Payne and Altman's (1962) conceptualization of human error as being a serial mechanism

involving sensory and perceptual errors (input errors), cognitive errors (mediation errors) and selection and execution of physical responses errors (output errors). Many of the theories and concepts in these times were serial in nature. Early attempts to explain human behavior were categorical in nature and often searched for causality. One difficulty is that human behavior is often not causal in nature, rather, human behavior is characterized by variability in performance and is not necessarily serial in nature. The serial mechanism categorization however fostered thought on the etiology of human error for other researchers. Meister (1965) augmented this serial classification of human error. Meister dichotomized human error but the errors remained consistently represented as a result of human characteristics in his initial classification. His classification included two distinct categories of errors; namely errors of omission and errors of commission (Meister & Rabideau, 1965). Errors of omission occur when the operator fails to perform a required action (analogous to the output errors of Payne and Altman). Errors of commission occur when an incorrect action is being performed. Errors of commission can be further divided into errors that result due to timing, to sequence, to selection errors, or to quantitative errors. When an error has occurred, Meister's classification then attempted to quantify the human response to the error. For this, he identified a classification for the degree of the error type as being recoverable or non recoverable errors (Meister, 1971):

- Operating error
- Design error
- Assembly/manufacturing error
- Installation or maintenance error

Information processing era

Meister's model and classification of human error lead to the development of information processing approaches for explaining the occurrence of human error. These information approaches began in the mid 1970's with Rasmussen's conceptualization of stages that are completed by people making decisions and an eight stage process characteristic of people's performance that depended on the familiarity that the respective individual possessed on the given task (Rasmussen, 1976). The eight-stage process involved agent activation of the respective information nodes within the environment, agent observation, agent identification, agent interpretation and evaluation, agent task definition agent formulation of procedure, and finally agent execution. This was termed the step ladder model of decision making. This eight-stage process served as the basis for Rasmussen's well-known and documented skill-, rule- and knowledge-based taxonomic model of performance[2] (Rasmussen, 1981). The framework for the skill-, rule- and knowledge-based model of human error embedded some characteristic functions for the causes/mechanisms that are involved in incorrect human performance. Ultimately, any plan using knowledge based behavior will require rule based procedures and skill based performance. The mechanisms of human malfunction included in this taxonomic model of performance are the reasons for the occurrence of the error. The mechanisms of human malfunction are further influenced by performance shaping factors and other situational factors. The root cause of the human malfunction can be discovered only by

[2] for a complete explanation of skill rule and knowledge based errors, please consult Rasmussen (1981).

examining the structure and sequence of the activities that precipitated the erroneous performance.

Norman (1981) built onto Rasmussen's information processing model by incorporating an intentional classification to human error. This intentional classification also possessed an information processing approach to quantifying and explaining human error. The intentional cognitive aspect included in its classification errors termed "slips". Slips were defined as being deviations from the intended goal and slips possessed immediate feedback about the erroneous performance. Reason (1987) built on this model to incorporate "mistakes" as an information processing approach to quantifying and explaining human error. "Mistakes" were said by Reason to occur as a result of an error in the planning process.

Around the same time as Norman was developing an intentional classification of human error, other researchers were thinking about human error in terms of mathematical relationships. In these mathematical representations, human error could be said to occur when an action violates a tolerance limit of a system. Systems vary as function of the boundaries of system limits in terms of accuracy, sequence, or time. Hagan and Mayes (1981) indicated that the term error is used when the end result could be damage to equipment and property or disruption of scheduled operations. Defining human error in terms of the end result of human performance may not capture the entirety of the situation surrounding the reasons for the emergence of the error. Each component, the physical error and the reasons surrounding the error, is required for a successful understanding of human error.

The above noted classifications of human error have dealt mainly with the human in relative isolation of complex work domains. As the work domain increased in complexity, there was an increase in the degree to which the human was required to deal with automation and decision support systems. Automation and decision support systems are characteristics of the modern work environment. The modern work environment comprises many complex and integrated components that interact together and impaact each other. A system view therefore begins to take on increased importance as compared to a restricted view of error being the result of the human. This system view however can not be looked at in isolation of the human component within the system. Each of the integrated players in the system possesses certain vulnerabilities but that these vulnerabilities intermix with one another and produce behavioral effects. Human error as a result of system components began to take on increased importance in the 1990's.

Reason (1990) defines human error as being the failure of planned actions to achieve a desired output. Reason indicates that failures can occur in one of two ways – a planning or an execution failure. A failure at the planning stage occurs when the action conforms to the plan but the plan is inappropriate for achieving the desired goals. A failure at the execution stage occurs when the plan is adequate but the actions deviate from the plan. Reason indicates that errors can be reduced or eliminated by improving information sources within the workplace. Information sources increase the cognitive requirements on the operators in a given system. In Reason's classification, errors are attributed as being either active human failures or latent human failures. Active human failures are failures that are committed by those in direct contact with a system. Latent failures are loopholes in the system's defenses and are points in the system where the potential for human error has existed for some time. The alignment of the system error

potential and the human component to the error performance can be seen in Figure 12. Tightly coupled systems provide error propagation paths in unpredictable linkages. Explanations for the latent error classification surrounds skill-based, rule-based and knowledge-based performance. The physical world is one that is characterized by skill-based rule mechanisms guiding the completion of performance on a task whereas the cognitive world is one that is characterized by knowledge-based mechanisms. Skill-based mechanisms are those mechanisms that are associated with routine, highly practiced tasks while the knowledge-based mechanisms are those that are characteristic of novel, difficult or dangerous tasks (Reason, 1990). Reason's human error concept is organizationally defined but has its etiology in identifying human error root causes that are associated at an individual level.

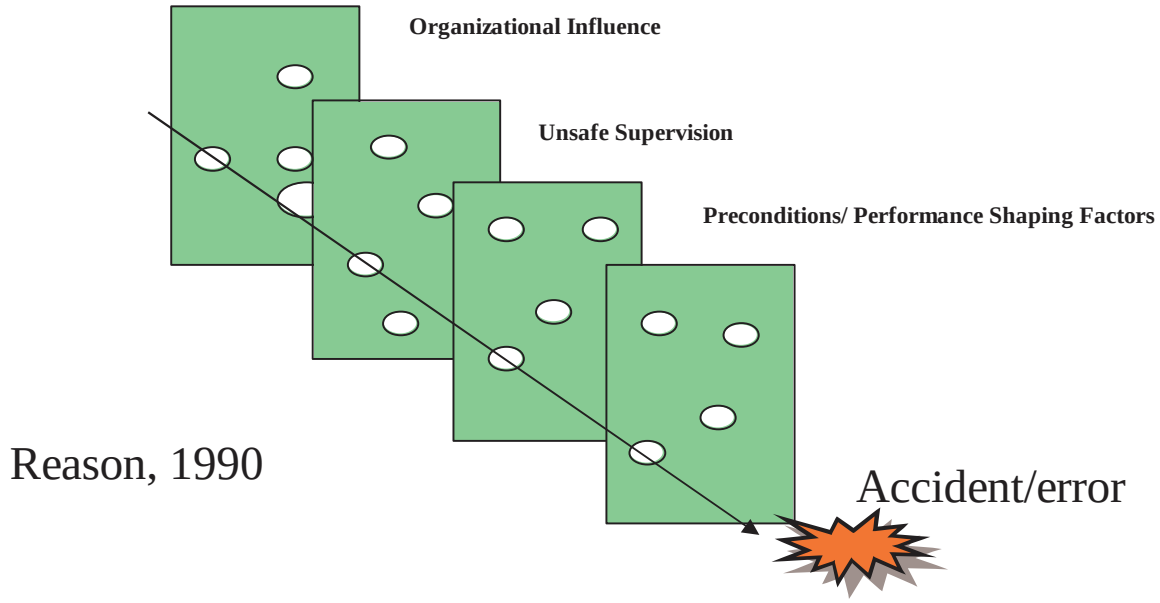

Figure 12. Reason's (1990) alignment of human-system vulnerabilities.

In a parallel theoretical development process to Reason's defined etiology (that has at its underpinning the psychological/cognitive level of human performance), Senders and Moray (1991) conceptualized two streams in defining human error as it relates to human behavioral processes. Senders and Moray's conceptualization differentiates between two forms of error, the first simply termed error, and the second termed human error. Errors are said to occur when there is any deviation from expectation, depending on statistical criteria or experience of normal performance standards. Human error is a deviation from expected human performance. The definition of human error implies that a judgement must be made to some criterion of performance. Senders and Moray state that all errors imply some deviation from intention, expectation or desirability. Failures can not be considered errors if a goal directed behavior was not scheduled to occur. Also, failures can not be considered errors if there was a correctly conceived plan that simply failed on the occasion in question. Senders and Moray reserve the term error for the events within the operator (the perceptual, cognitive and motor events). They differentiate this term with the expression and consequence of errors. Expressions of errors are actions in a well-defined system control task and consequence of error is an

unacceptable consequence in the output of a control system. Errors can only be defined in relation to correct and desired behavior.

Contextual era

Hollnagel (1993) refined Reason's (1990) definition of human error to one specifically aimed at predicting error in cognition. Hollnagel indicates that cognitive errors can be viewed according to how they account for the underlying causes of actions. He indicates that erroneous behavior can be viewed as resulting from sequential/ procedural errors or contextual factors. The procedural model of cognition is a normative model indicating how a task should be carried out. Any deviation to this plan results in an error. The contextual control model of cognition concentrated on how the control action selection occurs rather than focussing on the adequacy of the sequences of actions for attaining the goal. Technological increases in the human-system integration environment are often accompanied by increases in a reliance on human cognition for successful performance and these higher cognitive processes are characterized by higher error rates (Reason, 1990; Hollnagel, 1993). Given this relationship, it is being proposed that the use of cognitive modeling tools that possess validated memory representations will be useful in pinpointing vulnerable environmentally areas (context manipulations).

To date, human-out-of-the-loop (HOOTL) researchers have paid little attention to the environment's impact on the behavioral predictions generated by their cognitive models (with the exception of performance changing factors) and the link between the behaviors and the cognitive processes required by a given situation. One theory that attempts to provide such a link is Hollnagel's (1993) contextual control model (CoCoM) through its cognitive processing module. CoCoM states that a person's comprehension and action depends on how a context is perceived and interpreted. The purpose of the cognitive processing module within CoCoM is to meet a particular goal. This goal is satisfied by actively referring to the environment, to knowledge, or to cognitive processes as opposed to passively responding to the environment. WM plays into this process by storing contexts, which, in turn, trigger relevant answers. These WM modules are sequenced by WM storage. CoCoM views human performance as determined for the most part by the context that characterizes the environment of the human operator and the performance of the individual operator occurs as a result of the active planning ongoing by the individual operator in response to the environment. Hollnagel proposes that the actions that are carried out by the human can fail to achieve their goal as a result of accurate performance according to an inadequate plan (cognitive planning error) or deficient performance (physical error) in carrying out a successful plan. Hollnagel argues that research surrounding human error appears to confuse the causes of the events surrounding human error with the internal psychological processes or cognitive mechanisms that are presumed to explain the action (cause of event versus class of actions). CoCoM outlines the inter-relationship among human internal cognitive mechanisms and control levels on behavioral outcomes. All of these mechanisms demonstrate the impact that context has on impacting the performance of the individual in the environment rather than by an inherent relation between actions.

CoCoM asserts that actions are determined by context rather than by an inherent relation between actions (Hollnagel, 1993). This requires that the choice of future actions at any given point in time be determined by the current context (the situational elements/cues). Contexts are conditions that the operator currently perceives. Each

context is associated with a goal and the context drives goals at specific levels. The choice of action does not need to be a deliberate or conscious decision by the operator. This mechanism is a feedback mechanism contained within the human agent. The CoCoM concentrates on how the control of the choice of future actions rather than on the likelihood or correctness of certain action sequences is made. The sequential evaluation of the tasks is akin to the classical input-output models of behavior while a contextually driven approach may be viewed as a more comprehensive model of human performance prediction.

Error Perspectives

A very interesting approach to quantifying human error has been suggested by Reason (2000) in a recent British Journal of Medicine publication. Reason indicates that human error should be viewed in one of two ways: either from a person view or from a system view. Each view has its own model of error causation and therefore has different philosophies on management of these errors.

The human agent perspective.

The most prevalent view of human error is that error is related to unsafe acts performed by the human. These unsafe acts result in errors and procedural violations. These unsafe acts are attributed to aberrant mental conditions like forgetfulness, inattention, motivation, carelessness, recklessness, or negligence. Methods of reducing these forms of errors have typically been in the form of human performance variability reduction techniques such as increased signage, threats (litigation, retraining, naming, blaming), writing another procedure aimed at countervailing the error vulnerability by targeting the human.

The system agent perspective.

The second view proposed by Reason (2000) is one that views the system as the structure that responds to the inevitable errors that will occur whenever a human is relied on for completing a task or job. The basic tenet here is that the human is fallible and errors are to be expected. The origin of the error is in the upstream systemic factors as opposed to the disobedience of human nature. Errors are therefore seen as a consequence of the system or of the manner in which the system is created as opposed to a cause. The system factors include "error traps" in the workplace or in the organizational processes and procedures that give rise to them. Errors in this representation can be reduced only through changing the conditions under which the human works and not by changing the human condition. The central idea in the system perspective is that the system needs to be proactive in error prevention and take precautions against the erroneous action. This perspective is much less reliant on directing blame (because errors are expected) rather it is more reliant on identifying the reasons that the defenses failed.

In addition to the human component of the error equation, the system also brings some unreliability that may serve to increase or decrease the ability of the human to respond to environmental situations. For example, the environment may change to increase the stress on the operator that in turn serves to decrease the human ability to perform a given task. Stress has an effect on performance, sometimes this effect is a positive effect and sometimes it is a negative effect. Given that these components of the operating environment and of the operator interact and are highly dependent upon each other, it is unlikely that a clear delineation of the causality is possible. It becomes

difficult to anticipate all of the situations that may be faced by the operators when the system is modified and changes the context of the operators' operating environment. It is for this reason that computational human performance models have been proposed as a method to identify aspects of human-system vulnerability early in a concept development. Reason's classification is however driven by an organizational structure while Hollnagel's characterization is more general in nature.

Human Performance Modeling

Human Performance Modeling (HPM) is a human-out-of-the-loop (HOOTL) simulation methodology that uses computer models of human performance to create virtual human agents that interact with new technologies and procedures. HOOTL simulations can be used early in the development process of a product, system or technology to formulate procedures, and training requirements. Also, HOOTL simulations can be used to identify system vulnerabilities where potential human-system errors are likely to arise. This will have implications for operator safety, operator productivity, and efficient system design. This computer-generated representation of the human and the environment allows for the use of HOOTL methods early in the design phase of a product, system or technology. This possesses cost and efficiency advantages over waiting for the concept to be fully designed and used in practice (characteristic of human-in-the-loop, or HITL, tests). The system model development process allows the designer of the product, system or technology to fully examine many aspects of human-system performance with new technologies.

Many different forms of HOOTL simulations exist ranging from anthropometric human performance simulations, procedural static models, through to more complex dynamic representations of human-environment performance. These latter HOOTL simulation techniques include integrated human performance models which use computer models to characterize a human-system environment within a computational framework. The human characteristics that are embedded within the computational framework are based on empirical research collected over the past 20 years and these interact to comprise the virtual operator. The virtual operator is then set to interact with computer-generated representations of the operating environment over a series of repeated runs in much the same manner as testing human subjects over repeated experimental sessions. The model of human performance enables predictions of emergent behavior based on elementary perception, attention, working memory (WM), long-term memory (LTM) and decision-making models of human behaviors. This modeling approach focuses on micro models of human performance that feed-forward and feedback to other constituent models in the human system depending on the contextual environment that surrounds the virtual operator. One criticism of HOOTL tools has been that the software only predicts input-output behavior in mechanistic terms (Craik, 1947). The integrated and emergent structure of the tools however does more than solely represent input-output behavior, it attempts to prescribe how sequences of actions are planned and not simply prescribe a sequence of actions. The framework integrates many aspects of human performance allowing each micro model component to behave in its required method, the integration of which replicates a human (Gore & Corker, 2000a). Hollnagel (2000) indicates this as being critical for developing a good model.

The output measures of interest for HOOTL simulation efforts have traditionally included task demands, (mental) workload, task load, information load, attention

demands, stress and procedural timing measures. These measures have been used to identify if, when, where, and how often errors occurred within a specific job design and combined with the load measures could be used to determine re-organized procedures to reduce time and load demands. These measures have been validated on a number of occasions across many different domains ranging from helicopter operations (Atencio, 1998), nuclear power-plant control electronic list design for emergency operations (Corker, 1994), to advanced aviation concepts (Corker, Gore, Fleming & Lane, 2000).

Air MIDAS

Air MIDAS is an "emergent" model of human performance – one that is based on the mechanisms that underlie and cause human behavior (Laughery & Corker, 1997). The main components of the emergent model shown in Figure 13 comprise the simulated representation of the virtual operator's world, and a symbolic operator model (SOM) that represents perceptual and cognitive activities of an agent. An important element of the SOM is the Updateable World Representation (UWR). The world representation information (environment, crew-station, vehicle, physical constraints and the terrain database) is passed through the perceptual and attention processes of the SOM to the UWR. The world information is a complex environmental representation that is created by the researcher or programmer and serves to trigger activities in the virtual operator. The UWR represents the agent's cognitive constraints on procedural completion – it contains the WM, domain knowledge and required procedural activity structure. The UWR passes information to a scheduler within the SOM that determines the resources available for the completion of the activity. The scheduler views WM and the measures contained within it as a capacity-limited resource. A four-channel activity loading mechanism (Visual, Auditory, Cognitive, and Psychomotor) is representative of the measures contained within WM and these activity load factors are used as constraints on the scheduling process (McCracken & Aldrich, 1984). The scheduler controls the flow of UWR into and out of WM based on its knowledge of activities to be performed ensuring that the number of nodes in WM at any given time does not exceed the WM node capacity (with the exception of daemon-introduced nodes into WM). This cognitive structure interacts with physical constraints on an individual's performance and interacts with other representations of individuals in the simulation.

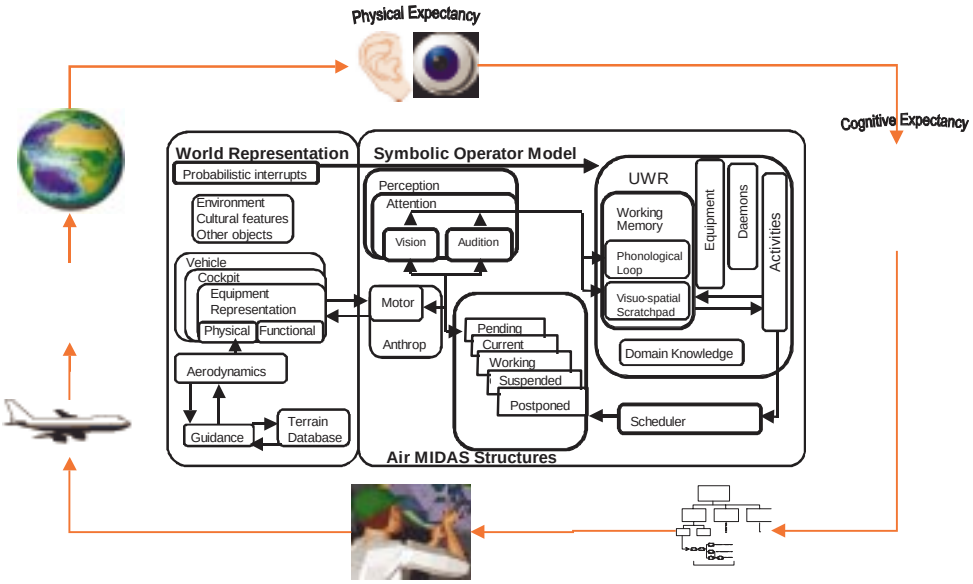

Figure 13. Internal structural representation of Air MIDAS.

The representation within the Air MIDAS structure possesses the ability to represent a planning mechanism in order to instantiate general plans based on the specifics of a given situation. The MIDAS architecture can not create new plans however. Air MIDAS is also able to engage in decision making behavior using heuristics and rule sets to guide the behavior of the model. MIDAS is further able to model multitasking due to its scheduling mechanisms, task interruptions and task priorities. Air MIDAS is also able to model performance on several tasks at once. This is invoked in the attention and multitasking mechanism contained within its structure demonstrated in Figure 13. The performance of procedures in this format is associated with scheduling priorities, importance, urgency, probabilities, training, and anticipated ability to accomplish certain tasks in parallel without specified loss due to sharing.

Air MIDAS is also able to produce emergent multiple operator behavior interacting within the same environment. This is particularly useful for modeling the aviation environment. Air MIDAS is exercised in a multiple run operating mode (termed Monte Carlo simulation). In this mode, each run constitutes a travelling (taxiing) event. The loading factors on the operator over time vary from run to run depending on the stochastic variations in each agent's behavior and stochastic elements in the environment. The result is that each run in unique and varies to some extent. This results in a distribution of performance times and potential differences in the quality of the simulated operators' performance and provides some insights into the system safety related effects of incorporating changes in the system environment.

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Appendix B - List of Human Performance Modeling Program Publications

Gore, B.F. (in press). Human performance cognitive-behavioral modeling: A benefit for occupational safety. In B. Chase & W. Karwowski (Eds.), Journal of Occupational Ergonomics and Safety.

Gore, B.F. & Corker, K.M. (2002). Increasing Aviation Safety Using Human Performance Modeling Tools: An Air Man-machine Integration Design and Analysis System Application. To appear in the Symposium on Military, Government, & Aerospace Simulation for ASTC 2002, The Society for Modeling & Simulation International (SCS), San Diego April 2002.

Gore, B.F. (in process). An emergent behavior model of complex human–system performance: An aviation surface-related application. To appear in the Fifth Proceeding of the Third Annual SAE International Conference and Exposition - Digital Human Modeling for Design and Engineering, Munich, Germany, June 2002.