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**AN INTEGRATED APPROACH TO ROTORCRAFT HUMAN FACTORS RESEARCH**

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**ABSTRACT**

*As the potential of civil and military helicopters has increased, more complex and demanding missions in increasingly hostile environments have been required. Although new subsystems are being designed to meet these requirements, mission demands may have increased to the point that pilots will be overloaded during critical flight phases. Consequently, users, designers, and manufacturers have an urgent need for information about human behavior and function to create systems that take advantage of human capabilities, without overloading them. Because there is a large gap between what is known about human behavior and the information needed to predict pilot workload and performance in the complex missions projected for pilots of advanced helicopters, Army and NASA scientists are actively engaged in Human Factors Research at Ames. The research ranges from laboratory experiments to computational modeling, simulation evaluation, and inflight testing. Information obtained in highly controlled but simpler environments generates predictions which can be tested in more realistic situations. These results are used, in turn, to refine theoretical models, provide the focus for subsequent research, and ensure operational relevance, while maintaining the predictive advantages of a theoretical foundation. The goal of this paper is to describe the advantages and disadvantages of each type of research, provide examples of experimental results, and describe the Ames facilities with which such research is performed.*

## INTRODUCTION

In the four decades since World War II, military and civil helicopter uses have expanded greatly. And, as an appreciation for the potential of helicopters developed, new dimensions in mission requirements evolved. As helicopters have acquired new missions, new tactics and performance requirements evolved that require the effective use of many subsystems and sensors in increasingly hostile environments. Traditionally, pilots have adapted to and integrated such increasingly complex displays and controls. However, the performance and attention demands of high technology vehicles are increasing so dramatically, that there is a growing concern that pilots will be unable to perform their missions safely and effectively. For example, the difficulty of nap-of-the-earth (NOE) missions and the complexity of systems that must be operated or managed at the same time, often imposes intolerable demands. It is becoming evident that the point has been reached where pilots are overloaded during critical phases of some missions, contributing to mission failures and the loss of life and costly equipment. Plans to reduce flight crew size (most notably to a single-member crew) will only exacerbate this growing problem. Although both cockpit and training system designers have tried to keep pace, it appears that advanced technology systems may not be making the most effective use of pilots' capabilities. Furthermore, even the most complex and expensive training systems may not prepare pilots to perform required functions effectively and safely.

There is a large gap between the information available from laboratory research about human behavior and the information required to predict pilot performance and workload in advanced helicopters flying the complex, difficult, and hazardous missions that are proposed. This deficiency may manifest itself in cockpit designs and unrealistic mission requirements that challenge human adaptability and excessive training system costs.

To provide the information that is needed, human factors researchers evaluate basic perceptual, cognitive, and manual control abilities and measure and model the relationships among such abilities, advanced design concepts, and different flight environments. They perform research in laboratories, computer simulations, aircraft simulators, and in flight. Each level of research has advantages and disadvantages and provides different types of information. The data obtained in the controlled environment of the laboratory generates detailed information about specific points and predictions about human behavior which can be tested in more realistic (but less well-controlled) situations. These results, in turn, provide a focus for subsequent research and contribute to the theoretical models. By taking advantage of a range of research facilities, the requirements of theoretical development can be balanced against those of the "real world" and operational relevance is ensured at the same time that the predictive advantages of a theoretical foundation are maintained.

This report will review the advantages and disadvantages of the different types of research. In addition, it will provide examples of the research results that have been generated by NASA and Army researchers in

collaboration with industry and academia that might be relevant to the design of advanced helicopters. Finally, the facilities available for human factors research at Ames Research Center will be described, very briefly.

## LABORATORY RESEARCH

### Description

Research conducted in a laboratory environment is generally simple, highly focused, and characterized by considerable experimental control. Laboratory facilities include an isolation booth (where the subject is protected from unwanted and irrelevant interruptions), microprocessors, visual and auditory displays, and discrete, vocal, and analog control devices. Experiments are designed so that the input (visual and auditory stimuli) and the output (verbal and manual responses) can be quantified accurately and directly. The intervening cognitive processes are predicted from psychological models and inferred from variations in the speed and accuracy of performance, physiological responses, and subjective ratings.

### Advantages and Disadvantages

The experimental tasks used at Ames, as elsewhere, are designed to develop and test theories of human performance, memory and attention or to resolve specific applied problems in a controlled environment. Their focus is narrow, the range of factors manipulated limited, and they provide highly simplified representations of "real-world" task components without the realism of interactions among multiple subtasks. Thus, their external validity (e.g., their immediate and obvious relevance to the complexities of NOE flight in advanced-technology helicopters) is not always apparent.

However, laboratory research *can* and does provide answers to fundamental questions about human behavior, because it is possible to eliminate or control irrelevant variables and manipulate relevant variables precisely. If the theories developed are sound, their predictions can then be generalized to other situations, beyond the original vehicle-specific focus that prompted the research. Because laboratory research costs very little, and can be accomplished quickly, solutions can be provided efficiently.

Unfortunately, many useful ideas and information developed in the laboratory are not brought to the attention of designers because the researchers often do not verbalize, or test, the applicability and validity of their results to operationally-relevant tasks and environments. In addition, the results of individual, microscopic, laboratory experiments are often organized by the theories they were designed to test. However, these theories and their data bases are rarely integrated into a cohesive body of useful knowledge. Thus, the results of many laboratory experiments are not available for and do not contribute to the design process.

## Examples of Research Results

### *Evaluation of Auditory and Visual Displays*

With the advent of increasingly sophisticated helicopters, such as the UH-60 Blackhawk and the AH-64 Apache, Army helicopters are increasingly able to penetrate the Forward Line of Contact. Along with this improved mission capability has come the increased likelihood of exposure to enemy-radar-controlled air-defense systems. The current Radar Threat Warning Indicator (APR-39-V1) depicts the presence of a radar emitter by a narrow strobe line displayed on a three-inch CRT (Figure 1a). A Proportional Rate Frequency audio signal accompanies the visual display to inform pilots about the type and status of a radar emitter.

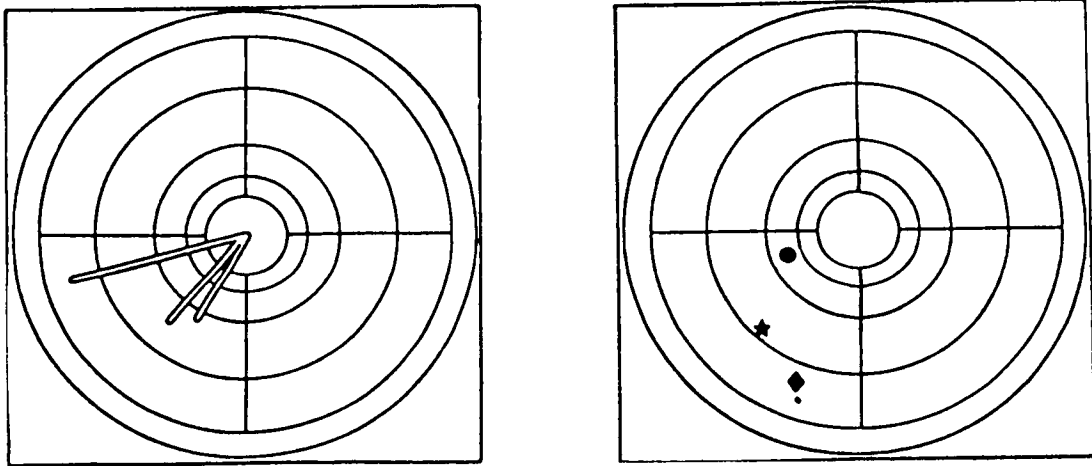


Figure 1: Current (a) and experimental (b) Radar Threat Warning Indicators

The current version has been improved with the development of a prototype APR-39 (XE-1). This display uses symbols presented on the CRT to indicate type of threat, position and status (Figure 1b), accompanied by a speech warning system to provide an optional machine-generated speech display to alert pilots to the presence or change in status of a radar emitter. Laboratory research, conducted by researchers in the NASA Helicopter Human Factors Office (Voorhees, Bucher, Remington & Williams, 1986) investigated many important attributes of the display (e.g., the symbols to be used, symbol placement and screen configuration, speech message vocabulary and construction, message display logic, and voice type). Laboratory experiments

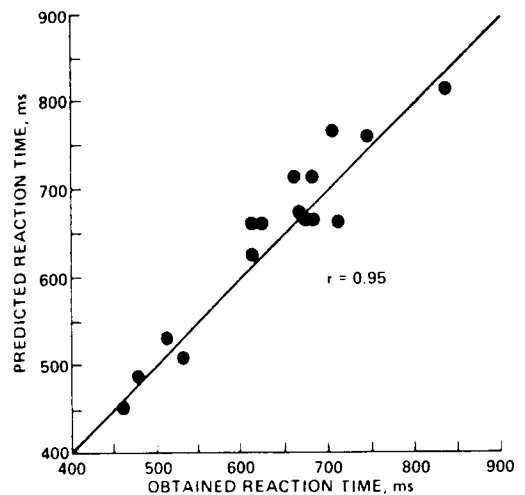


Figure 2: Obtained vs predicted reaction times for different symbols and symbol set sizes.

were conducted to determine the time required to identify visually displayed symbols and the effect of symbol set size. Figure 2 depicts the high correlation between the predicted and obtained reaction times when the predictions were calculated as a joint function of symbol design and symbol set size. As expected, reaction times increased as symbol set size was increased. Additional experiments were conducted to develop the speech warning system with a task that represented functional elements of NOE flight. Operational pilots' satisfaction ratings (given on a scale from 1 to 7) were considerably higher for the proposed system (6.5) than for the existing system (2.1). The results of these experiments led to a final set of visual symbols and auditory messages that will be used by the Army on the new generation Radar Threat Warning Indicator (APR-39-XE1).

### ***Workload Measurement***

Since 1982, researchers in NASA's Workload Program have evaluated the factors that contribute to the physical and mental workload of pilots and established measures and predictors of pilot workload that are appropriate for use under operational conditions (Hart, 1986; Hart, in press). To do so, theoretical information about workload from academia was related to the practical requirements of industrial and government organizations. The first phase of the program has been completed. The factors that contribute to pilot workload have been identified and a set of valid and practical measures have been developed: (1) the NASA Task Load Index (TLX) rating scale (Hart & Staveland, in press), (2) physiological measures (e.g., evoked cortical potentials, Kramer, Sirevaag & Braune, in press, and heart rate, Hart & Hauser, in press), (3) primary task measures (e.g., communications, Hart & Hauser, in press), and (4) secondary task measures (e.g., time production and choice reaction time, Bortolussi, Kantowitz, & Hart, 1986).

Such issues as the relationship between workload and training, the relative demands imposed by vocal or manual inputs and visual or auditory displays, the association between imposed demand levels, achieved performance, and different measures of workload were resolved. In addition, the information provided by different types of measures, and when each can (and cannot) be used, were determined. Laboratory research provided answers to specific questions in a well-controlled environment, while later simulation and inflight research verified that the results were meaningful in the "real world". The results of this fundamental research effort are now being applied to a variety of vehicle-specific problems.

However, selecting an appropriate and practical measure of workload is still difficult, due to the multi-dimensional nature of workload and the fact that different measures are selectively appropriate for different questions, tasks and test environments. Although hundreds of articles have been written describing the results obtained with one or two techniques and a specific task, it is difficult for individuals who are not intimately familiar with the literature to know what measures are available, how well they have been tested, and when they can be used. For this reason, a micro-

processor-based expert system (WC FIELDE) was developed at Ames to aid in the selection and application of workload assessment techniques (Casper, Shively and Hart, 1986).

The system suggests measures, in descending order of utility, based on a users' answers to questions about his goals, research environment, and available facilities. It draws from a data base of widely used measures and "rules-of-thumb" provided by experts in the field to propose alternatives. In addition, it provides sufficient information for the user to make an informed choice among the suggested alternatives and to implement the techniques included in the data base. Each measure is described and evaluated, studies in which it has been used are reviewed, and references are provided to allow the user to obtain additional information.

## COMPUTER SIMULATION

### Description

Until recently, complex systems have been evaluated by studying how well they actually perform. The time-honored method is to design the system, construct a prototype, and then measure its performance. If performance is not acceptable, the design and prototype steps are repeated, an expensive and time-consuming process. Since hardware changes are costly, there is a reluctance to correct design mistakes and it is difficult to make meaningful empirical comparisons among alternatives. Thus, the process quickly reduces to an evaluation of a single prototype design. These limitations exhibit themselves early in the design process. All modern vehicle designs begin with mission, function, and task analyses. They represent a minutely detailed enumeration of tasks and functions that will be performed by the pilots that generate the concepts and constraints from which the final designs are derived and against which performance is judged. Due to the huge expenditure in manpower they require, they too become fixed early in the design process. Since task and time-line analyses are vehicle-specific, atheoretical, linear, and non-interactive, they represent a fixed, descriptive, sequence of events. Computer simulations, on the other hand, may be based on general theories of human behavior. Thus, they may be applied to many vehicles, allow examination (in software) of alternative designs, and provide powerful tools to answer specific questions.

They can integrate models of human performance, attention, perception, manual control, and anthropometrics with vehicle models to create an environment where control laws, design concepts, and automation options can be evaluated in software. The models and algorithms may be based on theory, empirical data, "rules-of-thumb", or expert opinion. Their value depends on the completeness of their data bases and whether or not their predictions have been verified empirically. Their focus, as defined by the vehicles to which they may be applied and the aspects of human behavior they include, may be either extremely narrow or quite broad. Computer simulations are computation-intensive, and thus require considerable speed and memory, and

may require symbolic processors and object-oriented software. Advances in computer technology have increased their power and speed to the extent that they can now adequately represent the functional tasks inherent in the tactical world of Army aviators. Static or dynamic computer simulation results are presented either graphically or numerically, providing either summary or detailed information.

"Virtual" display environments can be used to present the results of computer simulations to experimental subjects and designers for evaluation. They provide a computer-generated version of proposed features or alternative cockpit designs projected onto the visor of a helmet. A user can interact with these alternatives to examine the effects of different control laws, vehicle configurations, and interactions among display elements based on software models (Fisher, 1986).

### **Advantages and Disadvantages**

Computer simulations allow designers to ask "what if..." questions very early in the conceptual stage of design so they can consider many alternatives in a cost effective way. This affords them the opportunity to adopt the best alternatives in the final design. In comparison to physical simulations, computer simulations are flexible and allow designers to consider design elements that do not yet exist. They can provide an excellent representation of flight-task interactions and the range of behaviors of potential human operators, depending on the quality of their data bases and algorithms. The level of control over "irrelevant" variables is excellent and replications may be obtained readily. Their external validity is not as good as piloted simulation and inflight research, however, and environmental realism is, obviously, low because the evaluations are performed in software without human operators or a physical representation of the vehicle. Nevertheless, their output may be generalized to more realistic situations if their predictions have been subjected to empirical evaluation.

### **Examples of Research Results**

#### ***Expert System for Symbology Evaluation***

Although candidate symbologies are usually evaluated empirically, it is more cost-effective to evaluate them in software. For this reason, an expert system was developed by the Perception and Cognition Group at Ames to automate the evaluation of helicopter display symbologies. The Ames Vision Model can be used to compute the perceptual distances among alternative symbols and fonts to provide objective criteria for selecting perceptually distinct symbols (Watson & Fitzhugh, 1986). This allows a designer to compare many alternatives to select the optimal set.

## Computational Model of Visual Flow Fields

Much of the information required for flight path control at very low altitudes is obtained by monitoring the environment, with only occasional references to flight instruments. For example, height above the terrain is estimated visually, rather than by reference to an altitude indicator, and rate of movement is estimated by motion cues available from the visual scene. Software tools developed at Ames can represent the visual information reaching the pilot's eyes, model how this information is used, and generate velocity flow fields. This information can be used to: (1) analyze the visual scene requirements for various phases of flight (based on rate of movement, height above the ground, field of view, and terrain features), (2) determine the resolution and field of view requirements of helmet-mounted displays and obstacle-avoidance systems, (3) develop guidelines for the placement and properties of sensors to provide optimal information for human users, (4) provide guidance and control algorithms, and (5) specify the visual information requirements for NOE flight in low visibility. In addition, display formats are being developed to provide pilots with additional information when available visual cues are inadequate (e.g., hovering with a narrow-field-of-view, monocular display, Watson & Ahumada, 1985).

Figure 3 depicts one way that such velocity flow fields have been used to evaluate the perceptual problems that are encountered during a hover using direct visual cues. The cross represents the direction of gaze. The length of the lines represents the direction and amount of apparent movement detected by the pilot's eyes viewing the terrain. As you can see, the flow fields generated by a pitch down maneuver (Figure 3a) and by a loss of altitude (Figure 3b) are virtually identical. Such flow field representations can be used to quantify and predict the perceptual confusions encountered under different flight conditions with direct vision and to estimate the additional perceptual problems that are encountered by a narrowed field of view (such as provided by most night vision systems).

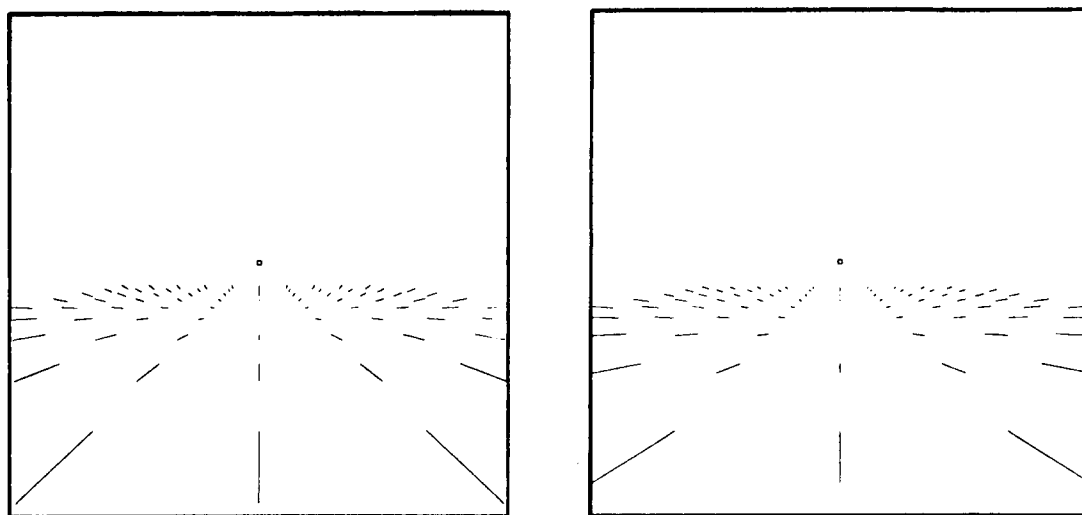


Figure 3: Flow field representations of terrain features during a pitch down (a) or loss of altitude (b) with a forward speed of 40 kts.



## ***Model of Helicopter Vibration***

The detrimental effects of vibration on visual acuity have been well documented for direct vision. They are even more severe with helmet-mounted displays where decrements are caused by relative motion between a displayed image (due to involuntary, vibration-induced head motions) and the eye. The normal vestibular-ocular reflex induces eye movements that oppose those of the head to maintain a stationary point of regard. While appropriate for viewing panel-mounted displays, it is not appropriate for helmet-mounted displays; relative motion is *produced* between the image on the head-coupled display and the eye, resulting in retinal blurring, increased errors and longer responses. Based on a computer simulation of the vibration frequencies of helicopters, an adaptive noise-canceling technique has been developed at Ames that minimizes the relative motion between viewed images and the eye by shifting displayed images in the same direction and magnitude as the induced reflexive eye movement (Velger, Grunwald, & Merhav, 1986). This filter stabilizes the images in space while still allowing the low-frequency voluntary head motions that are required for aiming accuracy.

## ***Army-NASA Aircrew/Aircraft Integration Program***

The technology gap between hardware complexity and interface design capability all too often results in systems which only work in the most benign environments. The adverse effect of this technology gap on new system capabilities motivated the Army-NASA Aircrew/Aircraft Integration (A<sup>3</sup>I) Program to provide a capability that would prevent future designs which are marginally capable or unnecessarily expensive because of inappropriate provisions for the human crewmembers.

The A<sup>3</sup>I program is a joint Army/NASA effort to produce a Human Factors Computer-Aided Engineering (HF/CAE) system. Conceptually, the system is a model and principle-based computer-graphic simulation of a manned simulation wherein models and heuristics of human performance and behavior replace the pilot. The program is focused on the concept formulation phase of future rotorcraft development. It is in this phase leading up to the final detailed design of any system that 70 to 80 percent of the life-cycle cost is determined. The objective is to provide designers with an opportunity to "see it before they build it", to ask "what if" questions, and be told "why" ideas will or will not work in the concept formulation phase. The goal is to make mistakes in software... not hardware.

Figures 4 and 5 compare the current system design process with a computer-aided design approach. Note that the current approach begins with the development of the conceptual issues leading to a design. Human engineering data and specifications are not applied until the final designs are established. From this stage on, the design process is accomplished in hardware, as indicated by the dashed-line box. The nearly insurmountable difficulty of making changes once hardware development has begun, precludes doing meaningful comparisons among alternatives and it is only after a

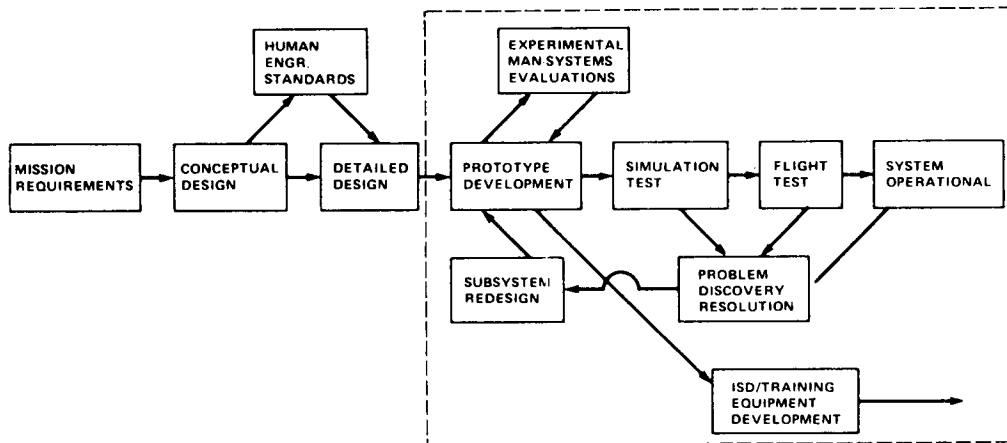


Figure 4: A schematic representation of the current development process.

physical prototype is built that training specialists can begin to estimate the cost of training systems. Thus, a design process quickly reduces to an examination of the only affordable prototype.

Figure 5 depicts the methodology under development for the A<sup>3</sup>I HF/CAE system. The elements in the dashed-line box represent utilities integrated into the A<sup>3</sup>I HF/CAE system which will be available for use early in a design process. Since people are used to obtaining information about the world visually and in three dimensions, the system provides graphic representations to give the user insight into the progress of a simulation and a global understanding of complex and interrelated man-machine factors. Traditionally, designers of helicopters have had to execute two-dimensional designs with two-dimensional tools that must serve the needs of pilots operating in a three-dimensional world. For this reason, the designer will be allowed to visualize the consequences of design alternatives in color graphics before committing to final design and hardware development.

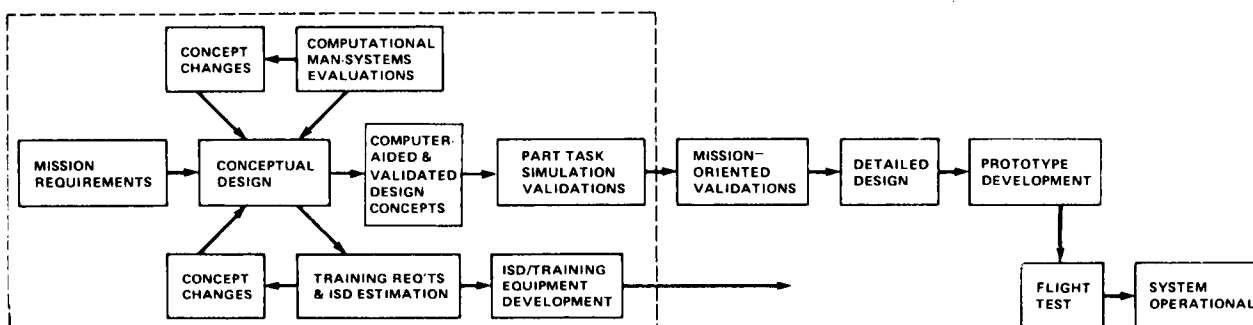


Figure 5: A schematic representation of a computer-aided development process

The use of graphic and iconic representations also facilitates communication between designers from different technical disciplines by substituting commonly understood pictures for words which may have different meanings to each. This new design methodology concept also permits training systems designers to become early participants in the design process. Further, mission specialists will be able to visualize missions and the pilot's tasks and activities before committing to final mission/task documents. Figure 6 depicts some of the initial display options available to the designer in the system.

The products associated with the A<sup>3</sup>I program that will be contained in the HF/CAE system are: (1) an automated mission editor, (2) a designer's simulation workbench which incorporates aircraft simulation models, human behavior/performance models, system function models, and workload assessment and prediction models, (3) an expert system model of training requirements, (4) CAD utilities to render cockpit layout, instruments and concepts, (5) a state variable/data information and analysis center, and (6) a simulation and integrating executive control system. The focus is on providing designers with interactive graphic tools which permit integration of sound human engineering principles early in the development process for future advanced-technology rotorcraft.

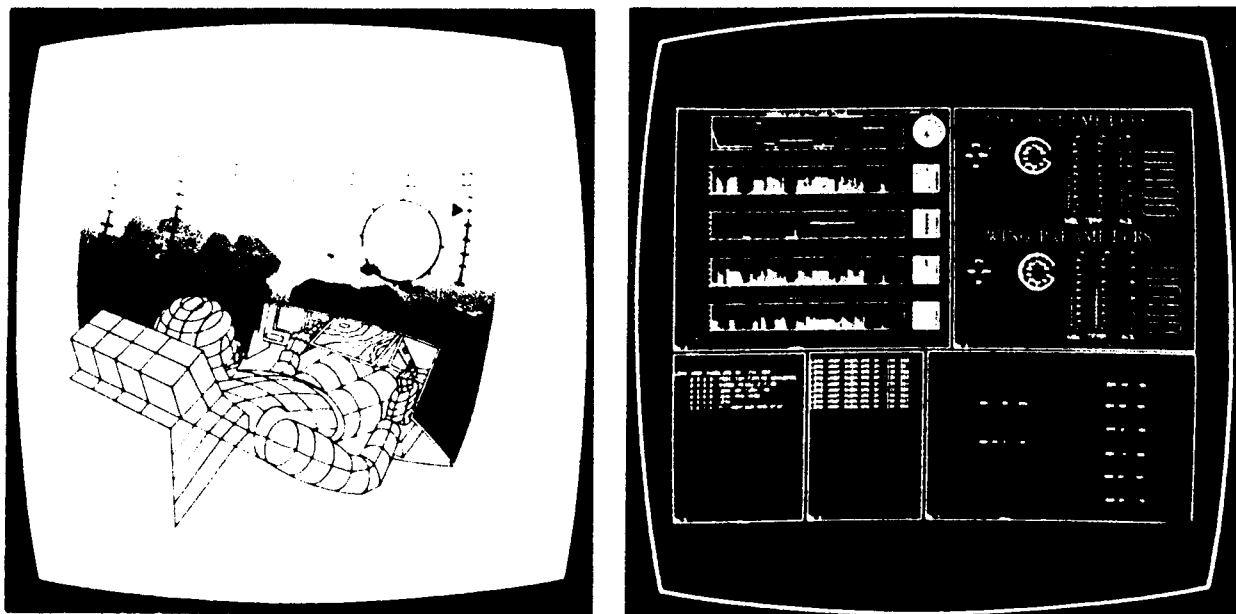


Figure 6: Graphic representation of what the pilot is seeing (a) and a dynamic, moment-by-moment representation of pilot workload, vehicle state, and the flight task components being accomplished (b).

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## PILOTED SIMULATION

### Description

Piloted simulations attempt to reproduce the controls and displays, aircraft and control dynamics, and visual flight environment of a specific vehicle or a "generic" representation of a class of vehicles to enable pilot-in-the-loop research. Most simulators replicate the physical cockpit. However, the fidelity of simulators vary widely in other respects. For example, simulator motion capabilities at Ames range from fixed base (the Crew Station Research and Development Facility) to high-fidelity, six-degree-of-freedom versions (e.g., the Ames Vertical Motion Simulator and the Man-Vehicle Systems Research Facility).

In addition, the visual systems range from no visual scene representation (simulating instrument flight in zero-zero conditions) to monochromatic dusk/night scenes (e.g., Man-Vehicle Systems Research Facility) and complex and expensive full color, computer-generated visual scenes (e.g., the Rotorcraft Systems Integration Simulator and the Crew Station Research and Development Facility). The resolution, detail, and field of view, required depends on the tasks that will be performed in the simulator. For example, a helicopter NOE simulation demands a high-fidelity visual environment to allow pilots to fly in and around the data base at very low altitudes, whereas a procedures trainer may require no visual scene at all. Simulators also differ in the fidelity of vehicle and control dynamics - - some represent a specific vehicle, whereas others use "generic" models - - and their representation of vehicle noise and perturbations due to simulated environmental or battlefield conditions, speed, or configuration. Again, the objectives of the work that will be performed in the simulator dictates the required level of fidelity. Finally, the data available about pilot and vehicle performance varies, although most facilities err on the side of too much rather than too little; even the simplest simulation generates hundreds of pages of data so that data reduction is always a major undertaking.

Simulators are used to evaluate or compare hardware options: instruments, panel and helmet-mounted displays, control configurations, automation options, and voice I/O systems. In some cases, innovative "glass cockpit" designs and integrated side-stick controllers that do not yet exist in operational vehicles may be evaluated. Simulators are used to evaluate different vehicle dynamics and stabilization systems and to determine the effects of environmental conditions, maneuvers, crew complements, and procedures on workload and performance. Finally, they may be used for initial, recurrent, and transition training. In some cases, simulators provide a realistic environment in which specific questions can be addressed. In others, they are used to evaluate the complex interactions among flight-deck hardware and software with a pilot closing the loop between system outputs and control inputs.

## **Advantages and Disadvantages**

The generalizability and external validity of simulation research is usually very good, depending, of course, on simulator fidelity. Although piloted simulators are not as flexible and efficient as laboratory facilities and computer simulations, they often do provide alternative vehicle models, controllers and control dynamics, display options, and simulated environments. Their representation of complex flight-task interactions is excellent. Because experienced pilots are used to fly the simulator, the representation of the human operator is realistic. However, this necessitates the use of a limited and costly resource - - operational and experimental test pilots. The environment they provide can be very realistic, although it is likely that pilots do not behave exactly as they would in the air. Even with highly realistic simulators, it is impossible to generate the stresses of actual flight and combat or to represent the complexities and unexpected situations that arise. On the positive side, because they are not the "real thing", they allow pilots to perform maneuvers that could not be performed (safely) in flight.

The primary drawback of simulation research is that simulators often cost more to develop than the vehicle simulated, and operating costs are high. However, once the initial expenditure is made, they provide a more cost-effective way to evaluate design alternatives than implementing them in a prototype vehicle. Furthermore, experimental control is often low and the number of different pilots and experimental flights that are included in individual studies is limited by the cost and availability of the simulator. Given the limitations of simulation research, no system can ever be fully examined until it is put into flight and tested in the operational environment. However, the use of full mission simulation is a critical link between laboratory research, computer simulation, and flight-test evaluation.

## **Examples of Research Results and Facilities**

### ***The Effects of Automated Systems on Training***

The introduction of automation changes the nature of the tasks performed by pilots, the types of workload they experience, and training requirements. Thus, a series of simulation experiments are being performed by the Helicopter Human Factors Program at Ames to investigate how automation should be introduced, so as to allow pilots to develop accurate mental models of the automated system(s), and to determine how task demands should be distributed among human operator(s) and automated subsystems in advanced helicopter designs (Tsang & Johnson, in press). The experimental task involves three-dimensional flight-path control, discrete target acquisitions, monitoring and supervisory control, and decision-making. Each axis of the tracking task can be performed manually or automatically, and failures may be introduced. Pilots are trained initially with either the manual or automatic control modes, and then transitioned to the fully automated flight mode. Their performance and workload during and after

training, their responses to system failures, and the accuracy of their internal model of the automated system are assessed.

### Single-Pilot Advanced Cockpit Engineering Simulation

Workload research has focused on a range of human functions from simple physical exertion to complex cognitive processing, with measures that range from subjective ratings to physiological and performance indices. After measures have demonstrated sensitivity to different types of imposed demands in the laboratory, they are evaluated in the context of more complex activities, such as simulated military helicopter operations. Here, multiple, overlapping sources of task demands and response requirements are imposed and their effects on one-and two-pilot crews evaluated.

The Single-Pilot Advanced Cockpit Engineering Simulation that was conducted in the Ames Vertical Motion Simulator is one example of such study. Several stability and control augmentation systems, coupled with different levels of automation provided alone or in combination were evaluated to compare single and dual-pilot performance and workload during low-level military operations in the NOE environment (Haworth, Bivens, & Shively, 1986). Two forms of subjective workload ratings, Cooper-Harper Handling Quality ratings, and heart rate measures, were obtained, to evaluate the effects of the experimental manipulations on the pilots. All of the measures provided converging evidence that single-pilot workload levels are high, unless significant levels of automation are provided. Due to the practical constraints typical of complex simulations, the number of pilots in the study was limited, scheduling constraints affected the experimental

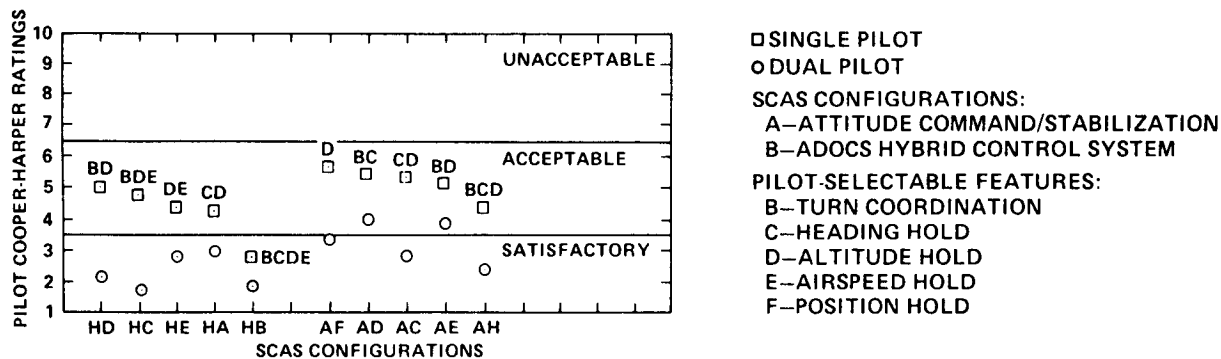


Figure 7: Cooper-Harper Handling Quality Ratings for Single- and Dual-Pilot configurations for the NOE segment.

design, and analysis of objective measures of performance proved to be an overwhelming task, due to the magnitude of the data collected. A clear difference in pilot ratings was evident between the one and two pilot crew complements, however. Figure 7 shows that only one configuration of the twenty tested was judged as satisfactory for flying NOE with a single pilot.

Both measures of workload (on-line SWAT ratings and post-flight NASA TLX ratings) were significantly correlated with each other ( $r = 0.76$ ) and with handling quality ratings (Figure 8). However, the correlation between handling quality and workload ratings was higher for mission segments where physical control demands were the primary source of workload. The correlation was lower for segments where mental activities contributed significantly to the pilot's workload.

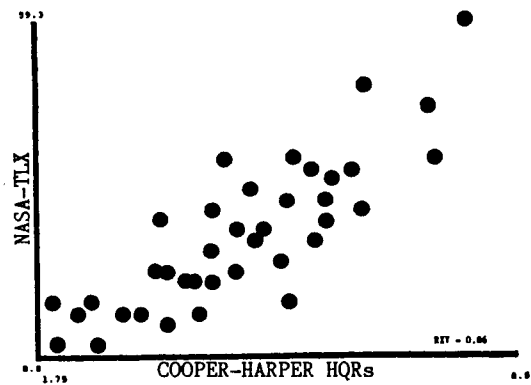


Figure 8: Relationship between Cooper-Harper Handling Quality and NASA-TLX workload ratings.

#### ***Voice-Activated Control Simulation***

NASA researchers will conduct a simulation in the spring of 1987 to test the efficacy of some of the features that have been proposed to reduce the workload of a single pilot for the next-generation of Army scout/attack helicopters (such as the LHX). In particular, the effects of automation and voice-interactive versus manual input for mission-related tasks will be examined in a simulated military NOE environment (Vidulich, in press). The results of extensive theoretical and laboratory research will be used to predict the possible benefits (and drawbacks) of using the two entry systems for weapon selection, data burst transmission, and counter-measure activation under each of three levels of automation (e.g., (1) none; (2) automated turn coordination and altitude hold; and (3) automated turn coordination, and altitude and position hold). It is expected that hover and combat tasks performed with no automation will be sufficiently demanding to overload the pilot's capacity for manual-control tasks. In this case, an advantage for voice-interactive input is expected. However, this advantage should be attenuated in less demanding portions of the scenario and eliminated as increasing levels of automation reduce the need for continuous manual control activities.

#### ***Off-Axis Tracking Simulation***

Even with direct visual contact with the outside scene, a large percentage of military and civilian helicopter accidents have been attributed to spatial disorientation. The problems are exaggerated with the use of narrow field of view, helmet-mounted displays and are expected to be particularly severe when a single pilot must track air and ground targets "off-axis" from the direction the vehicle is moving. Although this problem has been recognized, very limited information is available about differences in optic flow generated by out-the-window and sensor-based visual displays and about the limitations of pilots performing head-tracking tasks.

Recently, the components of visual flow that determine the direction of movement and the influence of visual flow on off-axis tracking of moving aim points were investigated in the laboratory. Here, specific target parameters (e.g., range elevation, azimuth, speed and transformation) were established and iso-velocity curves for each aircraft speed were computed and mapped against the local flow patterns viewed by pilots. This pilot study provided predictions that will be tested in simulated flight in the spring of 1987 (Bennett, Haworth, Perrone, & Shively, in press). Pilots will be required to track air and ground targets with a Honeywell head-tracker/helmet-mounted display system that presents a video image simulating the output of a remote sensor positioned on the nose of an attack helicopter. Some of the pilots will be required to detect, acquire, and track targets while flying a specified reconnaissance route, while others will perform the tracking task in a dual-pilot configuration where another simulated pilot is responsible for primary flight-path control. Vehicle speed, target range, azimuth, and elevation will be varied systematically. Detection times, acquisition times, and tracking error will be plotted as a function of local optical flow patterns projected to the pilot by the remote sensor.

#### *Crew Station Research and Development Facility*

In cooperation with the Aeroflightdynamics Directorate, NASA is constructing a realistic full-mission simulator, the Crew Station Research and Development Facility, to support Army and NASA research. The pivotal element of the facility is a two-seat tandem helicopter cockpit where the performance of operational pilots can be evaluated. Three Blue/Red team stations augment its realism by simulating other aircraft while a Mission Management Communications Station simulates supporting forces with which the crew interacts during an engagement. Experimental coordination is accomplished from the Experimenter/Operator Console, where a team of experimenters and simulation engineers control and monitor the scenario.

A composite mission scenario has been developed to produce realistic workload levels. By configuring the crew station to run with either one or two crew members, the effectiveness with which the missions are accomplished can be compared and the ability of a battle captain to control the resources of the Scout/Attack team, as well as those of his own aircraft, can be investigated under various circumstances.

A wide field of view Fiber Optic Helmet-Mounted Display which presents a panoramic view of the world coupled with sensor outputs and symbology for pilotage, threat alerts, and weapon release is the primary flight display for the pilot. Programmable display push buttons allow rapid input to critical aircraft systems such as weapons, countermeasures, and system malfunctions. Control of aircraft systems is effected using "glass cockpit" Systems Management Displays via tactile data entry devices (e.g., touchpads, touchscreens) or an interactive computerized Voice Input/Output system. The Tactical Situation Display, which displays a scalable plan view map of the



gaming area along with several overlays showing the status of threats and friendlies, is used to monitor the tactical situation. These may be modified using the touchscreen, as may the navigation and tactics overlays. Flight controls in each crew station consist of two, four-axis, limited-displacement controllers plus foot pedals (allowing full control in each crew position). The longitudinal, lateral, directional and collective controls may be assigned to any combination of the hand controllers and pedals in a given crew position. This flexibility enables the impact of various control configurations on crew member efficiency to be investigated. Further, a key consideration in the study of pilots' performance is the level of noise to which they are subjected. Thus, the crew station is surrounded by a six channel sound system that provides directional sound cues for rotor and transmission noise, weapon firing effects, dispensing of chaff and flare, and other noises that occur during a tactical mission scenario.

The changing nature of mission requirements dictates that the facility must be easily reconfigurable to support future experiments. To that end, interactive editors have been developed to modify all of the pilot interfaces and to integrate these modifications into the simulation with a user-friendly system. Data-base processors automatically extract terrain information from the visual data base to build forward view displays and Tactical Situation Display contour maps. Utilities allow the threat laydown and characteristics to be modified between experiments. Using these software tools, the facility may be radically reconfigured in a very short period of time to accommodate experimental investigations of virtually any pilot/cockpit integration issue.

## INFLIGHT RESEARCH

### Description

Inflight research provides the ultimate validation of the utility of new systems, designs, processes or modifications. Thus, it generally takes place after preliminary testing in the laboratory, computer-based and piloted simulation. The aircraft available at Ames for research fall along a continuum that extends from production models to highly instrumented experimental aircraft.

For example, an AH-1 Cobra helicopter is being used to investigate training and performance with a FLIR/PNVS system and voice input/output system. An experiment investigating pilot workload employed an SH-3G helicopter equipped with data collection and telemetry instrumentation. This experiment was able to take advantage of the laser tracking facilities located at Crow's Landing NALF, which provided detailed x,y and z coordinates for the aircraft during maneuvers in that area. The CH-47 Chinook helicopter represents even further modification of an aircraft for research purposes. The right seat is essentially a "flying simulator" with a reconfigurable cockpit and onboard computers that can change the dynamics of the flight controls to simulate handling qualities of different aircraft.

## **Advantages and Disadvantages**

There are many advantages to performing research in flight. The fact that it is performed in the target environment establishes excellent external validity and generalizability, due to the realistic representation of flight task interactions and environment. While many questions can be answered in laboratories and simulators about the feasibility of new systems or designs, there is no substitute for an actual pilot flying an actual aircraft. While these represent major advantages of inflight research, there are drawbacks. Inflight research is, by its nature, focused on a specific vehicle type. Experimental control is difficult to achieve, due to various factors such as weather, traffic, aircraft downtime, etc. Unless special instrumentation is available, little or no performance data can be recorded. Further, the cost of inflight research is very high. Initial aircraft cost, maintenance, and pilots all contribute to this high cost.

In considering the advantages and disadvantages of inflight research, one of its greatest benefits is that it allows research to come full circle. That is, a project does not stop after flight test. Most experiments generate more questions than they answer, and this is certainly true of inflight research. Questions arise in operational research that might otherwise be overlooked, providing an opportunity to test techniques and designs and identify problems. Then, it is possible to complete the circle by taking these problems and questions back into the laboratory and simulators for further research. Thus, flight test is a major and necessary element of the human factors research process.

## **Examples of Research Results**

### ***Inflight Voice Recognition System Evaluation***

Computer-recognized voiced commands and computer-generated speech messages have been proposed as methods by which pilots could interact with cockpit displays. Since visual and manual-control demands are generally high in helicopters, auditory displays and spoken commands might be less disruptive to manual flight-path control than additional visual displays or keyboard entries. In flight, recognition accuracies of 95% or better were obtained for mission segments selected to be particularly troublesome for a voice recognition system. For example, one speech recognition system was tested in a Bell Jet Ranger helicopter in level cruise, sustained turn (that created blade slap noise), approach to VNE (that created additional vibration), and hover in ground effect (that created high pilot workload). Each pilot trained the system individually to his voice for the 20-word vocabulary. Recognition accuracy was not affected by cockpit noise or vibration as much as expected. However, increased pilot workload did degrade recognition accuracy. In the NASA SH-3G helicopter, equally good recognition accuracies were found with cockpit noise levels ranging from 102 to 106 dBA, although recognition accuracy decreased from 100% to 93% as the vocabulary was increased from 10 to 36 commands. It was suggested that using a command

syntax to divide the vocabulary into subsets could have achieved a consistently high level of recognition accuracy (Coler, 1984).

### *Inflight Workload Research*

The study of mental workload is one endeavor that has benefited from flight test validation. The Helicopter Human Factors Program recently completed an experiment in NASA's SH-3G helicopter to provide the final validation of workload measures developed in the laboratory and tested in simulated flight and to develop a database for workload prediction (Shively, Battiste, Matsumoto, Pepitone, Bortolussi and Hart, in press).

Subjective, objective, and physiological measures were employed. Four NASA test pilots flew each of two scenarios. Each flight began and ended at Moffett Field NAS. On the way to and from Crows Landing NALF, a variety of tasks were imposed: visual, TACAN, and ILS approaches, in- and out-of-ground-effect hovers, contour flight, a search task, and visual and instrument navigation (depicted by the line graphs in Figure 9). The bar graphs in Figure 9 represent the workload ratings obtained for each flight segment. Relatively high workload levels were reported by the pilots for the search task and in the hovers, as expected. The workload of instrument approaches and landings was predictably greater than for visual. Other flight segments such as flying contour with or without performance constraints, fell into functionally related groups. Measures of performance provided additional insight into pilot workload levels. Heart rate measures are currently under analysis. The data obtained from this experiment will form the foundation of a helicopter-specific computer model for workload prediction that will be incorporated into the A<sup>3</sup>I computer simulation.

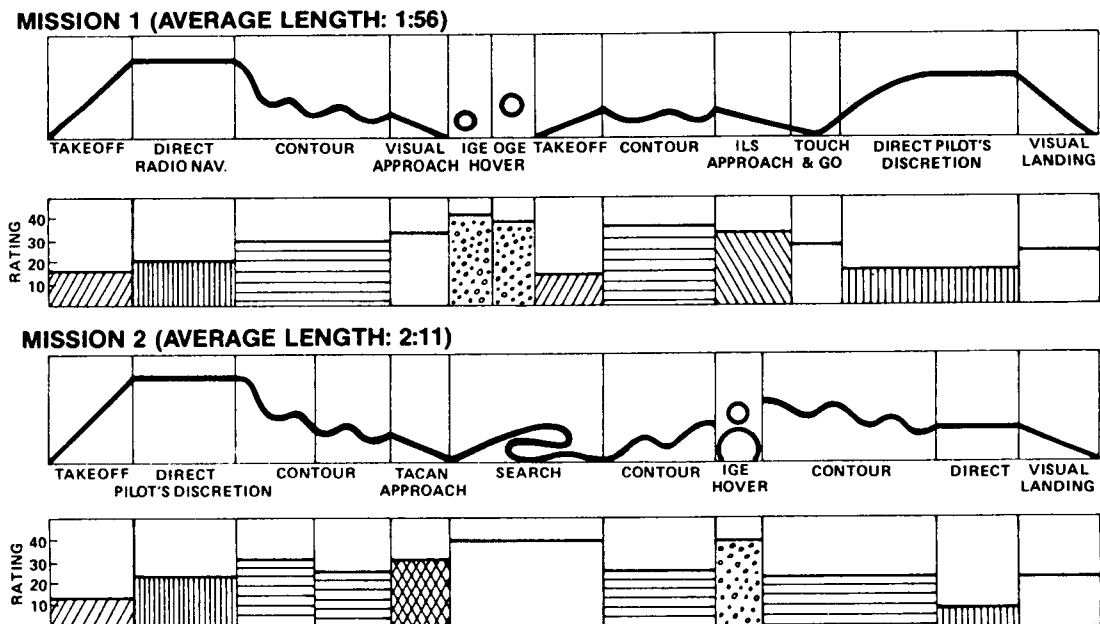


Figure 9: Stylized representation of flight segments and average workload ratings given by four pilots for two missions flown in the NASA SH-3G.

## SUMMARY

At each stage in the research process, information obtained in more realistic situations can be used to refine theoretical models and provide the focus for well-controlled laboratory studies to address specific issues. The relative advantages and disadvantages of laboratory, computer simulation, piloted simulation and inflight research are summarized in Table 1.

Each level of research can contribute to developing an understanding of the capabilities and limitations of the human element in advanced-technology systems. By moving back and forth among these research environments, the requirements of theoretical development can be balanced against the requirements of the "real world". Furthermore, operational relevance can be insured at the same time that the predictive advantages of a theoretical foundation can be maintained. Finally, each environment can be used for those aspects of research for which it is uniquely suited, resulting in a cost-effective and efficient use of available resources.

Scientists must become familiar with applied problems (through participation in simulation and inflight research) and designers, engineers, and operational test and evaluation personnel must be exposed to the advantages of experimental control, a theoretical foundation, and the use of validated measures, in order to capitalize upon the advances in each others' fields. This is the unique role that a government research laboratory, such as Ames

Table 1: Summary of the Advantages and Disadvantages of Different Research Environments.

	LABORATORY	COMPUTER SIM.	SIMULATOR	INFLIGHT
COST	LOW	MODERATE	VERY HIGH	VERY HIGH
EXPERIMENTAL CONTROL	EXCELLENT	EXCELLENT	GOOD	POOR
GENERALIZABILITY OF RESULTS	GOOD	GOOD	VERY GOOD	EXCELLENT
EXTERNAL VALIDITY	POOR	GOOD	VERY GOOD	EXCELLENT
REPRESENTATION OF FLIGHT-TASK INTERACTIONS	POOR	CAN BE EXCELLENT	EXCELLENT	EXCELLENT
REALISM OF ENVIRONMENT	POOR	POOR	GOOD	EXCELLENT
FLEXIBILITY AND EFFICIENCY	EXCELLENT	EXCELLENT	GOOD	POOR
EASE OF REPLICATION	EASY	TRIVIAL	MODERATE	DIFFICULT
QUALIFICATIONS OF EXPERIMENTAL SUBJECTS	NONE	MODELS REPLACE HUMAN SUBJECTS	MUST BE TRAINED PILOTS	MUST BE TRAINED PILOTS

Research Center, can play. Here, scientists, engineers, and pilots work in close proximity to each other and conduct collaborative research in which each take advantage of the other's knowledge and tools to provide a strong research foundation that can be transferred to industry. If nothing else, this environment creates a unique opportunity for each group to learn the other's language. This provides a vehicle for translating the considerable data base available in academia and the pragmatic experiences of designers, engineers, and pilots into a useful body of knowledge.

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