Human Performance Modeling: A Cooperative and Necessary Methodology for Studying Occupational Safety

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Abstract: Integrated Human Performance Modeling (HPM) is a human-out-of-the-loop (HOOTL) methodology for studying complex human-system performance. The U.S. and international military forces have used HOOTL methodologies for years to study complex human-automation integration and system flow patterns in battlefield management simulations. More recent application of HOOTL technologies has been in complex work environments such as aviation, medical and nuclear power plant domains. It is proposed in this methodological paper that the use of HOOTL technologies when used cooperatively with human-in-the-loop (HITL) simulations can result in human performance vulnerability identification and may provide clues on ameliorating human performance when operating in complex work environments. Demonstration of the use of human performance models from a recent NASA Ames Research Center study on a Distributed Air-Ground Traffic Management (DAG-TM) concept known as free flight will provide evidence of the value of HPM tools when used early in a system design phase. Model predictions and human performance predictions will provide evidence of the value of HOOTL system predictions of intervention strategies in complex systems. A parallel will be drawn to more traditional occupational safety applications.

1. Introduction

A similarity exists between the aviation and the occupational safety fields. Both fields are attempting to integrate new technologies with current procedures in an effort to increase productivity while maintaining safety in the operational environment. One common method to examine this automation integration is through the use of Human-In-The-Loop (HITL) simulations and another more recent method is through the use of Human-Out-Of-The-Loop (HOOTL) simulations. The occupational safety field is facing a similar constraint to the one challenging the aerospace industry, that of HITL simulations leading the HOOTL requirements when HOOTL techniques should be used as a process to assist the HITL simulations. In both aviation safety and occupational safety, simulation involves an integration of independent elements (technologies, service providers, and service receivers), the logistics of whose coordination places a complexity and expense burden on HITL simulations. In commercial aviation, there is a balance between the safe transport of passengers in the National Airspace System (NAS) and efficiently providing the transport services. One proposal that has been made in the NAS has been to reduce some of the rigid airway structure guiding the current aviation community by bringing more separation authority into the cockpit and removing some of the responsibility from the ground. This has been termed "free flight" or Distributed Air-Ground Traffic Management (DAG-TM) [1]. This reduction in rigid airway structure has led to increases in automation in both the cockpit and on the ground, with the cockpit display of traffic information for the flight crews, and the User Request Evaluation Tool and the Display Suite Replacement for the air traffic controllers. The use of automation has been proposed as a means of increasing worker productivity and reducing worker error. Often times however, the introduction of automation has an unforeseen impact on the human operator, changing the nature of the responsibility of the human operator from physical task execution to cognitive task processing which results in new kinds of errors and error patterns [2,3]. A complete examination of the specific paradigm that surrounds the human operator interacting with performance modifiers is indeed warranted prior to the adoption of any such modifying technology.

A number of methods exist for studying human performance in systems and consequently human error in systems. We are able to examine the performance of individuals in HITL, high-fidelity simulations as the human operates in the complex system or HOOTL predictive simulations. The use of HITL simulation has been proposed as a methodology for examining human-systems performance in a safe and controlled environment in the surface transportation and aviation communities [4,5]. This technique has proven to be successful in accomplishing the goal of safely and realistically evaluating human-system behavior but has the disadvantage of being very complex and costly, often times prohibiting its use. A second methodology, HOOTL simulation, is one that uses computer models of human performance as the human agent interacts with new technologies and procedures. HOOTL simulation is an alternative methodology to these expensive HITL simulations in that

HOOTL simulations can be used at an earlier process in the development of a product, system or technology. HOOTL simulation tools are computer-based simulation processes where human characteristics, taken from years of research from respective fields, are embedded within a computer software structure to represent the human operator interacting with computer-generated representations of the human's operating environment [6,7,8]. The human characteristics in many of the integrated HOOTL simulation tools include visual and auditory perceptual and attention systems, anthropometric characteristics, and environmental characteristics (including workstations as well as the outside environment). These structures feed-forward and feedback with the goal of predicting human behavior. These complex integrated HOOTL simulation tools permit researchers to formulate procedures, to generate hypotheses, and to identify variables for upcoming HITL simulations. The output measures of interest for HOOTL simulation efforts from the aviation community generally include workload and timing measures. These measures have been validated measures of human performance on a number of occasions across many different domains ranging from helicopter operations [9], to nuclear power-plant control electronic list design for emergency operations [10], to advanced concepts in the aviation domain [11,12]. Many different forms of HOOTL simulations exist - these can range from anthropometric simulations of human performance to procedural static models, through to more complex dynamic representations of human performance within an operating environment. These latter techniques include integrated human performance models. The dynamic representations of human performance require a static representation of the overall task structure that is performed by the agent in the simulation. Since the human operator responsible for interacting in these systems is not present in the actual system evaluation, the risks to the human operator and the costs associated with system experimentation are greatly reduced: no experimenters, no subjects, and no testing time. One criticism of HOOTL tools is that the software only predicts input-output behavior in mechanistic terms.[1] The integrated structure of the tools however does more than solely represent input-output behavior. 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.

HOOTL simulation tools have been especially useful in studying complex input and output behaviors [4,5]. The recent growth in HOOTL simulation tools have been focused on the study of human performance interacting with systems [5] and to support prediction of future system state [4]. These hybrids of continuous control, discrete control and critical decision-making models have been undertaken to represent the "internal models and cognitive function" of the human operator in complex control systems, and involve a critical coupling among humans and machines in a shifting and context sensitive function. A pictorial representation of one of the integrated HOOTL simulation tools, Air MIDAS, can be found in Figure 1. Air MIDAS was co-developed by NASA Ames Research Center (ARC) and San Jose State University (SJSU) primarily for aviation-related applications such as the examination of procedural rule set changes on critical event recovery in the NAS.[2] Given that the tools have been applied to the aviation domain, the current paper will demonstrate some of the recent aviation related modeling applications.

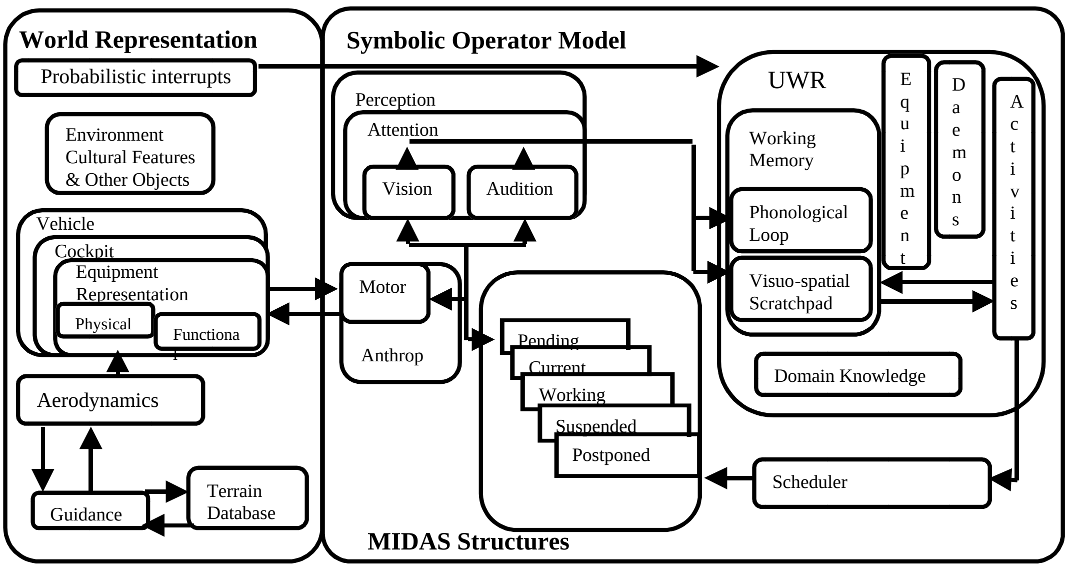

Figure 1. Internal structural representation of Air MIDAS.

[1] For a complete discussion of the advantages and disadvantages of HPM, please consult [5].

[2] Air MIDAS is differentiated from Core MIDAS, the NASA/Army simulation software tool.

Air MIDAS is based on "first principles" of human performance [6]. The first principles approach to modeling human performance is based on the mechanisms that underlie and cause human behavior. The main components of the first principles model shown in Figure 1 comprise the simulated representation of the real world within which the agent modeled by Air MIDAS exists, and a symbolic operator model (SOM) that represents the perceptual and cognitive activities of the agent. An important element of the SOM is the Updateable World Representation (UWR). The world representation information (environment, crewstation, vehicle, aerodynamic constraints and the terrain database) is passed through the perceptual and attention processes of the SOM to the UWR. The UWR represents the agent’s working memory, domain knowledge and activity structure of the tasks to be completed. This UWR passes information to a scheduler within the SOM that determines the resources available for the completion of the activity. The activities that are contained within MIDAS are procedures of operator actions. The environment triggers the activities (procedures) within the agent and the agent completes the desired procedure in accordance with the availability of the resources in the agent. The scheduler invokes rules to determine the triggering of procedures. Procedures can be postponed, suspended, working, current, or pending. In turn the SOM selects activities to perform, some of which interact with the representation of equipment in the simulated world and change the behavior of the relevant part of the system. This series of actions and interactions among the structures within the HOOTL software is key when attempting to model contextual effects on performance.

Current NAS research efforts have focussed on creating dynamic models of human performance and, more recently, on anticipating human error. The motivation within the aviation community is to economically provide the greatest volume of air service in the safest possible fashion. The agencies involved in NAS operation are looking to automation as the means of accomplishing this goal. The occupational therapy world is also considering technological advances for increasing worker productivity in the safest possible fashion. In both cases the introduction of automation may change the nature of the human agent's task, may change the responsibilities, may change the agent's situation awareness, may affected the agent's vigilance and there may be changes in the pattern that surrounds the error rates of the human agent [2,3]. The aviation community uses a system of reporting accidents and incidents termed the Aviation Safety Reporting System (ASRS) or a newer reporting system known as Aviation Safety Action Program (ASAP) [13]. While these mechanisms have been useful for examining precursors to aviation-related incidents, they are also used as the basis for creating research concept plans. A similar reporting mechanism to the ASRS and the ASAP exists within the occupational safety field. The Occupational Safety and Health Administration (OSHA), the National Institute of Occupational Safety and Health (NIOSH), the Society of Work Science (SWS), and the International Labor Organization (ILO), among others are groups, were formed to develop a voluntary standard and regulatory regime to protect the individual worker within the work environment. These groups have the goal of reducing and, where possible, eliminating work-related illnesses. OSHA was developed in the 1970s to establish some guidelines for the majority of the working population and did not reserve their findings to a select group. In 1995, OSHA documented a number of risk-mitigation requirements to control problem jobs by reducing or preventing worker exposure to certain workplace risk factors. OSHA and NIOSH standards however deal mainly with physical issues of completing a task and do not necessarily pay credence to the cognitive issues or the cognitive-physical interaction issues that occur during a job. The more complex HOOTL simulation tools integrate both the physical world with the cognitive world and create an emergent model's prediction of a human operator agent's performance in a complex work environment. The emergence of these predictive HOOTL simulation tools to safely examine system concepts designed to increase productivity while maintaining safety can be used as a starting point for human-system interaction considerations in the occupational safety field. The research plans would use the wealth of literature from the physical issues within a job environment from existing reporting mechanisms. The occupational field can then work to create valid representations of linkages between the physical and the cognitive worlds as applied to the occupational world to augment the HOOTL technologies from other fields. The visualization component of the Core MIDAS simulation software co-developed by the Army and NASA at NASA ARC as shown in Figure 2 exemplifies this cognitive and physical linkage. This graphic demonstrates an anthropometric figure interacting with an environment (left-hand screen), and the corresponding view from the anthropometric figure's eyes. The subsequent six-channel workload representation can be found on the lower left portion of the screen while the situation awareness of the anthropometric agent in response to the environmental conditions is presented on the lower right panel.

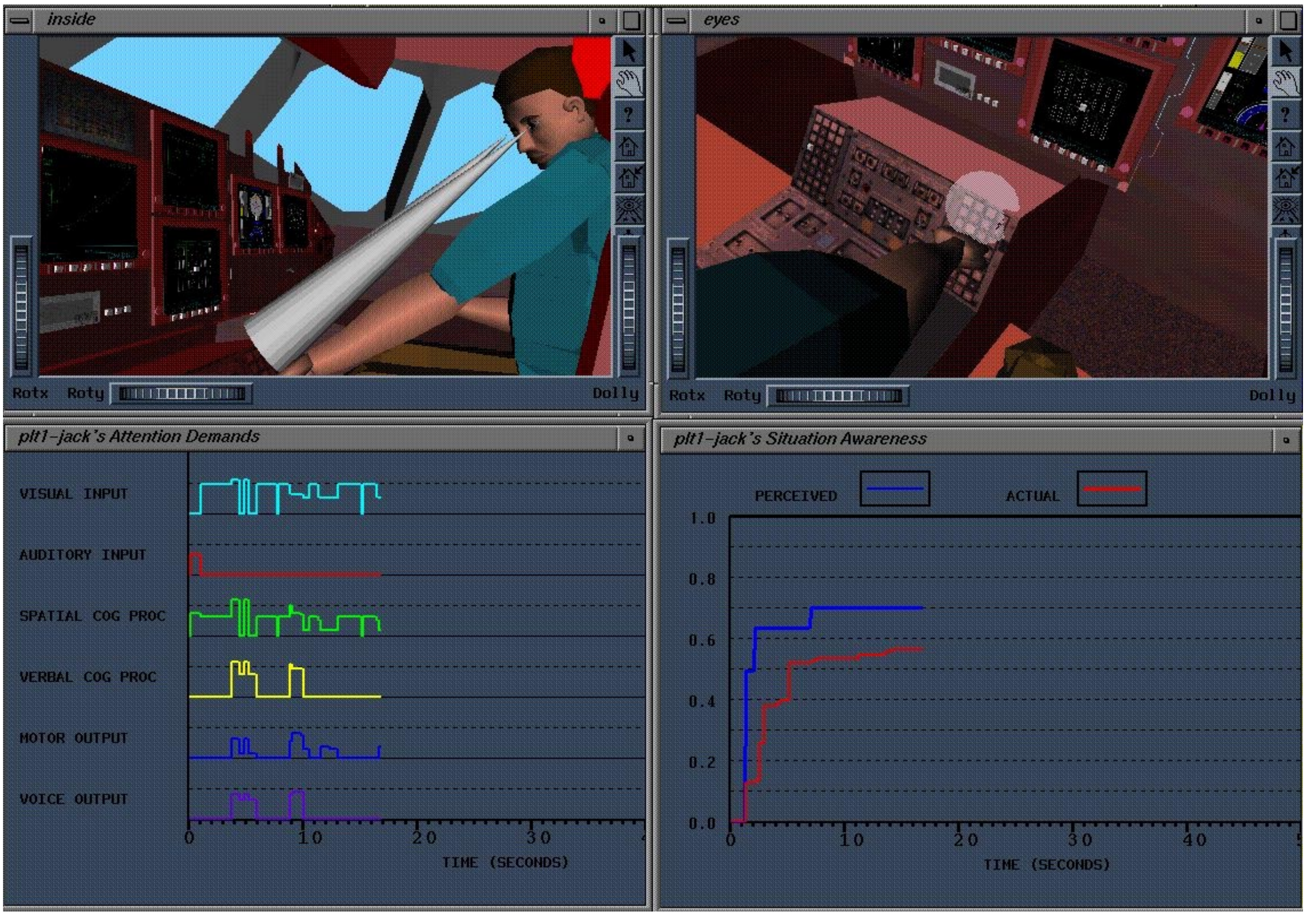

Figure 2. Core MIDAS' Operating Environment Visualization of an agent profile (top left), agent's eye view (top right), agent's workload (bottom left) and Situation Awareness (bottom right) along a scenario timeline.

2.1 HOOTL Prediction of Operator Performance - Experimental Design and Assumptions

An experiment conducted at NASA ARC examining the NAS-effects of a procedural rule-set change demonstrates the impact on workers of incorporating advancing technologies and automation on human performance through a HOOTL experiment and a corresponding HITL simulation experiment. For the purposes of the current paper, we will be focussing on the procedural rule set's effect on human performance. We are particularly interested in looking at the workload data in the comparison between HOOTL and HITL data.

The first stage completed was a procedural identification of the current day rules followed by an identification/prediction of procedures required for the successful navigation of the NAS in an advanced concepts environment. This required some expansion on existing procedures due to the introduction of new technology and automation. The examination of the current operating environment was completed through an evaluation of documentation on the procedures that are currently undertaken by the worker in the system, in this case, the flight crew and the controllers. The ASRS and ASAP programs were used to identify certain system vulnerabilities in the aviation system; this being the rules of travel and aircraft separation as proposed by the Requirements for Technical Concepts in Aviation (RTCA). This recommendation committee identified vulnerable aviation operations areas and outlined where automation was likely to be designed in an attempt to counter the system vulnerability [1]. A HOOTL simulation of the predicted performance in the DAG-TM was completed. A complete review of the experimental design is available [7] but some context is provided here. Two scenarios were created in the current effort and each scenario was run through 50 Monte Carlo runs for each of two agent crew (ground and air). There were four data sets per simulation run made up of the manipulation's 'agent location', and 'locus of control' (rules of travel). Each scenario was run in an en route flight condition of twenty minutes in duration traveling through a generic ‘high altitude’ airspace section. In all scenarios the aircraft was subject to an airspace conflict with an intruder aircraft approaching from the East heading West. The multiple passes through the scenario are analogous to testing multiple subjects. This experiment collected data on four categories of dependent measures including safety-, operational-, controller/internal-, and flight crew/internal-related measures. The safety-related measures included efficiency information including aircraft positional information, clutter, and time in sector. Operational measures included controller-related operations and flight crew-related operations. Controller operations included calls to adjoining sectors, clearances to aircraft, and controller calls received. The flight crew operational measures included calls to the aircraft from the controller, time of call and flight crew action taken.

[1] HOOTL Prediction of Operator Performance - Results

The output measure of interest in this paper was the human agent workload. For a complete discussion of the HOOTL simulation results, the reader is directed to consult [5] and [7]. The workload data were measured along a seven-point scale. Results of the current HOOTL simulation data indicate that the procedural rule set change does in fact possess a significant effect on the agent's conflict resolution performance. The mean data presented in Figure 3 show that the DAG-TM operations resulted in significantly greater workload than did the current day operations, $\underline{F}$ (1,98) = 11929.43, $\underline{p} \leq .001$.

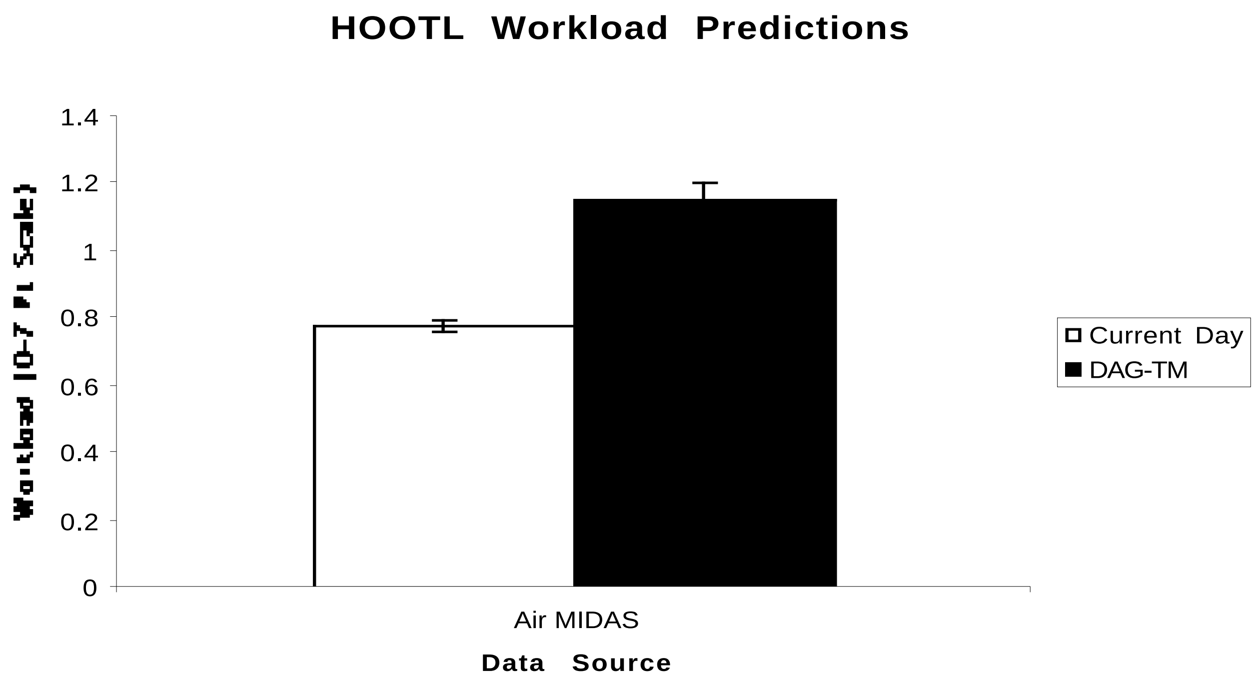

Figure 3. HOOTL workload prediction data.

Of note in the examination of the HOOTL workload prediction data is the relatively small difference among the predictions of both rule sets for workload. This difference, although small, is indeed a significant difference between the two rule sets' impact on the agent's workload. Although this modeling effort has been fully verified and the strictest alpha levels were used for the statistical comparison, the model predictions should be examined within the framework of the actual operational environment as a method of validating the findings of the model

3.1. HITL Prediction of Operator Performance - Experimental Design and Assumptions

The model predictions were compared to findings from a separate project, a HITL research project, completed by Embry-Riddle Aeronautics University (ERAU) and SJSU that examined the impact on workload of varying levels of control of aircraft separation. Please consult [11] for a complete review of the HITL experiment. The HITL experiment was intended to explore the limits in performance of DAG-TM operations (in the form of aircraft free maneuvering and self-separating) undertaken in a complex center airspace. The experiment concentrated on the performance of the air traffic controller working the radar and communication position in a sector of Jacksonville Center.

[1] HITL Prediction of Operator Performance - Results

The parallel research effort from ERAU and SJSU study examining the HITL performance effects of a procedural rule set change provided a similar data trend to the HOOTL simulation. The workload data were measured along a nine-point workload scale in the HITL simulation. Upon examination of the difference between the rule sets (Figure 4), it can be seen that the HITL simulation data provided a similar significant pattern to the one predicted by the HOOTL, with DAG-TM rules requiring significantly more workload than did the current day (F (3,31) = 40.89, $p \leq .0001$).

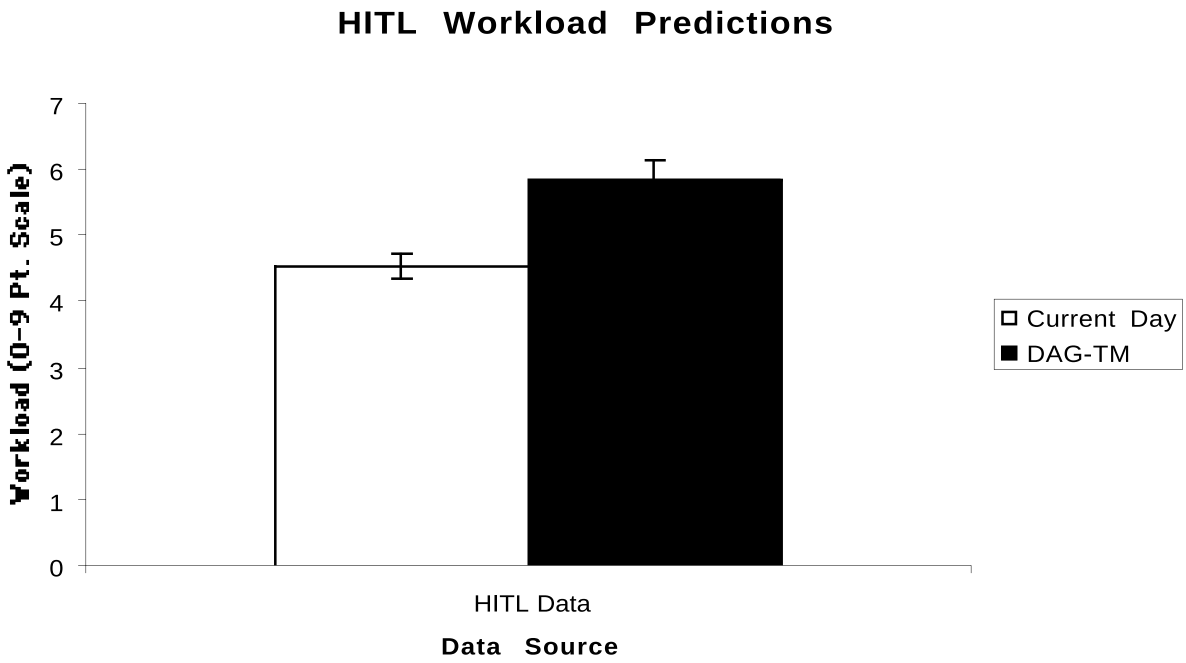

Figure 4. HITL workload prediction data.

This significant result is not surprising because the incorporation of the DAG-TM rules into the current operations will likely increase due to the additional controller monitoring tasks and the increased flight crew monitoring and re-action tasks that are required during the phase-in period of DAG-TM. Some differences can be seen when comparing this HITL data to the HOOTL data in the variability around the means and in the actual workload numerical values. These differences were expected and were thought to not be critical given that this effort was designed to test some of the procedural methods and timing requirements of incorporating new technologies and automation into a complex operating environment.

4. DISCUSSION

The NASA-SJSU software tool, Air MIDAS, as well as other integrated HOOTL simulation tools that currently exist (e.g., IPME, Micro SAINT, ACT-R, EPIC, OMAR, SOAR) are able to model many different components of occupational work environments and the contexts impacting upon the operator. The research presented from the aviation domain demonstrates one of the possible approaches to modeling human-system performance in one such occupational environment. The environmental/contextual characteristics that were examined in the current study were those associated with the system - the rules of flight. Other environmental/contextual characteristics to the task flow-rates associated with the introduction of new technologies/procedures discussed in the current paper could have been modeled to see the predicted effect of the environment/context on the operation of the agents in the operational environment. Some other possible application areas that are ripe for modeling contextual effects include[3]: extreme temperature's impact on performance, air turbulence or convective weather's effect on performance, an increase in time pressure (work/rest schedules), staff deployment due to environmental event or flow movement in an operating environment. In addition to the environmental characteristics, user specific characteristics such as a

[3] This is just a partial list of some of the application areas; other application areas are possible.

user's experience level, time since training, a change in worker skill level or the impact of additional 'workers' on performance of the primary crew member could also be modeled. This last example shows to the usefulness of these modeling tools to the application area of modeling team coordination (crew communication), operator actions and operator error pattern issues. Given that all of these are possible influences on human performance in an occupational environment, the use of the integrated HOOTL simulation tools merits some attention for consideration in the Occupational Ergonomics and Safety Field.

An important consideration in selecting a HOOTL simulation tool is the degree to which it has been successfully validated both within the field to which it is being applied and validated in a general sense across fields. The validation efforts are HITL simulations that are compared to the HOOTL simulations. Many of the micro models contained within the NASA-SJSU HOOTL simulation tool have been appropriately validated across a wide range of application areas: evaluations of nuclear power-plant electronic checklist design [10], advanced concepts in aviation [11,12], emergency dispatch console design in 911 stations [14] short-haul civil tilt rotor [15] and integrated protective aviator suits [16]. Some additional validation efforts include the levels of staffing required for successful completion of a work-related activity [17], the interaction of the different levels of training among crew members [17], and the effect of stress, skill level, and fatigue on performance [17]. The research from the aviation community presented herein demonstrates that the integrated HOOTL simulation tools' findings are valid representations of the performance of individuals operating in complex work environments, specifically as applied to system performance. The value of the data presented in this paper lie in the presentation of integrated structure of the HOOTL simulation tools' output being representative of HITL experimentation. Human performance is predicted to be influenced by the incorporation of automation designed to assist the human performer overcome some of the vulnerabilities in system performance. The precise values associated with the human workload however, are not necessarily correct in an absolute sense. The relative effect of the manipulations that were made in the study were supported by the HITL data from the ERAU and SJSU study completed in 2000. This demonstrates that the HOOTL simulation tools do provide data that trend in similar directions to HITL performance. The experiments must be designed to evaluate similar components to the aviation domain. This is providing some evidence that HOOTL simulation tools should be used early in the design phase as they provide valuable insights into certain human performance vulnerability potentiality. The key to the usefulness of the HOOTL data is in its validity to actual HITL performance data. In order to do this, a statistical comparison is required of the HOOTL and the HITL data but these data comparisons and thus the data collection needs to be compared in an a-priori fashion. This means that the HITL simulations and the HOOTL simulations need to be created and evaluated in parallel.

This article suggests two inter-related ideas for the advancement of safety in the occupational ergonomics and safety world. The first is that the two methodologies outlined, the HOOTL and the HITL simulations, need to be used in a cooperative manner. An example of the method in which this is possible is demonstrated from the advanced DAG-TM concept in the aviation domain. The iterative design process with early and constant input from the human factors researcher allows for more usable products and concepts. The lessons that are learned from the HOOTL domain need to be augmented and validated with the use of the HITL simulations and that the HITL simulation domain needs to recognize the findings from the predictions being generated from the modeling domain. HOOTL simulations have been shown to be useful for gaining an understanding of complex human-system operations and areas of human-system vulnerability at a very early stage of technological integration. These simulations are created as a means of identifying potential problem areas and possible solution alternatives for the system. Once these vulnerable areas have been simulated, modifications can be made to the procedures or technologies within the system to examine the impact on the human performer and hence on the safety of the system. The practitioner or researcher needs to carefully consider all the implications of a specific design on human performance. If considerations are omitted due to design oversights they may negatively affect human performance. The identification of the "system vulnerabilities" permits system designers to improve system design through safety assessments and system risk mitigation efforts, through predicting appropriate staff selection and training, and through predicting correct specification of organizational patterns to be performed by the human operator agent.

The second idea is that HOOTL technologies permit one way of quantitatively measuring the system effects of implementing automation and system changes in a relatively *cost effective manner* for the user population. The introduction of automation designed to increase human performance often results in unforeseen consequences that negatively affect the safety of an occupational system (2,19). Some common issues with automation in the occupational safety and aviation domains include: higher level operator errors, workload effects due to operator role changes, inaccurate situation awareness resulting in decreased productivity, misallocation of attention and cognition, environmental and human reliabilities in response to specific events, out-of-the-loop unfamiliarity, loss of coordination between human operators and the effects of automation on system vulnerabilities. This fact often calls for higher fidelity and more comprehensive HITL simulations to fully examine the human performance impact of the technological introduction. Inserting advanced technology and automation into costly high fidelity HITL simulations without a full understanding of the likely human performance effects a-priori, results in inefficient uses of HITL simulation. As with any research field, the HITL simulation field is attempting to maintain an acceptable level of cost in a very expensive simulation environment (computationally and monetarily) while studying all relevant aspects of human performance as they interact in the complex operating domain. If the entirety of the system is not fully studied, the technology integration may result in unsafe system implementation. HOOTL software tools are able to provide insights into this system-safety-related information through quantitative output of workload and timing performance. Once the system-safety-related information and its human performance impact is known, manipulations can then be made to the environment (context) in order to examine the impact on the productivity of the human operator. This is performed in an effort to assist in creating a fault-tolerant system (mitigating the consequences once an error has occurred) and to assist in optimizing task organization and allocation. Besides solely predicting the vulnerabilities in human-system integration, the HOOTL simulations may be able to identify and recommend remedies to likely human error points and to identify the steps that need to be taken in order to rectify the situation through contextual manipulations. Once the vulnerability has been identified, a manipulation can be made to the components of the system in an effort to target the vulnerable aspect of the system. This HOOTL/HITL coordination may allow the occupational safety field to find human performance vulnerabilities for the complex integration of technologies that are aimed at augmenting worker productivity. The balancing act of attempting to increase worker productivity and monitoring costs incurred in doing so requires a fully researched paradigm. One method of obtaining this difficult goal is through the HOOTL/HITL coordinated efforts.

The HOOTL methodology serves as an example of the considerations that need to be heeded when examining the performance of humans in the increasingly complex work environment that generally surrounds efforts aimed at increasing worker productivity. An often-omitted area of human performance is the interaction of the physical environment with the cognitive environment. Some HOOTL software tools[4] attempt to integrate the two aspects of human performance and create an output that is characteristic with HITL performance. Many studies exist that demonstrate the validity of these tools and therefore lend credibility to the findings that are generated from the model's outputs of system performance. The lessons learned from the aviation domain may assist in the considerations of the occupational safety field when attempting to find suitable processes for the examination of system effects within such a complex system as the one facing the increasingly complex occupational work environment.

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