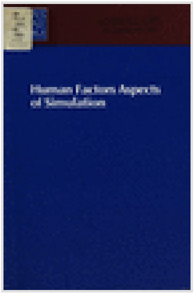

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and Stanley Deutsch, *Editors*

Working Group on Simulation
Committee on Human Factors
Commission on Behavioral and Social Sciences and Education
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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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FOREWORD

The Committee on Human Factors was established in October 1980 by the National Research Council. The committee sponsors are the Office of Naval Research, the Air Force Office of Scientific Research, the Army Research Institute for the Behavioral and Social Sciences, the National Aeronautics and Space Administration, and the National Science Foundation. The principal objectives of the committee are to provide new perspectives on theoretical and methodological issues, identify basic research needed to expand and strengthen the scientific basis of human factors, and to attract scientists both inside and outside the field to perform the needed research. The goal of the committee is to provide a solid foundation of research as a base on which effective human factors practices can build.

Human factors issues arise in every domain in which humans interact with the products of a technological society. In order for the committee to perform its role effectively, it draws on experts from a wide range of scientific and engineering disciplines. The committee includes specialists in the fields of psychology, engineering, biomechanics, cognitive sciences, machine intelligence, computer sciences, sociology, and human factors engineering. Other disciplines participate in the working groups, workshops, and symposia sponsored by the committee. Each of these disciplines contributes to the basic data, theory, and methods required to improve the scientific basis of human factors.

PREFACE

The Committee on Human Factors established the Working Group on Simulation for the purpose of identifying behavioral issues and problems common to the wide variety of uses and types of simulation involving human participants. The objectives of the study were to assess broadly the design and use of simulation and to recommend behavioral research and other courses of action that will improve their effectiveness. The field of simulation is of increasing national interest and of particular importance to most of the committee's sponsoring organizations, which are heavily involved in system development and training and need to ensure system readiness and operational utility. Simulators, depending on their purpose and the systems represented, are found in various degrees of complexity and in an increasing variety of settings in addition to the military and other government agencies, such as commercial airlines, universities, and the aerospace and nuclear electric power industries.

During the period from January 1982 to July 1983, the working group members examined the entire field of simulation. We were able to assess the fragmented activities in a cohesive way and gained some interesting insights on needs for behavioral research, methodology development, the use of simulation for research and systems acquisition, the use of simulation for initial and operational training, and education and training needs for developers and users. The resulting report is an overview of simulation and a guide for fundamental research and educational activities that can improve future design and use of simulation. It is intended for the use of groups concerned with simulation, both inside and outside the human factors community, including those involved in research, training, engineering, systems acquisition, operations, programming, and budgeting.

It is important to note that members of the group were familiar with many of the major activities that have not been reported in the open literature in widely available scientific and engineering journals or, in many cases, not reported at all, as is typical of much work accomplished in industrial or operational settings and of information that resides in military documents with limited distribution. The majority of this literature was found to be highly specific to particular simulators, predominantly training simulators, and describes physical characteristics, evaluation of performance, or recommendations for research within a limited scope. Most simulation research reports consist of comparisons among specific alternatives rather than tests of general principles.

In addition, a great deal of information was obtained by various working group members at conferences and workshops held by the Department of Defense and the National Aeronautics and Space Administration, visits to facilities and program offices such as the Navy Visual Technology Research Simulator in Orlando, Florida, and the office of the Air Force Deputy for Simulators at Wright-Patterson Air Force Base, Ohio.

I thank the members of the working group for the many hours they devoted to the meetings and to preparing materials for the report. They were especially adept at accommodating a variety of viewpoints. I am grateful to the Committee on Human Factors, whose important contributions included determination of the need for the study and providing an overview.

I am grateful to Robert T. Hennessy, who helped to organize the working group meetings, for his active participation in the meetings and substantial contribution to the content of this report. In addition, he performed the unenviable editorial task of merging the written pieces contributed by each of the working group members into a coherent report. His efficient handling of administrative matters of the working group is also gratefully acknowledged.

I appreciate the efforts of Stanley Deutsch, study director, for his extensive assistance in the preparation, editing, and organization of the final report for publication.

Jeanne Richards, Anne Sprague, and Margaret Cheng, administrative secretaries for the Committee on Human

Factors, deserve special thanks for the multiple duties they performed so well in support of the working group by arranging meetings, typing drafts, and distributing written materials and information to the members. Substantial editorial improvements to the economy, sharpness of expression, and organization of the report were made by Christine McShane, editor of the Commission on Behavioral and Social Sciences and Education. I thank her for helping both the writers and the readers of this report.

Edward R. Jones, Chair
Working Group on Simulation

CONTENTS

SUMMARY

The increasing importance and pervasiveness of simulation is due to a variety of factors, including cost and time savings that can be realized in system design and in training, the ability to reproduce and examine situations that would be unsafe using actual equipment, the control and measurement of human-machine performance, and the capability to investigate conditions that would be impractical to arrange otherwise. Additional impetus has been provided by the tremendous technological advances in computer hardware and software capabilities, especially in visual simulation, allowing for the creation and control of complex, realistic environments.

Simulation is used to support the design, development, and test of many advanced systems and to provide for training on their operations; for example, it enables an aircraft to "fly" realistic missions years before its first actual flight. The technology incorporated into a new system may have been developed using research simulators, and the test and evaluation of the integrated system may have been accomplished largely using engineering simulators.

The Working Group on Simulation was asked to assess broadly the design and use of simulators, to identify behavioral issues and problems common to different uses and types of simulators, and to recommend fundamental research and other courses of action to improve the understanding and efficiency of human factors applications in simulation. The range of applications they considered includes training, system design and development, test and evaluation, and research. The emphasis was primarily on the use of simulators by the Department of Defense (DoD) and the National Aeronautics and Space Administration (NASA) as major users of simulators; however, other users were also considered. The working group also considered the changing role of the human as an operator and maintainer resulting from increased automation, and the effect of the resulting complex decision-making roles. The uses of simulation and the relevant literature were examined systematically.

The report identifies behavioral issues and problems common to many simulators involving human participation and recommends research intended to enhance their effective use. The report contains an overview of simulation including some historical perspective and provides a guide for research and educational practices aimed at improving the future design and use of simulators.

The working group represented a broadly balanced composition of disciplines and organizations as shown on page iii of this report. Their areas of specialization include systems and design engineering, simulation engineering and training, control systems, performance measurement, psychology and cost-benefits analysts. They represent expertise in industry, university, and government R&D and operational organizations (see Appendix B for biographical sketches of the working group members).

RESEARCH ISSUES

The working group identified nine specific issues involved in the design, use, and application of simulators; most of them have to do with features and practices for effective employment of simulators. They are examined in detail in Chapter 5. These nine major research issues were organized into three major categories: (1) Design--training simulator design guides, improved task analyses methodology, and stress in simulator training and testing; (2) Operational--scenario construction and simulation control support features, experimental design, and performance measurement; and (3) Applications--training simulator instruction guides, cognitive skills, and training for failures and out-of-tolerance conditions.

Behavioral issues are of particular concern in the development of simulators, and major improvements in simulation involve behavioral science research as well as technological advances. One concern is that human factors and equipment issues tend to be viewed separately when in fact they are intimately intertwined in terms of system design and testing, personnel, selection, and operational training. Rather than being isolated, these areas should be developed through a system engineering process that fully integrates human factors engineering considerations. The concern is how functional requirements become defined and translated into physical simulator characteristics, and how the devices are acquired and used. The process has a major impact on equipment and personnel costs and on the effectiveness of the end product. Although procurement and design practices continue to concentrate on the physical characteristics of simulators for systems design and simulators for training, psychological factors (i.e., the behavioral objectives) should be given greater consideration in simulator design and in procurement specifications.

CONCLUSIONS AND RECOMMENDATIONS

In discussing the problems involved in simulation, the group arrived at eight interrelated conclusions:

1. Physical correspondence of simulation is overemphasized for many purposes, especially training.
2. Simulators are often not used properly.
3. Simulation could be more cost-effective.
4. The role of behavioral science and human factors engineering in simulation is neglected.
5. Many persistent simulation problems are common across types and uses.
6. Our capability to measure operator performance is limited.
7. The use of modeling in simulation is not well developed.
8. Science and technology of simulation are not well developed or integrated.

On the basis of discussions of these fundamental problems, the working group makes three key recommendations* to create the conditions essential to attack them:

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*Working group member Jesse Orlansky disagrees with the first two recommendations; his dissent appears at the end of Chapter 7.

1. Long-range, comprehensive, and forward-looking research plans should be developed to address persistent and emerging simulation problems.
2. Long-range, stable funding should be provided to encourage the development of academic bases for simulation research.
3. Research to develop near-real-time human performance assessment capability for simulation is urgently needed.

ORGANIZATION OF THE REPORT

Chapter 1 provides background information on the characteristics of simulation. Chapter 2 focuses on how simulators have been used and issues in their applications. Chapter 3 identifies many of the behavioral issues that apply to the design of simulators. Chapter 4 describes earlier contributions of behavioral sciences to simulation. Chapter 5 describes specific behavioral research issues relevant to simulation. Chapter 6 predicts future trends in systems and simulation. The final chapter summarizes the findings and makes a set of three key recommendations. The report has two appendixes: Appendix A provides examples of particular simulators; Appendix B contains biographical sketches of the working group members.

1

INTRODUCTION

Although the term simulation has multiple meanings that differ according to various classes of applications, this report refers only to simulation that involves human interaction with equipment and that permits observation or analysis of analogues of real-world situations not otherwise accessible with adequate convenience, unobtrusiveness, cost savings, or safety. Simulation in the context of this report is the representation of equipment, systems, events, and interaction processes. A simulator may be similar to the real equipment in some ways and unlike it in others; some components, functions, or system events may not be represented at all. The realism and comprehensiveness of a particular simulation need only be sufficient for the user's purposes; trade-off decisions are made to determine the extent of realism and comprehensivenesss that is necessary and affordable. Factors such as the objectives of the designer or user, the questions the user wishes to be answered, data to be provided, analysis to be performed, and the behavior to be elicited determine what must be represented in the simulation. The medium for implementing the simulation (digital computer, electro-mechanical, or manual, for example) may also determine the form of the simulation.

Simulators are used for four fundamental purposes: (1) training; (2) systems and equipment design, development, test, and evaluation; (3) research on human performance; and (4) licensing and certification. However, this simple division is not absolute. For example, battle or warfare simulators are used frequently to develop tactics, train participants in combat management skills, and evaluate the operational system. Thus, the use may be a blend of more than one purpose--in the case of battle simulators, systems development, operational procedures, and training.

CHARACTERISTICS OF SIMULATORS

Simulators differ in their physical characteristics. The most prominent physical dimensions that distinguish them are their realism and comprehensiveness. By realism is meant the fidelity of physical representation. A simulator may be very abstract, consisting of a computer representation of a process displayed on a screen controlled through a keyboard. At the other extreme, the simulator may consist of the actual equipment augmented with additional equipment or special software. Most simulators fall between these extremes of realism.

Independent of the degree of realism, simulators may also differ along the dimension of comprehensiveness. Comprehensiveness is the degree of completeness and accuracy of representation of all functions, environmental characteristics, situational factors, and external events that are present in the target system or affect its function. Fidelity of simulation, usually intended to mean some combination of realism and comprehensiveness, is a topic of much concern and controversy that is discussed at length in Chapter 3.

Simulators generally have scenarios--that is, a schedule or script that drives the course of events and action of simulated components to which the person or system under study reacts. Commonly, some computational rules and data files are provided for the purpose of generating the sequence of scenario events; they may also be used in keeping track of events. In some cases, such as air combat involving live participants, human initiative determines the course of events. In many cases the actions of simulated agents as adversaries or other team members provide the cues or conditions for responses from the participant. The sequence may be deterministic or probabilistic. In a deterministic scenario, the sequence of events is fixed and unchanged by the actions of any human in the loop. More complex scenarios may have probabilistic rules that generate variable events for given sets of scenario conditions and may also change the sequence in response to actions of the human.

Models are used in human-in-the-loop simulations to represent endogenous and exogenous variables and processes of the system being simulated. For example, atmospheric models may be used to generate weather conditions or vehicular models may be used to generate movement characteristics of an aircraft or ground vehicle.

In addition to a functional representation of a system and environmental effects, a simulator also includes subsystems for the control of the simulator, means for monitoring the progress of an exercise, instructional support features in the case of training simulators, and performance measurement capabilities. The control station for the early Link flight trainers consisted of a desk with a few instrument displays and a ground path plotter (Faconti, 1979). Since that time, control and instructor stations have evolved into rather complex devices in their own right, with numerous capabilities for controlling and directing simulator exercises. Soon after digital computers became common in simulators, discrete indicators and controls for various functions proliferated. More recently the tendency has been to reduce the number of displays by using cathode ray tubes that are capable of displaying a variety of images, and to use conventional keyboards and multifunction switches for simulator control.

Training simulators, particularly the more complex devices, include a number of features for training purposes, such as automated demonstrations, automated cueing, manual and programmable sets of initializing conditions and malfunctions, freeze (the ability at any point to stop the action and later continue the simulation), recording and replay of the simulation exercise, and hard copy printouts of performance information (Semple et al., 1981a). Engineering simulators generally have similar control capabilities plus additional features to permit changes in the basic algorithms driving the simulation.

INVESTMENT IN RESEARCH AND DEVELOPMENT OF SIMULATORS

The relative dearth of behavioral research relevant to simulator design and use is apparent from a review of the recent research funding patterns of the Department of Defense, the government agency that provides the largest amount of research funding and is also the largest user of simulators.

In the report of the Joint Directors of Laboratories Technology Initiative Panel for Training and Simulation, Alluisi (Alluisi et al., 1983) noted that the total DoD investment in research and technology development, which includes the Basic Research Exploratory Development and Advanced Development budget categories, was $7.06 billion. Funds for training and simulation research and development performed by government laboratories, including awards to outside contractors, totaled $62.7 million, or 0.9 percent of the DoD technology investment. DoD support of academic institutions for training and simulation for fiscal 1981 and 1982 together amounted to slightly more than $20 million.

The same report states that of the $62.7 million total, $1.4 million, $23.3 million, and $38.0 million were spent for basic research, exploratory development, and advanced development, respectively. During this same period, $62.3 million was invested by industrial firms in training and simulation research and development.

The Manpower and Training Research Information System (MATRIS) of the Defense Technical Information Center was queried to determine the number and nature of DoD supported work elements (research projects) started, continuing, or ending in the period from fiscal 1981 to mid-1983 in the simulation and training devices category, or work elements closely related to simulation and training devices in other categories. The work elements were segregated by the three budget categories for technology base development, i.e., basic research, exploratory development, and advanced development. The number of work elements found by the MATRIS query are shown in Table 1.

The summary descriptions provided by MATRIS of each of the 101 identified work elements were reviewed to discover which ones involved at least a component of behavioral research or formal behavior evaluations. The purpose of this review was to make an approximate determination of the number of DoD work elements that directly or indirectly are likely to provide behavioral data relevant to the design and use of simulators. The results of the review are summarized in Table 2. From this table it is apparent that very few work elements (only eight were identified) are devoted to basic research on simulation and training devices. Six of the eight involve behaviorally related research or evaluation. While the number of work elements in either exploratory development or advanced development is much larger, only one-third of these work elements involve a component of behavioral research or formal behavioral evaluation. The vast majority of work elements are equipment or software

TABLE 1 Research on Simulation and Training, October 1981 to mid-1983

Budget Category	Simulation and Training Devices	Nonsimulation Training and Devices	Total
Basic research	5	3	8
Exploratory development	37	15	52
Advanced development	41	0	41
Total	83	18	101

NOTE: The table shows the number of DoD work elements within the categories of simulation and training devices and closely related work elements from the other categories that started, continued, or ended in the period from fiscal 1981 to mid-1983. Work elements are segregated by technology base development budget category.

developments, analysis of requirements for simulators or training devices, or demonstrations of technology or equipment capabilities.

It is apparent from the foregoing that the amount of funding for technology base research and development supported by the Department of Defense is small relative to its overall research and development budget. Whether or not the level of funding for simulation is adequate, the number of research projects devoted to behavioral aspects of simulation and training devices, particularly basic research, is very small compared with those devoted to equipment development and cannot be considered anything but minuscule relative to the large investments in and number of simulators used by the Department of Defense.

At least three recent high-level reports (U.S. Department of Defense, Defense Science Board, 1982; Herman, 1982; Alluisi et al., 1983) address in whole or in part simulation and training device developments and acknowledge their importance to the Department of Defense.

TABLE 2 Research on Simulation and Training Devices With and Without a Behavioral Component

Budget Category	Behavioral Component	No Behavioral Component	Total
Basic research	6	2	8
Exploratory development	13	39	52
Advanced development	10	31	41
Total	29	72	101

NOTE: The table shows number of DoD work elements within the categories of simulation and training devices involving or not involving a component of behavioral research or formal behavioral evaluation by research-level budget category.

However, none of these reports distinguishes between development of equipment, hardware, and software and development of behavioral principles for the design and use of simulators. Opportunities and needs for improvements in simulation and training are discussed solely under the aggregate term "training technology."

Simulation is an immensely important tool for the nation. Billions of dollars have been spent on simulation and billions more will be spent in the near future (Deegan, 1981). Tens of thousands of people are involved in the construction, operation, and maintenance of simulators. Although the military services, NASA, commercial airlines, and the aerospace industry were traditionally the principal users of simulators, the use of this tool is growing rapidly in other areas such as the electric power industry and in the development of complex hardware and software systems, particularly those with significant human operator involvement such as automobile driver training.

This national investment continues to grow because of the cost-effectiveness and utility of simulators. For example, for the new Boeing 767, aircraft training time costs $7,000-8,000/hour, as opposed to average expenditures of $400/hour for full flight simulators. In addition, the simulator has provisions for training in emergency procedures that cannot be accomplished safely in the aircraft (Aviation Week and Space Technology, 1983). During 1980 and 1981, the median flight simulator/aircraft operating cost ratio of 42 military aircraft was 0.08, down from 0.12 three years earlier. Under the Federal Aviation Administration's (FAA) Advanced Simulator Program, airline pilots may be certified entirely in an approved simulator that meets specific requirements. A simulator was approved for certification of the United Airlines B-727 and for other airlines in 1982; approval of other airlines' simulators may soon follow. The design of new military aircraft is supported by mission simulators that permit representative military missions to be "flown" and thereby reducing the redesign requirements after the aircraft is built and resulting in more effective fighting machines (Aviation Week and Space Technology, 1983).

DEFINITION OF SIMULATORS

In general, simulators may be defined operationally as encompassing the following characteristics: (1) A specific system or equipment is represented through either artificial duplication of equipment or embedding artificial input and measurement features in actual equipment. In the case of war games, scenarios alone or scenarios plus equipment may be used. Simulators may be employed in contrast to the use of the actual equipment. (2) Simulators not only duplicate equipment, but they are also used to create and control external events such as malfunctions, targets, and environmental effects. (3) The system is interactive in that human input results in changes to the equipment and equipment changes are responded to by the operator.

ORIGINS OF SIMULATION AND SIMULATION RESEARCH

The precursors to simulators were the primitive devices used as flight trainers before World War I. The mechanical Link trainer developed before World War II for instrument flight training was a generic device, i.e., it did not represent any specific aircraft. A simulator of the Lockheed Hudson aircraft, developed in 1942, was the first simulation of a specific aircraft (Whiteside, 1983). Modern electronic simulators were first used in the early 1950s by commercial airlines for the PanAm B-377 Stratocruiser (Brice, 1951). This airline simulator was followed closely by devices for the U.S. Air Force's B-50D strategic bomber (Dice, 1953) and the U.S. Navy's SNJ trainer (Wilcoxon et al., 1954). These early simulators had fixed (nonmoving) bases. Sophisticated visual systems and complex motion bases appeared soon thereafter. There was a proliferation of training simulators in other areas, including ground transportation, mining, maritime activities, space, command and control functions, and training of control room operators in nuclear power plants.

As early as the mid-1950s, there were several significant reports on the human factors aspects of simulators that continue to be classics in the field. Six of these are cited here with brief annotations of their particular value.

(1) Robert Gagne, "Training Devices and Simulators: Some Research Issues." *American Psychologist*, August 1954. An early and insightful discussion of training research issues.

(2) Robert B. Miller, *Psychological Considerations in the Design of Training Equipment*, WADC Technical Report 54-563. Wright Air Development Center, Ohio, December 1954. Identified the difference between psychological and engineering fidelity and the implications for design.

(3) *Flight Simulator Utilization Handbook*, HFORL Report No. 43. Human Factors Operations Research Laboratories, Bolling Air Force Base, Washington, D.C., August 1953. Recognized that the effectiveness of a simulator is dependent on utilization techniques and showed how quality training programs could be developed.

(4) H.C. Wilcoxon, E. Davy, and J.C. Webster, *Evaluation of the SNJ Operational Flight Trainer*, Technical Report SPECDEVCEN 999-2-1. Port Washington, N.Y., 22 March 1954. Transfer of training experiment with early Navy electronic simulator.

(5) H.M. Parsons, *Man-Machine System Experiments*. Baltimore, Md.: Johns Hopkins Press, 1972. Documentation of training and research use of simulators primarily for command, control, and communication systems.

(6) Adorian et al., 50 Years of Flight Simulation. Royal Aeronautical Society Network, Buckingham, England, 1979. An outline of the evolution of flight simulators from their early inception to modern devices.

Other important reports are U.S. Air Force, 1978; NATO Advisory Group for Aerospace Research and Development, 1980b; U.S. Air Force, 1982; and Richards and Dismukes, 1982.

2

THE USES OF SIMULATION

The primary use of simulators is for training. However, they are being used increasingly for design, development, and evaluation of systems; analysis and evaluation of standards and procedures; and conduct of basic and applied research. The large number and variety of simulators in use in the United States make it virtually impossible to compile a comprehensive list. Furthermore, simulators are rarely treated as a separate category for purposes of inventory, but are treated as integral parts of the facilities in which they are used and classified according to their use. Training simulators, for example, are normally classified under the more general category of training devices. Engineering simulators are used for system development and research simulators are regarded as laboratory equipment.

Tables 3 and 4 illustrate the proliferation of simulator types and uses, and Appendix A describes particular simulators in five categories of simulation, which differ either in their principal purpose or major physical characteristics: (1) design, development, and evaluation simulators--in short, engineering simulators; (2) training simulators; (3) research simulators; (4) battle simulators; and (5) embedded simulation.

The first two columns of Table 3, labeled "Simulator Types," show the kind of equipment and activities that are simulated in the military and civil sectors. The third column, labeled "Cognizant Government Agency," indicates the branch of government that has cognizance over or support of the activities in a sector. Table 4 lists the principal uses of simulators.

A cross-indexing of each type and use has not been made because we did not conduct an inventory; an exhaustive listing of every particular simulator within

TABLE 3 Simulator Types

Types of Sumulators		Cognizant Government Agency
General	Specific	
Aircraft	General aviation	FAA
	Commercial	FAA
	Military	DoD
Spacecraft		DoD/NASA
Surface transport	Automobiles	DoT/DoD
	Trucks	DoT/DoD
	Locomotives/trains	DoT
Civil marine transport	Propulsion systems	DoD
	Collision avoidance	DoT
Marine warfare	Subsurface	DoD
	Surface	DoD
Command and control	Military	DoD
	Space	DoD/NASA
	Civil air traffic	FAA
	Industrial	
Tactical surface Warfare	Direct fire	DoD
	Tanks	DoD
	Artillery	DoD
	Missiles	DoD
	Electronic	DoD
	Battle	DoD
Tactical/strategic Air warfare	Ranges	DoD
	Air combat simulators	DoD
Energy systems	Nuclear	DoE/NRC
	Mining	BuMINES
Environmental	Centrifuge	DoD
	Ejection	DoD
	Diving	DoD
	Motion base	DoD
	Fire bighting	DoD
Medical		DoD

FAA:	Federal Aviation Administration
DoD:	Department of Defense
NASA:	National Aeronautics and Space Administration
DoT:	Department of Transportation
DoE:	Department of Energy
NRC:	Nuclear Regulatory Commission
BuMines:	Bureau of Mines

TABLE 4 Typical Uses of Simulators

Research
Workload
Decision-making
Performance assessment
Stressor effects
Visual/motion systems
Criterion development

Design and Development
Concept/system demonstration
Parametric studies
Alternate configurations
Subsystem evaluation
System evaluation
Aircrew advisory
Prototype assessments
Procedures development
Tactics development
Mission capability assessment
Modification studies

Test and Evaluation
Subsystem/system
Operational capability
Fly-offs

Operations Crew
Initial training
Instrument training
Normal procedures training
Emergency procedures training
Transition training
Refresher training
Tactics training
Mission/battle training
Individual/team assessment
Accident investigation
Selection-initial/operations

Maintainer
Procedures training
Troubleshooting training

type, if feasible, would fill a large book. The purpose of the table is to illustrate the pervasiveness of simulation.

TRAINING

The forerunners of modern, interactive simulators were the flight trainers developed in the 1920s and 1930s (Adorian et al., 1979). The Link Trainer, used by the Army Air Corps for instrument flight training, and its successors were viewed as devices that could substitute on a restricted basis in the training of a limited number of tasks and skills for actual equipment. Early trainers were generalized representations of aircraft; their dynamics were like those of an aircraft, but no particular one, and the kind of training that could be accomplished was somewhat restricted. What could not be learned in a device or learned to the level of proficiency required was learned during practice with operational equipment. In the late 1940s flight trainers evolved from generalized devices to simulators of specific aircraft. Because their appearance and their flight dynamics, implemented by analog computers, were faithful representations, more tasks could be trained to the levels of proficiency required operationally.

Engineering Advances

From the 1950s through the early 1970s, the prominent concerns were mostly engineering issues related to extending the range of tasks that could be performed or trained in simulators and to providing greater fidelity and realism in the simulation of system functions and environmental effects. Engineering advances in simulation have been closely linked to the evolution of mechanisms to produce the operational functions, especially in aircraft. Mechanical and electromechanical methods were supplanted by analog computers and, finally, by digital computers that are the heart of all modern simulators. It is interesting to note that the minicomputers in common use today had their origins in the Universal Digital Operational Flight Trainer project, which developed a digital computer to solve aircraft dynamic equations. Progress in computer technology, especially in processing speed and memory capacity, permitted simulation of multiple, complex functions in real time.

Interrelated developments in display technology allowed the development of visual displays portraying detailed scenes of the outside world as well as simulation of sensor displays. Model terrain boards and television systems, which have been used extensively in aircraft, automobile, and ship simulators to create scenes of the external environment, are rapidly being replaced by computer-generated imagery systems. The same systems are being used for simulating displays of infrared imagery as well as radar and sonar returns. Advances in displays also permitted the portrayal of active elements, e.g., other aircraft or ground vehicles.

Part-Task Simulators

Many modern simulators can support a wide range of tasks; however, because of their complexity, these devices are also quite expensive. For some training purposes it is not cost-effective to use complex devices for training a limited set of tasks or simple tasks, such as procedures; the full range of capabilities of a simulator may not be necessary. And when a large number of people needs to be trained, multiple large simulators may not be affordable. For these reasons, less expensive part-task simulators have been developed.

The availability of minicomputers and microcomputers has greatly facilitated the development of these devices. Part-task trainers can be designed to perform only those functions necessary for a specific purpose. For example, Navy Device 2C62 is a low cockpit procedures trainer for the SH-3H helicopter (Caro et al., 1984). This device has only a few instruments and dials that operate, and the dial needles move in discrete steps rather than smooth movements; other indicators are only photographs of instrument faces. Cockpit dimensions are approximate rather than exact. Cues indicate onset of malfunction but not progressive degradation. Also standard chairs rather than cockpit seats are used. The control station for the simulator is a conventional computer terminal consisting of a cathode ray tube display and keyboard.

Nonrealistic or schematic representations of system functions that still allow operator interaction are another form of low cost, part-task training simulators. The simulation may occur entirely on a computer terminal. The propulsion plant simulator STEAMER, described in Appendix A, is an example of this type of device. The important aspect of this type of simulator, other than its low cost, is that it represents the function of a system in a way that is more easily understood than would be the case if the simulator were a physical representation of the actual power plant. This example vividly illustrates the fact that knowledge of behavioral principles, i.e., how people acquire information and develop mental representations, greatly extends the range of possibilities for simulator design beyond achieving physical realism.

ENGINEERING DESIGN AND RESEARCH

Although training has been the principal application of simulators, they have also been used for equipment design, development of operating procedures, and research on human-machine interaction since at least World War II. The first simulation laboratory for such purposes appears to have been the one established at Beavertail Point, Rhode Island, in 1945 under the sponsorship of the National Defense Research Committee (Parsons, 1972). Simulated shipboard combat information centers were used to test new equipment, methods, and procedures for plotting hostile aircraft paths and communicating this information to antiaircraft directors. In the late 1940s, a 1-CA-1 Link flight training device at the University of Illinois, Aviation Psychology Laboratory, was used for the development of pictorial displays for aircraft (Williams and Roscoe, 1950). In 1950 an air traffic control simulator was built at the Technical Development Center of the Civil Aeronautics Administration in Indianapolis to study terminal area approach procedures, display design, and human factors issues. Parsons (1972) describes over 30 large-scale simulation studies of human-machine interaction that occurred between 1948 and 1966 in which simulators were used for projects ranging from investigations of team composition to equipment design for Apollo lunar missions.

Today simulators for engineering design and research are common in government laboratories, universities, and civilian industries. Engineering applications are as diverse as the development of command-and-control equipment and the assessment of ride quality of farm machinery. One indication of their importance and widespread use is the fact that Aviation Week and Space Technology, a major aerospace industry trade publication, featured in its

January 17, 1983, edition 12 articles on the use of simulators in aircraft design.

LICENSING AND CERTIFICATION

A relatively recent but important use of simulators is for licensing and certification. In 1980 the Federal Aviation Administration issued a rule titled Advanced Simulation (Federal Register, June 30, 1980), which permits all operational training and crew member certification (except preflight checks) to be conducted in a simulator that meets certain requirements and is part of an approved training program. In effect, a simulator meeting the requirements is a substitute for the use of an aircraft to qualify personnel. In 1982 the first simulator to receive FAA approval for training and crew certification was a Boeing-727 simulator operated by United Airlines. This milestone vividly documents the high degree of fidelity and realism that can be achieved in simulators. It also indicates the degree to which simulators have been accepted and are relied upon for training purposes (see also "Airplane Simulator and Visual System Evaluation," Advisory Circular AC No. 120-40, Federal Aviation Administration, Washington, D.C., January 31, 1983).

Only aircraft simulators are used currently for certification. However, the Nuclear Regulatory Commission is developing requirements to certify nuclear power plant control room simulators for operator training (Rankin et al., 1984). Ultimately these simulators may have the capability to perform certification tests for nuclear power plant operators.

NUMBERS AND COSTS OF SIMULATORS

The military services are the largest users of simulators with the greatest financial investment. They will request a total of over $6 billion for simulators and training devices between 1982 and 1986, and the rate of expenditure will increase annually (Deegan, 1981). Approximately 35 percent of these expenditures will be for flight simulators. NASA has approximately 30 large simulators, mostly aircraft simulators, with an estimated total value of $100 million.

The Army's Index of Training Devices (U.S. Department of the Army, 1980) contains a list of approximately 390 types of training devices. Over 300 of these are simulators and, since there are often multiple copies of devices, the actual number of individual devices, each costing from a few thousand to several million dollars, is probably in the thousands. The Army has spend nearly $140 million thus far on the development and procurement of its Multiple Integrated Laser Equipment System (MILES) (Remhotz, 1982). This system simulates and records the effects of direct engagements between small arms, anti-tank, and tank weapons; it is used to train infantry and combined arms units up to battalion size. The eventual procurement cost to equip each of the 16 active Army divisions and the National Training Center is projected to approach $1 billion.

The Navy's Index of Training Devices (U.S. Department of the Navy, 1981) contains approximately 2,700 individual training devices, primarily simulators. Privately compiled lists of military aircraft simulators (Defense Market Survey, 1980a, 1980b) show that the Navy and the Air Force have 462 and 232 of these multimillion-dollar devices, respectively. A recent two-cockpit Naval air combat simulator, Device 2E6, costs over $25 million. Training simulators for the U.S. Marine Corps AV-8B aircraft consist of three devices: a part-task procedures trainer, an operational flight trainer, and a weapons system trainer: one set costs nearly $50 million. It should be noted that research and development costs frequently inflate the cost of a simulator when procured as a prototype or on a one-of-a-kind basis. Currently, B-52 weapons systems trainer simulators cost about $44 million each. The B-1 simulator is estimated to cost $75 million (Burpee, 1981).

Worldwide there are about 290 large commercial aircraft simulators operated principally by airlines, each device costing up to $10 million (Whitaker, 1981). There are 19 existing nuclear power plant simulators costing approximately $7 million each, and 16 more are on order (Rankin et al., 1984).

Procurement of maintenance trainers, both simulators and actual equipment, by the Department of Defense has increased since 1977. Current annual procurement costs are estimated to be about $120 million. Expenditures for maintenance simulators and actual maintenance equipment trainers in the military services were projected to be $620 million between 1975 and 1985 (U.S. Department of

Defense, 1982). About two-thirds of this procurement is for maintenance of aircraft; the remainder is divided among all other areas of maintenance of military equipment.

Another large use of simulators is for development and evaluation of command, control, and communication (C^3) systems. Currently the Department of Defense has 41 operational C^3 manned test beds with another 16 either under procurement or proposed (Gasparotti et al., 1981).

The number of personnel required to support simulators is also substantial. The Navy estimates it has 2,200 people employed in the operation and maintenance of 300 major simulation devices. The McDonnell Douglas Aircraft Company employs approximately 150 support personnel for its Flight Simulation Facility, which consists of five separate cockpit stations sharing common computer and imagery sources and is used for engineering design and development of fighter aircraft.

NEEDED TECHNICAL IMPROVEMENTS

Although simulators have reached an advanced state of technical maturity, there are still some areas where technical improvements are desired. The succeeding chapters of this report largely focus on the importance of behavioral science and human factors contributions to simulator design and use; the remainder of this chapter provides a brief discussion of technological and engineering advancements needed to extend the capabilities of simulators.

Visual Simulation

One of the most prominent technical concerns is improvement of the quality of visual scenes for military flight training simulators. For certain applications, greater detail and realism of visual scenes is thought to be necessary to support such tasks as low-level, high-speed flight for military aircraft (Richards and Dismukes, 1982) and nap-of-the-earth flight by helicopters. The judgments of experienced pilots as well as performance tests have shown that current visual system technology is not sufficient to provide the distance and altitude cues required for these flight regimes. While one possibility is to make better use of the capabilities of existing visual systems, it is commonly believed that simulated low-level flight will be possible only by providing greater detail, such as ground vegetation and texture.

Voice Communications

Technical advances are desired in voice communications, both the production and recognition of human speech. In this area the problems are producing variable content messages as if spoken by a human and recognizing what is said by participants so that appropriate simulated events or actions can occur. For example, in training air traffic controllers, it would be desirable to have simulated pilots who can engage in two-way communication with the controller and respond appropriately to the controller's directives. Similar needs exist in command-and-control and battle simulation devices, in which receiving and producing voice messages are primary activities.

System Models

A third area of concern is improving the comprehensiveness, accuracy, and resolution of system function models for both normal and abnormal modes of operation. Almost all simulator functions are an implementation of a simplified or superficial model of actual system functions. For example, models used in nuclear power plant simulators do not allow for all possible interactions between system variables. A simple model of normal operation of the plant may be adequate for training operators in standard procedures. However, in training emergency procedures, a simplified model of the power plant operation may unduly restrict the kinds of failures that can be simulated, or worse, produce effects that are not equivalent to what would actually occur in a real power plant. The general problem is that real-time simulation always involves a trade-off between the amount of computation that can occur in a given time frame, the complexity of the functions to be computed, and the cost of doing so (Belsterling et al., 1982). Another approach is to partition the software architecture into submodels that emulate smaller segments of the system in greater detail.

When system models are implemented on digital computers, the model of functions that are continuous in the real world may be updated at discrete intervals. The update interval of a function can affect performance whether or not these differences are perceived. For example, the equations simulating performance of the engines of the T-2C aircraft in the Naval Training Equipment Center's Visual Technology Research Simulator are updated 7.5 times per second. Pilots frequently comment that the response of the simulated engines to throttle changes seems different than in the actual aircraft. An experiment in which the engine equations were updated 30 times a second was found to be subjectively more realistic to the pilots and also yielded a small but reliable improvement in performance as well (Westra et al., 1981).

Communication Links Among Simulators

Simulators have been developed that involve multiple scenario components such as aircraft crews, ships, bridge teams, and command center staffs. It is now considered desirable to extend simulation to involve multiple components at dispersed sites that act either cooperatively or as adversaries. For example, it would be desirable to have attack aircraft simulators linked through telecommunications with tactical air control simulators to conduct cooperative exercises. Another alternative is to link attack aircraft simulators with air defense weapon simulators to permit both sides to practice against a realistic adversary. Attention is also being given to a network that would permit as many as 1,000 players, e.g., tanks, antitank weapons, and aircraft and antiaircraft weapons, to engage each other in realistic but simulated attacks on a 100-mile-by-100-mile terrain area.

Low-Cost Simulation

Development of low-cost simulators that can be produced in large numbers is of particular concern to the Department of Defense (U.S. Department of Defense, Defense Science Board, 1982). These devices would take advantage of the availability of inexpensive microcomputers and relatively new technology developments such as video disks and speech synthesis and recognition systems. Time-sharing of a single processor among several trainees/operator stations is another approach. It is particularly applicable to simulation that is predominantly information flow rather than equipment operation. This approach has been used for some of the Army's war games simulators.

Another means for achieving relatively low-cost simulation is by using embedded simulation in operational equipment. Since most modern systems are computer-based devices, embedded simulation can be accomplished with software and little additional hardware, an important factor when space is at a premium such as in aircraft or on ships. Using operational equipment as a training device allows maintenance of skills or refresher training in the operational context and reduces the need to conduct training at special facilities.

The approaches described above for improving simulation technology reflect a general desire to extend the scope of simulation and increase its effectiveness while at the same time minimizing costs. Extending the comprehensiveness of simulation by linking remotely located simulators and lowering the cost of simulation by the use of simple devices and embedded simulation raises questions about what degree of comprehensiveness is necessary, how much physical fidelity is enough, and in what ways is it desirable and effective to depart from physical fidelity to achieve the intended purpose. Answers to these questions must come from a consideration of the behavioral and not the physical aspects of simulation.

3

BEHAVIORAL FACTORS IN SIMULATON

At this stage of advanced simulator technology, human behavior, rather than equipment, has become the central concern in simulation. Improvements in the design and use of simulators are more likely to depend on greater development and use of behavioral knowledge than on advances in engineering technology. In terms of behavior, the primary goals of simulation are facilitating the learning that transfers to the operational context in the case of training simulators and eliciting valid performance in the case of simulators used for design, research, or certification purposes.

In this chapter, the behavioral bases for simulator design and measures of effectiveness are reviewed. Simulator validity is advanced as a more productive concept than fidelity as a criterion for evaluating simulator requirements and as a focus for research on simulation. This chapter is concerned with the need to improve our understanding of behavioral processes relevant to simulation. Few of the many recommendations for fundamental research made during the past 30 years have been acted on (Gagne, 1954; Miller, 1954; Wilcoxon et al., 1954; Parsons, 1972). A brief review of current DoD research in the area of simulation and training devices indicates that relatively little effort is directed toward fundamental behavioral issues in simulation. Analysis of cognitive processes and development and use of human performance models are seen as two of the potentially most effective means for developing and expressing behavioral knowledge necessary to enhance simulator design and application.

PHYSICAL FIDELITY AS A DESIGN GOAL

As described in Chapter 2, the evolution of simulation has been primarily a matter of technological advancements to make simulators more realistic, accurate, and comprehensive representations of a particular item of equipment or system. There are good reasons why simulators should be realistic and comprehensive representations of real equipment and systems. The more like the real-world counterpart, the greater is the confidence that performance in the simulator will be equivalent to operational performance and, in the case of training, the greater is the assurance that the simulator will be capable of supporting the learning of the relevant skills. Everyday experience confirms that a simulator of sufficient fidelity will produce learning or performance approximating that which would be expected if actual equipment were used.

From a practical standpoint, striving for realism and comprehensiveness greatly simplifies the simulator design problem. Designing a simulator to realistically and comprehensively duplicate a real-world item of equipment or system is a matter of achieving physical and functional correspondence. The characteristics of the human participant can be largely ignored. When compromises in realism are necessary due to technical limitations, they are based on physical rather than behavioral criteria and commonsense interpretations of their consequences.

However, there are limitations and cost penalties associated with relying on the duplication of physical characteristics as a design guideline. The degree of duplication possible has a natural limit--the operational system. In most cases, perfect duplication is limited not so much by the characteristics of the target system but by characteristics of the operational environment or events. Simulating the outside environment and events that affect or drive the simulation can be difficult and expensive, and small gains in realism often can be achieved only at relatively great incremental costs. For example, realistically simulating visual scenes is still one of the most challenging technical problems, and the visual system is often the most costly component of a simulator. In addition, when the operational environment includes complex active elements, e.g., opposing and friendly units in battle simulation or multiple aircraft in an air traffic control situation, simulating the actions and communications is very difficult.

Another limitation is that evaluation of features of a simulator is a matter of relating specific characteristics to specific task performance outcomes. Under these circumstances it is not possible to generalize about or predict what features will be useful in another simulation context, or how a person will perform if the task is changed.

The premise that precise physical duplication is important has commonsense appeal. However, this premise has no theoretical foundation to predict how departures from realism and comprehensiveness might affect simulator effectiveness.

THE BEHAVIORAL APPROACH TO SIMULATION

As stated above, the premise in the behavioral approach to simulation is that the primary goal of all simulators that involve human participation is to support learning in the case of training simulators or valid system performance in the case of engineering design and research simulators. That is, the purpose of a simulator is to provide the conditions, characteristics, and events present in the operational situation necessary for the learning of skills that will be performed with actual equipment or for eliciting performance identical to what would occur in the operational context.

Two related principles derive from this premise. First, the characteristics and methods of using simulators should be based on their behavioral objectives. Second, physical realism is not necessarily the only or optimal means for achieving the behavioral objectives of simulation. Because the history of simulator development is characterized by striving for improved realism through the advancement of technology, it is easy to forget that the learning or performance--not physical duplication--is the primary goal.

Measures of Simulator Effectiveness

Following World War II, the expense associated with the development of simulators became of increasing concern. As early as 1949 questions about the importance of physical fidelity of simulators were raised (Williams and Flexman, 1949). Robert B. Miller (1954) pointed out that, although realism and cost might be closely related, simulator fidelity and value, at least as measured by transfer of training, probably were not. There is a level of realism, Miller hypothesized, at which the cost of additional realism rises more rapidly than the additional training value that can be derived. Therefore, the need for realism in all simulators began to come into question. Greater use could be made of simulation if the cost of simulators could be reduced. Studies by Semple et al. (1981b) and Waag (1981) on visual and motion simulators indicated that physical fidelity is not essential in evoking transfer of training.

A basic question is whether simulators can be as effective as actual equipment for training on maintenance tasks. Such comparisons were made in 12 different studies and summarized by Orlansky and String (1977). As measured by achievement at training stations, roughly similar results were obtained with either type of device. Students trained with simulators performed slightly better in two cases and slightly poorer in one case. These differences were statistically significant but small.

Another study on the extent of fidelity required was recently performed to compare the maintenance training effectiveness of actual equipment and simulators with both high and low physical fidelity for the 6883 Converter/Flight Control Test Station (Cicchinelli et al., 1980). Maintenance performance test scores were essentially equal for students trained on the actual equipment and on either simulator. Yet there are dramatic differences in the 15-year life-cycle costs for these items. Actual equipment cost is $5.3 million, the high physical fidelity simulator cost is $2.1 million, and the low physical fidelity simulator cost $1.6 million.

Several studies involving simulators of low realism demonstrated that effective training could be conducted in them (e.g., Prophet and Boyd, 1970). In fact, for many tasks, training in low-realism devices enabled trainees to perform as well on operational equipment as personnel who were trained on high-realism devices or even on the operational equipment itself. In these studies, the low-realism devices had training value equal to that of high-realism simulators.

It was apparent from several of these studies that the manner in which the low-realism devices were used was a factor in the effectiveness of the training conducted in them. Successful training concentrated on the meaning, or cue value, of stimuli present in the device, thus equating functionally rather than objectively with the stimuli and responses found in the devices and in the operational equipment. It was necessary, of course, for trainees to conceptualize realism in the devices to make them functionally equivalent to simulators of much higher physical realism compared with the equipment simulated. Given these requisites, it was evident that the high cost of realism was not necessary if the manner in which a simulator were to be used could be appropriately structured along behavioral principles.

Examples of Simulators With High Fidelity

As noted earlier, pilots now may be certified in a simulator that meets fairly rigorous fidelity standards established by the Federal Aviation Administration. Such a simulator must faithfully duplicate physical and functional characteristics of an aircraft as well as the conditions of flight. Similarly, in engineering design, where critical and expensive design decisions may be based on performance in a simulator, high fidelity is the best insurance for obtaining valid performance data.

Specific mission rehearsal is another instance in which high-fidelity simulators are appropriate for training. The objective of mission rehearsal is to attain a final performance level in the simulator equivalent to what is expected in the operational setting. Mission rehearsal involves not only training but also, implicitly, evaluation of performance as well. High-fidelity simulation is probably necessary to satisfy both the rigorous training and the evaluation components involved.

Thus, while low-realism simulation can be used extensively for training and in limited ways for other requirements, a rational case can easily be made for continued reliance on realistic simulators for many nontraining applications. Even in the case of training simulators, there are likely to be tasks that would benefit from realistic simulation because of the difficulty of building training exercises that would permit the requisite cue development. In addition, personnel attitudes toward training and simulation, particularly when familiarity with mediational processes may be limited, may constitute justification for greater realism in simulator design.

THE IMPORTANCE OF VALIDITY IN SIMULATOR DESIGN

Fidelity in the sense of close physical correspondence, although frequently cited as a measure of the value of a simulator, clearly is not an end in itself. The concept of simulator validity must be considered. This term refers to the correspondence between the actual results of using the simulator and a set of outcomes that are needed or desired and constitute the objectives of its use. These two implications of simulator validity are discussed below.

Application Purpose

To evaluate the validity of a simulator, it is necessary to take into account the purposes for which it is to be used and to formulate objectives for that use (see Appendix A). Characterization of a simulator as having high or low validity for one purpose or use will not necessarily imply the same degree of validity for another use. Furthermore, specific objectives are required in order to judge whether the use of the simulator will have outcomes that match objectives of its use. For example, training as a general purpose is insufficient to allow a characterization of the validity of a simulator; the specific objectives intended to be accomplished in training with the simulator must be considered.

To illustrate, training aids consisting of two-dimensional reduced-scale paper representations of aircraft cockpits, missile control panels, and other operational equipment have been used very effectively for training various cognitive, discriminative, and procedural tasks associated with the use of such equipment. There is evidence that for these objectives, outcomes of training are quite satisfactory; that is, the paper devices, when used with appropriate mediational processes, have high validity for the purposes of training cognitive, discriminative, and procedural skills. These paper "simulators," however, are likely have low validity for training or assessment of manipulative or control tasks, since they do not permit these components of performance to be practiced.

Outcome Specification

To evaluate the validity of a simulator, it is also necessary to have a set of outcome specifications. Using the training example, outcome specifications consist of the performance objectives that underlie the training programs to be conducted in the simulator. For personnel testing, outcome specifications consist of the performance that will be sought in tests that will use the simulator. For use in system design, outcome specifications consist of the kinds of information about system performance, including human performance, that will be assessed in performance trials using the simulator.

High potential validity for an intended outcome indicates that the outcome can be fulfilled, either fully or in large part, provided appropriate programs of use are carried out. Low potential validity indicates that an intended outcome cannot be fulfilled at all or only in small part, regardless of the programs in which the simulator is used. In the case of a simulator to be used for training, its level of potential validity can be viewed as an indication of the amount of training on it that potentially can transfer to the operational system or equipment, i.e., its training effectiveness potential.

Formulation of meaningful outcome specifications involving behavioral and cognitive factors requires analysis of the psychological requirements of tasks to be performed in the simulation situation as well as in the operational environment that is simulated. The need for meaningful outcome specifications implies the need for procedures or processes to analyze behavioral and cognitive requirements of human performance in developing specifications for simulator systems.

It should be noted that these behavioral analyses cannot be reduced to a uniform procedure. Knowledge of learning, cognition, and other behavioral processes are necessary to understand the requirements implied by the behavioral outcomes and to conduct the analyses necessary to develop the simulator specifications.

4

CONTRIBUTIONS OF THE BEHAVIORAL SCIENCES TO SIMULATION

The key to successful application of the behavioral sciences approach to simulator design and use is broader and more detailed understanding of the behavioral processes that mediate between the simulation context and elicited performance. The development and refinement of general and specific behavioral principles applicable to simulation must continue to advance through both laboratory-based research as well as research performed in the simulation context itself.

REVIEW OF PREVIOUS RESEARCH RECOMMENDATIONS

For this report the working group reviewed research recommendations drawn from a variety of studies performed to assess the design and use of simulation. Over the past 30 years, behaviorally oriented research has been stressed frequently and consistently as a critical need to improve the design and use of simulators. Many of the findings and recommendations are formulated in general terms; others focus on specific types or uses of simulators. However, even in these latter instances, the generic behavioral questions underlying the specific problems are apparent. It will also be apparent that many of the same issues are repeated in different contexts or have persisted in the same contexts for decades.

Most of the reports of interest are from the literature on flight training simulators. This reflects the fact that flight training is the major area of application and has the longest history of the use of simulators, involves the greatest number and most expensive devices, and therefore has received the most attention. It should be noted, however, that most issues that have been identified for flight training simulators are applicable to other types and uses of simulators (see Table A-1 in Appendix A).

Table 5 shows some of the major behavioral research related to simulation that has been undertaken in the past 30 years. The research is organized in terms of nine major topics, which are discussed below.

TABLE 5 Examples of Recommendations for Behavioral Research Related to Simulation

1. Fundamental Behavioral Processes	
Structure and acquisition of skills	Gagne, 1954 Muckler et al., 1959
Cognitive skills	Prophet et al., 1981
Motivation and learning	Gagne, 1954 Muckler et al., 1959
Behavioral mechanisms of transfer	Gagne, 1954
Perceptual learning	Hennessy et al., 1980
Visual perception	National Research Council, 1982
2. Fidelity of Simulation	
Important and unimportant simulator characteristics	Miller, 1954
Effects of fidelity on transfer	Muckler et al., 1959
Interaction of fidelity with (a) Instructional variables (b) Experience level	Smode and Hall, 1966
Fidelity requirements	McCluskey, 1972 Huff and Nagel, 1975 Hayes, 1981 Gaffney, 1981
Departures from fidelity of dynamics to compensate for simulator deficiencies	NATO-AGARD, 1980 Adams, 1978

3. Visual Simulation	
Visual display characteristics	Muckler et al., 1959 Smode and Hall, 1966 Huff and Nagel, 1975 National Research Council, 1975 Hennessy et al., 1980 NATO-AGARD, 1980, 1981 Kraft et al., 1981
Scene content and visual cues	Matheny, 1975 National Research Council, 1975, 1982 Thorpe, 1978 Hennessy et al., 1980 NATO-AGARD, 1980, 1981 Prophet et al., 1981
4. Vehicle Motion	
Motion cues	Muckler, et al, 1959 Huff and Nagel, 1975 NATO-AGARD, 1980 Prophet, et al, 1981
Interaction of motion and vision	Smode and Hall, 1966 Matheny, 1975 National Research Council, 1975
Interaction of motion and skill level	Smode and Hall, 1966
Effects of motion on transfer	Smode and Hall, 1966 Matheny, 1975
5. Performance Assessment	
Criteria for performance	Gagne, 1954 Center for Nuclear Studies, 1981

	Performance measurement	Gagne, 1954 Muckler et al., 1959 National Research Council, 1975 USAF-SAB, 1978 Center for Nuclear Studies, 1980 Gaffney, 1981 Prophet et al., 1981
	Automated performance monitoring	USAF-SAB, 1978 Center for Nuclear Studies, 1980
	Measurement of team performance	Parsons, 1972 Gaffney, 1981 Prophet et al., 1981
6.	Modeling	
	Models of visual and motion simulation	Waag, 1981
	Sensory system modeling	USAF-SAB, 1978
	Model of multisensory spatial orientation	NATO-AGARD, 1980
	Models of visual environment to identify variables relevant to training	NATO-AGARD, 1980
	Models to predict training effectiveness	Prophet et al., 1981
7.	Training	
	Critical characteristics for transfer	Miller, 1954 Caro, 1976 Waag, 1978
	Effects of change in task characteristics on transfer	Muckler et al., 1959
	Measurement of transfer effectiveness	Smode and Hall, 1966 Williges et al., 1973 NATO-AGARD, 1980

Systematic method for developing training requirements that provide guidance for simulator design	AIAA, 1980 NATO-AGARD, 1980
8. Training Methods	Gagne, 1954 HROL, 1953 USAF SAB, 1978 Center for Nuclear Studies, 1980
Sequence of training	McCluskey, 1972
Use of feedback and guidance	Prophet et al., 1981
Instructional features	Prophet et al., 1981
Instructor training	Prophet et al., 1981
Simple (part task) versus complex (whole task) simulators	Muckler et al., 1959 Smode and Hall, 1966 National Research Council, 1975
Generic versus specific simulation	Center for Nuclear Studies, 1980
9. Other	
Documentation and use of lessons learned from past simulators	Smode and Hall, 1966 Caro, 1976
Experimental design	Muckler et al., 1959 Williges et al., 1973

Fundamental Behavioral Processes

As a logical extension of the principle that simulator characteristics should be determined by behavioral consequences, several studies have recommended research on the behavioral processes relevant to simulation. For example, learning or skill acquisition is the fundamental process of concern in the use of simulators for training. Gagne (1954) and Muckler et al. (1959) advocate research on the structure of skills, the acquisition and transfer of learning processes, and the role of motivation in learning. Prophet et al. (1981), recognizing that the operation of most modern systems increasingly demands information processing and decision skills as much or more than psychomotor skills, recommend research on these and other cognitive processes as a basis for development of training procedures, devices, and simulators for cognitive tasks.

A working group on visual simulation of the National Research Council's Committee on Vision concluded that requirements for visual scene content must be based on a better understanding of perceptual processes. This group recommended research on a computational analysis approach for determining visual cue requirements and verification through psychophysical experiments as well as research on the contributions of optical flow and peripheral vision to spatial orientation (Richards and Dismukes, 1982). Hennessy et al. (1980), in a report on research needs for vertical/short takeoff and landing aircraft simulator visual systems, proposed several studies in the area of perceptual learning.

Behavioral Fidelity of Simulation

Numerous recommendations have been made to investigate fidelity of simulator characteristics as they affect learning or performance. Usually, a specific domain, such as visual cues (Matheny, 1975; National Research Council, 1975; NATO-AGARD, 1980b) or motion cues (Muckler et al., 1959; NATO-AGARD, 1980b; Prophet et al., 1981), is addressed. Smode and Hall (1966) recommended research on fidelity interactions with instructional variables and level of experience of trainees. Other recommendations on simulator fidelity are cast more broadly, calling for research on the topic in general (McCluskey, 1972; Huff and Nagel, 1975; Hays, 1981; NATO-AGARD, 1980b; Gaffney, 1981). In all instances, the authors acknowledge that fidelity requirements should be evaluated in terms of the behavioral consequences rather than in terms of physical correspondence to a real system.

Visual Simulation

Because of the large number of flight simulators equipped with visual systems to portray outside visual scenes as well as the expense of these systems, there have been numerous studies in this area to identify issues and recommend research. Recommendations fall in two broad categories, characteristics of visual displays and scene content. The former category includes recommendations for determining field of view size necessary, requirements for resolution, luminance and contrast, the value of color, and effects of distance of the display (Muckler et al., 1959; Smode et al., 1966; Huff and Nagel, 1975; National Research Council, 1975; Hennessy et al., 1980; NATO-AGARD, 1980b; Kraft et al., 1980). Many of the same authors and groups as well as others have recommended research on scene content. Research topics include scene detail, degree of abstraction of portrayed objects and terrain, texturing of surfaces, the kinds and density of objects in the scene (Matheny, 1975; National Research Council, 1975, 1982; Hennessy et al., 1980; NATO-AGARD, 1980b, 1981; Prophet et al., 1981). A working group of the Air Force Office of Scientific Research (Thorpe et al., 1978) noted that there is not even an adequate lexicon for describing factors in scene content.

Issues related to visual simulation have been with us for a long time. Striking advances in the technology of computer-generated imaging are taking place now that will improve visual resolutions and their quality and detail and possibly reduce overall cost. It is possible (some say likely) that extremely high visual fidelity, in the engineering sense, will soon overtake the current need for perceptual research on visual displays for simulators.

Vehicle Motion

The value of motion cues for training and engineering design flight simulators has long been a topic of debate and one of the few areas, along with visual system requirements, that has received substantial research attention. The crux of the problem is that motion platforms and other motion cueing systems cannot duplicate sustained accelerative forces; all motion cues are onset cues. The principal issues have been the importance of these cues for training and performance, the form of the motion functional equations, and the number of degrees of freedom (Muckler et al., 1959; Smode et al., 1966; Huff and Nagel, 1975; Matheny, 1975; National Research Council, 1975, 1980; NATO-AGARD, 1980b, 1981; Prophet et al., 1981). Despite the large number of studies that have been performed on motion cueing (see Waag, 1981), there seems to be no consensus on its value (U.S. Air Force, 1978). Waag (1981) attributes this state of affairs to the fact that the studies performed were so specific in nature that it is impossible to develop any general principles or conclusions from the results.

Performance Assessment

Performance measurement and establishing criteria for performance are essential not only to all uses of simulators but also for evaluating and improving simulator design. What constitutes necessary and effective characteristics of simulators remains a matter of opinion without reliable and valid performance information. For these reasons many reports on simulation have recognized performance assessment as a key area for research (Gagne, 1954; Muckler et al., 1959; National Research Council, 1975; USAF Scientific Advisory Board, 1978; Center for Nuclear Studies, 1980; Prophet et al., 1981). While there are a host of problems in performance measurement in general (these are discussed in Chapter 5), the development of automated performance measurement systems (U.S. Air Force, 1978; Center for Nuclear Studies, 1980) and the measurement of team performance (Parsons, 1972; Gaffney, 1981; Prophet et al., 1981) have been viewed as particularly pressing problems by both the user and the research communities.

Modeling

The need to determine simulator requirements based on behavioral research is reflected in the recommendations presented in several recent reports. The USAF Scientific Advisory Board (U.S. Air Force, 1978) encouraged continued development of models of human sensory systems that can be used to evaluate the consequences of motion cueing. A NATO-AGARD group (1980b) made similar recommendations for the development of a model of multisensory spatial orientation and a model of the visual environment to identify variables relevant to training. Waag (1981) calls for a model of visual and motion simulation to provide a structure to aid in developing testable hypotheses that might subsequently lead to generalizable research findings.

Reflecting many of the same concerns, Prophet et al. (1981) recommend the development of models to predict training effectiveness of simulators as well as normative performance models for proficiency evaluation. Several reports that have included recommendations for research on behavioral topics relevant to simulation have also called for development of human performance models in the areas of vision and motion sensation and perception (Waag, 1981; U.S. Air Force, 1978; NATO-AGARD, 1980b). The importance of human performance models to simulator design as well as to practical application of simulators is discussed at length later in this chapter.

Training and Training Methods

Research recommendations specifically related to the training function principally address issues of transfer of learning and training methods. Answering the most fundamental question--what are the critical simulator characteristics necessary to produce transfer--has been discussed as a research need (Miller, 1954; Caro, 1977; Waag, 1981) as well as how changes in task characteristics affect transfer (Muckler et al., 1959). Task analysis and instructional system development methods are useful to determine what is to be trained but not explicitly to determine what is required to conduct training. In recognition of this shortcoming, two recent reports include recommendations for research to develop systematic methods for establishing training requirements that provide guidance for simulator design (American Institute of Aeronautics and Astronautics, 1981; NATO-AGARD, 1980a).

In acknowledgment of the maxim that how a simulator is used is as important as its physical characteristics, several reports have addressed research needs to improve the methods of use of simulators for training (Gagne, 1954; U.S. Air Force, 1978; Center for Nuclear Studies, 1980). Training on a series of tasks from beginning to end as they will be performed in the real world may not be the most effective sequence for simulator-based training and has been recommended as a subject for research (McCluskey, 1972). Out of 21 high-priority research needs to improve aircrew training devices, developed by Prophet et al. (1981), 12 were specific to simulator use. The research topics involving utilization included feedback and guidance in the instructional process, control of the evaluation and measurement process for individuals and crews, training and evaluation of instructors, and self-instruction methods.

Although simplified or part-task simulators have a long history of use and have been proliferating since the advent of inexpensive microprocessors, the range of their potential utility is not clear. Research to determine the relative merits of part-task versus whole simulators for training and what tasks are most suitable for each type have been included in the recommendations of several reports (Muckler et al., 1959; Smode et al., 1966; National Research Council, 1975). A closely related issue is the value of generic training devices representative of a type of system versus simulators of specific systems. This is a particularly important issue in the training of nuclear power plant operators that deserves research attention (Center for Nuclear Studies, 1980).

Documentation and Research Design

In addition to the research described in the above categories, two other noteworthy recommendations have been made for courses of action to improve simulation that have been drawn from the literature. Smode et al. (1966) and Caro (1977) have advocated documentation of lessons learned from past and existing simulators to improve the design of future ones. Implicitly this suggestion acknowledges the lack of a systematic base of knowledge about simulator design practices. Each technical evolution or variation in simulator design is an experiment of a sort and worthy of assessment and documentation for the benefit of future simulator developments.

The second recommendation is for both research and application of experimental design methodologies that maximize the useful information that can be extracted from simulator-based research studies and engineering test and evaluations (Muckler et al., 1959; Williges et al., 1973). Formal experiments tend to use full factorial designs that, for practical reasons, limit the number of variables that can be tested in one study. Engineering tests and evaluations are often conducted without regard for the control of artifacts or the possibility of formal statistical analysis of the derived data. Both practices are wasteful in terms of the information gained for the effort expended. The need for further development and application of economical, multifactor designs in simulation studies is discussed in Chapter 5.

The Persistence of Research Needs

All these previously identified issues are still essentially valid questions that yet have to be answered. The fact that the same research issues continue to persist suggests that the required research has not been performed or the research that has been performed is either inadequate or inconsequential.

The lack of basic research of the kind necessary to build a behavioral base of knowledge and principles applicable to simulation design and use has been stated in several past reports. It is worth repeating their conclusions, for they express the need for fundamental behavioral research as pointedly and clearly as we possibly could.

Smode et al. (1966) reviewed and assessed research relevant to pilot training. The authors preface their specific suggestions for research needs for simulation training with the observations that devices used earlier as simulators bear little resemblance to the complex weapons systems trainers and training facilities in use today. However, there is little evidence that research has been performed concerning the use of these sophisticated equipments. What research has been undertaken appears minuscule considering the huge stake involved in the development and use of simulators.

Smode believes that the real issues are being neglected and that a serious, sustained program is needed to gain an understanding of the full value of simulation for aviation training and for the specification of the design requirements necessary for achieving the potential of simulation training.

What research has been done has contributed little to the development of fundamental principles. Visual and motion systems for flight simulators have been two of the most intensively researched topics in simulation, yet little of lasting value has emerged. Waag (1981), in concluding a review of the literature on these topics, noted that there exist no quantifiable models of visual and motion simulation that enable testable hypothesis to be generated that might subsequently lead to some generalizable findings.

The National Research Council's Committee on Vision addressed research needs for flight simulation and also noted the lack of basic research in this area (Richards and Dismukes, 1982:8):

> Current research attempting to define relationships between visual simulation variables and flight control performance has immediate value for evaluating specific displays and equipment features, but will not provide fundamental knowledge that is cumulative and that might allow prediction of visual information requirements for a wide range of simulation training tasks.

Huff and Nagel (1975) pointed out the lack of development of fundamental knowledge of behavior relevant to simulator design and use. They indicated that it is essential that new ways be developed to conceptualize and measure pilot experience as a necessary step for the continued development and use of flight simulators. Current techniques have not provided a firm foundation on which to build simulation design. They end with a quotation from Adams' (1973) preface to a special issue of the Journal of Human Factors devoted to simulation. It is equally apt to quote it here, more than a decade later (p. 501):

> We often seem content with the routine testing of training devices which engineers create, and this is an important contribution, but where are our systematic research programs that will produce principles and provide guidance for the simulation engineers of tomorrow?

THE NATURE OF THE BEHAVIORAL PROCESSES IN SIMULATION

In this section we discuss two broad topics: analyses of cognitive processes and knowledge and human performance modeling. We believe these are two key methods for characterizing and expressing the behavioral processes of interest in simulation as well as identifying and facilitating the behavioral research necessary to improve the design and use of simulators.

Fundamental to realizing the behavioral objectives of simulation--the desired learning or performance--is the need to understand the cognitive processes that are responsible for the interpretation, transformation, and retention of information, its consolidation into new processes, i.e., skills and their ultimate manifestation in performance. From a behavioral perspective, the central issue is understanding the internal processing and transformation of information, the development of abilities, internal processes themselves, and decision and response mechanisms that produce overt behaviors. In other words, it is important to know how to characterize the hidden, internal cognitive activities and how external and internal events interact.

Complementing the need for analysis of cognitive processes is the need to synthesize these processes into a coherent and tractable form. Human performance models fulfill this need because they are explicit expressions of behavioral processes. A model has a theoretical base inherent in its construction and is both extensible and verifiable. A model is thus an orderly means to accumulate behavioral knowledge and predict effects that can be empirically tested. It serves as a framework for research programs but also can be used as a tool for the design of simulators as well as other systems. It has the singular virtue of communicating knowledge of behavior in the same way as the physical models that design engineers are accustomed to using.

Used in concert, analyses of cognitive processes and knowledge and their expression in human performance models provide a strong mechanism for guiding research on behavioral issues in simulation and translating the research results into design practice.

Analyses of Cognitive Processes and Knowledge

Many difficulties in the design and use of simulators could be reduced with more thorough and specific analyses of the human skills and knowledge required for the operation and maintenance of equipment. In the past, contributions of behavioral scientists to simulation have been based on the available psychological principles and methods and have provided useful insights into the requirements for effective training and other functions using simulation. Recent scientific developments have provided methods of empirical analysis and theoretical concepts that make possible a significant increase in the detail with which cognitive requirements of complex task performance can be specified.

The term cognitive science is used to refer to a growing body of scientific work, using methods and concepts from cognitive psychology, artificial intelligence, and linguistics, consisting of analyses of relatively complex cognitive processes and systems. Major recent contributions and topics of rapidly advancing knowledge are summarized in the report of the Research Briefing Panel on Cognitive Science and Artificial Intelligence prepared in 1983 for the President's science adviser under the auspices of the National Research Council's Committee on Science, Engineering, and Public Policy (National Academy of Sciences-National Academy of Engineering, 1983). The summary given here emphasizes aspects of special relevance to simulation.

Skills Acquisition and Instruction

Scientific analyses of the cognitive processes and knowledge that produce skilled performance provide a new target for the analysis of learning. With more detailed characterizations of the knowledge and skills that are acquired, analyses of learning should be directed toward understanding how these specifically characterized processes are learned.

Cognitive scientists have studied the process of instruction and have developed analyses of the cognitive processes and knowledge used in successful tutorial teaching. Studying performance by tutors, Collins and Stevens (1981) concluded that a tutor uses a model of the student in which the student's knowledge is compared with knowledge of the subject, represented as a hierarchy of topics with a hierarchy of information within each topic. Collins and Stevens developed a model that simulates--and conducts--tutorial instruction, adding knowledge or changing mistaken beliefs through Socratic dialogue.

Another idea used in tutorial systems is a detailed model of the system that a student is learning about, which is used to simulate performance of that system.

This idea is used in the STEAMER system (described in Appendix A), which simulates the operation of a steam plant. Students are thereby able to observe the effects of actions they can perform, such as opening or closing a valve. A system model is also included in SOPHIE, a tutorial system that provides instruction in troubleshooting electronic equipment (Brown et al., 1983). SOPHIE includes a simulation of a piece of equipment that enables a student to obtain readings of voltage or current that would be obtained when the device is in a variety of malfunctioning states. It allows the student to specify faults whose effects can then be investigated. SOPHIE also includes a simulated expert troubleshooter that can identify the faults that student selects, allowing the student to observe successful performance in the troubleshooting task.

Information Processing

Another area in which important advances are occurring is information processing, including speech understanding and visual information processing. A new theoretical advance in the form of a computational theory of vision, developed by Marr (1981), makes significant headway toward an understanding of the mechanisms of visual information processing that convert energy patterns on the retina into information about contours, surfaces, textures, objects, and motion. Visual imagery, including imaged information retrieved from memory, has been studied in some detail (Kosslyn and Schwartz, 1977), and it has been found that the spatial properties of images (e.g., their sizes and the relative distances among their parts) play significant roles in cognitive tasks.

The relevance of information-processing research to simulation includes use of the findings to guide the design of information presentation in simulators and auxiliary information sources. As we learn more about the properties of information in visual images, we can design displays to present the information critical for the cognitive tasks to be performed and the skills to be acquired. For example, the use of the computational theory of vision to determine requirements for flight simulator visual systems is discussed in a recent report of the Committee on Vision (Richards and Dismukes, 1982).

Qualitative Understanding

An exciting current topic of research in cognitive science is the investigation of cognitive structures that provide qualitative conceptual understanding of procedures and systems. Although instruction in science and engineering emphasizes formal methods, such as procedures for calculation and the correct use of formulas, it is widely understood that formal knowledge is not sufficient for solving problems and reasoning about novel situations in scientific and engineering domains. The additional knowledge, sometimes called "intuition," involves understanding of qualitative relations and conceptual structure. Recent research has begun to identify properties of this knowledge and to develop theoretical methods of characterizing it in useful ways.

One of the major lines of research on qualitative understanding involves analysis of mental models that individuals have of physical systems (Gentner and Stevens, 1983). In general, mental models consist of knowledge or beliefs about causal relations among components of systems. The model may refer directly to the system or may be based on analogy with some other system that the individual knows about (or has beliefs about). An example of the latter is a set of common beliefs about electrical circuits, based on an analogy to hydraulic systems.

Another line of research is investigating understanding of the structure of causal relations among quantities in a system. For example, the quantities in a simple electrical circuit are linked in a structure of causal relations: the total amount of resistance and the circuit voltage determine the amount of current, the amounts of resistance connected in series determine the total amount of resistance, and so on. Causal knowledge of quantitative structure has also been studied in mechanics, where it has been shown to provide an important basis for the representations that expert problem solvers construct (Larkin, 1983).

As more is learned about the cognitive structures that constitute general conceptual understanding, the design and use of simulators can be facilitated by identifying those features of simulations that contribute to the acquisition of significant qualitative understanding in training and that permit its assessment in simulation-based testing. STEAMER, mentioned above, is one example of a simulation designed to communicate general causal knowledge about interactions between components of the system.

Human Performance Modeling

As person-machine systems become more and more complex, the need to account for the human elements in these systems in an orderly and quantitative manner assumes ever-increasing importance and recognition. This is reflected not only in the growing use of simulators in the design and evaluation of such systems but also in the expanding interest in the modeling of human performance. The breadth and importance of human performance modeling is such that a separate working group has been established by the Committee on Human Factors to examine this subject in detail. In this report, modeling is discussed briefly in terms of its potential roles in support of simulation studies and in the development and design of simulators.

Human performance modeling and simulation involving human participants are complementary activities that can be used iteratively and synergistically to enhance the achievement of overall design or training objectives. Appropriate human performance models can play a role prior to, during, and after the simulation exercises occur. This role is apparent when one considers some of the basic intended functions of human performance models in person-machine systems analysis (Pew and Baron, 1982):

1. To provide an organized approach to the formulation of person/machine problems that forces consideration of the many factors influencing system performance.
2. To predict "closed-loop" person-machine performance.
3. To provide a concise and systematic framework for organizing experimental data.
4. To serve as an embodiment of concepts or derived parameters that are useful as measures of performance.

Engineering Design and Research Simulators

As has been noted elsewhere, the development of engineering requirements for human-in-the-loop simulation is a complex task involving numerous trade-offs. Among the principal issues confronting the developer of a simulator are the design of the cue environment so as to meet simulation objectives and the design of the simulation model of the functions of the operational system to fulfill the real-time requirements with appropriate accuracy.

In specifying the cue environment, the designer must establish the need for particular cues as well as the requisite fidelity for their presentation. The choices made here are important because the validity and utility of the resulting simulation can be critically dependent on them and because the decisions involve major costs of the simulation. Unfortunately, these decisions are quite difficult to arrive at rationally, inasmuch as the choices depend on complex psychological as well as engineering factors. The specific requirements are, of course, governed by the purpose of the simulation; training simulators have different needs from engineering design and research simulators. They are also problem-dependent (e.g., the need for motion cues in the analysis of aircraft control in a gusty environment will depend on the gust response of the aircraft). Finally, the capabilities of the adaptive human controller both help and compound the problem. The human operator may be able to compensate for simulator shortcomings and maintain system performance; however, this could result in negative transfer in a training environment, or reduced acceptability of the device, or an incorrect evaluation in a research simulation.

The adequacy of the cueing environment is related to the accuracy of the simulation model used in representing the operational system's functional characteristics, as well as to the cue generation hardware itself. This is particularly true for discrete simulation models that introduce delays in the information presentation paths that are present in the actual situation.

In the development of engineering design and research simulators, the consideration of a suitable model will force the designer or researcher to a more precise formulation of the problem to be investigated, the factors needing control, and the measures of human and system performance that are appropriate. Moreover, with a predictive model, it is possible to establish and evaluate preliminary design concepts and parameters. Not only will these activities make the overall evaluation or experimental process more efficient, but they will also maximize the likelihood that critical conditions will be focused on in the simulation environment.

An example of the use of a human performance model for experimental planning is given in the work of Junker and Levison (1978). They used the Optimal Control Model

(OCM) of the human operator to design an experiment to examine the effects of platform motion cues on manual tracking performance. In particular, the RMS amplitude and spectral shape of the system inputs, the control gain, and the performance criterion were all designed, using the OCM, to provide conditions that would resolve the experimental questions while meeting the experimental constraints.

During and after simulations, models can serve principally as aids in reducing, interpreting, and extrapolating the data obtained in the simulations. Because of the adaptive nature of human response, changes in system variables may not result in discernible changes in system performance under the conditions investigated. They may, however, result in subtle alterations of human response characteristics or behavior that may be important in different circumstances. These changes are often more easily discerned in terms of parameters of human performance models. In short, model parameters can be succinct, diagnostic, and sensitive measures of the results of simulator evaluations and experiments. Models can also serve as insightful ways of looking at and compressing empirical data so that they can be extrapolated to new situations. That is, predictive models can be used to interpolate or extrapolate to conditions that are untested in the course of a specific simulation study.

These uses of human performance models in analyzing and interpreting simulator data are widespread. For example, instrument monitoring models have been used as a basis for analyzing eye movements in flight simulators and relating those movements to workload (Senders et al., 1969; Weir and Klein, 1970). An instance of particular relevance to simulation technology is provided by Levison and Junker (1977). The OCM was used to provide a single, coherent explanation of simulator data on the effects of motion cues on performance for the cases of disturbance motion and target motion. Phenomenological, or purely empirical, descriptions of measured human and system performance yield significant differences for the two motion conditions. However, the OCM predicts results without changing the model structure or human behavioral parameters--i.e., it predicts how the human uses motion cues differently according to the specifics of the task.

Training Simulators

In the training applications of simulators, human performance models play a similar role. They can be used prior to development of training curricula to determine the areas of human performance most critical to knowledge of the system, so that these may be emphasized in the training process. Perhaps a more important contribution of modeling to training would be the use of normative models as yardsticks against which to measure trainee performance, thereby providing mechanisms to be used in an adaptive training scheme. The parameters of an analytic model may also prove to be sensitive measures of operator performance and learning. These uses of human performance models in support of training simulation are principally in the research stage; they require further development in modeling skill acquisition and in methods for integrating such models into the instructional process.

Flight Simulators

The problems in simulator design involving the cue environment and real-time functioning have received the most attention in the context of flight simulation. Recently, the potential value of human performance models for helping to resolve them has been recognized and several research and development efforts have been undertaken. One of the early efforts was aimed at developing a model for human sensory mechanisms that would allow simulator motion cueing systems to take full advantage of their basic characteristics (Borah et al., 1977). Individual models for vestibular, visual, tactile, and proprioceptive sensors were combined in a composite model structure that used a Kalman filter to integrate the information from the various modalities. Several recent studies have centered on the application of the Operational Control Model (OCM), as this model allows for direct incorporation of sensory submodels, such as that just mentioned, to provide a multicue model for continuous manual control.

Baron et al. (1980a) developed techniques for using the OCM to predict the effects on performance of certain simulation model design parameters, such as integration scheme, sample rate, data hold device, etc. The model was applied to a relatively simple air-to-air tracking task and showed significant sensitivity to several simulator parameters. Model results were later compared (Baron and Muralidharan, 1980) with data from an experimental study of Ashworth et al. (1979), and the agreement was very encouraging.

In a series of studies (Baron et al., 1980b; Baron, 1981; Ricard et al., 1981), the OCM was used to examine human performance while hovering a helicopter, using a computer-generated image visual system and a motion system with six degrees of freedom. The hover task was separated into longitudinal and lateral control tasks. Performance/workload effects of these simulation elements were analyzed by incorporating submodels into the OCM. The model results suggested that minor simulator deficiencies could result in substantial performance and/or workload deviations from those expected in actual flight. Unfortunately, there were no corresponding experimental data to confirm or deny these predictions.

Also of interest are two ongoing experimental/analytical efforts that are aimed at collecting additional data on simulator fidelity while further refining the pilot/simulator model. One effort, sponsored by NASA-Langley Research Center, involves both in-simulator experiments with various degrees of cueing (fixed base, platform motion, g-seat) and actual in-flight duplications of the same flight control task. This task involves a high-performance aircraft (F-14) tracking a target aircraft that is executing a windup turn. Where possible, the same pilots are used for both in-simulator and flight experiments. Model predictions will be used in the experimental design phase. These predictions will then be compared with the data obtained in the corresponding simulator experiments. Parameters of the model that yield the best match to the data will be determined to tune the model. These parameters, which will also reflect the individual characteristics of the people involved in the experiment, will then be used to predict results for the flight experiment. Again, model/data comparisons will be made and parameters yielding a best match to the flight data determined. Discrepancies between simulator and flight data will be explored, using the model, to provide analytical bases for the differences in terms of cueing deficiencies and/or changes in pilot strategies and to further upgrade and develop the analytical models.

The second effort is a three-year program sponsored by the Air Force Aerospace Medical Research Laboratory to develop further understanding of a pilot's use of visual and motion cues so as to aid development of simulator requirements. In this work, a significant element is the development of models for the processing of visual stimuli to generate estimates of self-motion (Zacharias et al., 1983). As in the previously described work, analytic models are being used before simulation for experimental design and after simulation for analysis.

Models of human performance can also be used to help design algorithms to compensate for simulator shortcomings. For example, Crane (1981) has used the crossover model of McRuer et al. (1965) to determine the parameters of a lead-lag network to be used to compensate for unwanted time delays in the generation of visual cues. Baron et al. (1980a) have shown how the OCM could be used to design compensators aimed at restoring, as closely as possible, pilot performance and behavior to that which would be obtained if there were no simulator delays. The OCM has also been used to derive a washout scheme for a motion platform (Baron et al., 1980c).

Finally, it should be mentioned that real-time simulation models of human operators may be valuable as substitutes for some of the operators in multiperson systems evaluation, research, or training. Thus, for example, in investigating or training the interactions of the crew of a single aircraft in dense traffic, simulating the crews of other aircraft by modeling their performance is an attractive alternative to live simulation of these crews both for economic reasons and as a means for reducing experimental variability or maintaining consistency in the training environment.

Research Needs for Human Performance Modeling

Of course, the uses of models described above in conjunction with simulation presuppose the existence of appropriate, validated models. For many problems of interest, such models do not exist or have not been suitably validated. This is the other side of the model/simulation synergism, in that the development and validation of the models cannot proceed without the extensive input of data from experiments conducted with simulators.

Although fairly advanced models for the use of perceptual cues in vehicle control exist, there are still significant gaps in the knowledge. For example, modeling the use of instruments and of motion cues (as provided by motion platforms) is well advanced, but much less is known about external visual cueing and proprioceptive cueing. In addition, the models are generally suited to the prediction of the performance of skilled operators; there has been much less effort and progress in modeling the effects of various cues on skill acquisition or maintenance.

The use of models to guide the design of simulation is likely to be most important in the near term for simulations in which vehicle control is the major task. This is principally because the models for the operator are most highly developed for this task. However, as supervisory control models that treat multicue, multitask environments are developed, similar roles are envisioned for these models.

5

SPECIFIC RESEARCH ISSUES IN SIMULATION

The working group has identified nine major issues that deserve research attention or other action to improve the design, use, and application of simulators. These issues are concerned with the effective employment of simulators that either have not been previously discussed as issues or have not received the attention they deserve.

In Chapter 4 we noted that most reports on behavioral issues in simulation have concentrated on research related to physical fidelity and its consequences for performance and training, general behavioral subjects (i.e., perception, learning, and memory) as well as verification of simulator worth (i.e., validity and reliability of performance and transfer of learning). Support requirements for operator or instructor use and training features have also been identified as research topics, but have not been emphasized to the same degree. Most reports have focused on the core of simulation and not on the supporting features that make a simulator a design tool, research vehicle, or training medium rather than simply a bare representation of some system.

The research recommendations proposed in previous reports are important and we agree that they should be carried out. However, we do not wish to restate and reargue in this chapter the importance of the recommendations made in the past; the original authors do that well enough, and most recommendations have been repeated often enough. Instead our intent is to focus on research issues and other needs that are new or have not received sufficient emphasis, are relatively independent of each other, and do not presume major advances in understanding the fundamental behavioral processes involved in simulation. Each of the specific issues is a problem of some consequence, and the recommended research and actions have significant potential for improving current and future applications of simulation.

In this chapter we therefore discuss nine specific issues and their associated recommendations, which fall roughly into three categories: design, procedures, and applications of simulators. The first issue, design guidelines for training simulators, addresses the problem of collecting behavioral information, gained through research as well as past experiences with simulators, in a form that is useful to simulator designers and managers of simulator procurement programs. The second issue, improving task analysis methods, focuses on the need to develop a more formal procedure for translating operational performance requirements into requirements for simulator characteristics and, in the case of training simulators, into methods for training. The third issue, stress in simulator training and testing, addresses the long-standing concern about the performance and learning differences that may occur between any simulated and real-life situation.

The next three issues discussed deal with efficient and effective use of simulators. Scenario construction and simulator control features, experimental (test) design, and performance measurement are all key components of the supporting structure of simulation. The seventh issue, guides for training simulator instructors, addresses the need to develop the means for educating instructors in the capabilities of a simulator and its proper use; doing so can be an important but relatively straightforward means for enhancing the value of training simulators.

The last two issues, training of cognitive skills and training for failures and out-of-tolerance conditions, focus on the application of simulation to training operators of highly automated systems in which the primary tasks will be assessing abnormal situations and making decisions rather than performing well-defined routine procedures.

The discussions of the nine issues follow a common format. We introduce each issue with a statement of the problem and its relevance for simulation. We then present recommendations for research or other courses of action and state the potential benefits to be derived.

TRAINING SIMULATOR DESIGN GUIDES

To the extent that the intended use of a simulator requires that it have a close physical correspondence to the system simulated, simulator design criteria are generally obvious and straightforward. To the extent that intended use permits a simulator to deviate from physical correspondence as the primary design criterion, or as technology limitations and funding constraints necessitate such deviation, the appropriate design criteria are less obvious. In the case of a training simulator, for example, criteria for design to facilitate the transfer of training or specification of stimuli to be provided in the simulator as substitutes for stimuli found in the operational system must be based on knowledge of human perception and principles of learning as well as the engineering specialities underlying simulation technology. Often, simulator design teams lack the requisite knowledge of perceptual and learning concepts, and information to overcome this deficiency is not readily available to them.

An additional simulator design problem relates to the simulator controller interface. As is the case in the design of any complex human-machine interface, the controller position of a simulator must be designed around the process to be controlled. In the case of a training simulator, that process is the instructional process and includes problem setup and control, provision of guidance and feedback to the trainee on-line as well as during debriefings, and measurement of trainee performance in real time. Such processes for most simulators are often poorly defined, and easily applied criteria for controller position design seldom exist. In fact, the inefficiencies in the use of many simulators can be attributed to the limitations imposed on controllers by their designs.

Recommendations

The working group recommends that design guides be developed for use by personnel involved in the process of specifying requirements for, designing, and developing simulators for training. Guides are needed that address functional design considerations, the cue value of stimuli, and the extent to which realism can be conceptualized to make a simulator functionally equivalent to an operational system. These processes include operator-controller interactions, the provision of guidance and feedback to operators, the measurement and meaningful summarization of performance to operators and controllers, and the development and administration of scenarios.

These guides should concentrate on the definition of the objectives for and processes of use of the intended simulators. The guides should provide detailed instruction for design personnel to follow concerning identification of operator tasks to be performed in the simulator and cues relevant to those tasks operationally; description of simulation components and features necessary to the practice of those tasks (including cue substitutions where appropriate); and definition of the procedures to be employed by the simulator controller in setting up the simulator for a period of use and conducting training, performance measurement, or other activities in it.

Benefits

The benefits to be derived from the availability of simulator design guides are primarily reduced reliance on the necessity to use the operational system as the principal design model, with a consequent reduction in simulator complexity and cost, and the more efficient and productive use of simulators to achieve the purposes for which they were developed.

IMPROVED TASK ANALYSIS METHODOLOGY

Improvements are needed in task analytic techniques and associated inferential methodologies. They are used to estimate attributes and parameters of the user-system interface and personnel subsystem. The use of behavioral science and technology in the design and support of systems has led to an expansion in the scope of applications, extension into more detailed levels of data, and the need for more powerful techniques.

Task analysis was introduced originally (Miller, 1953) for the purpose of developing training equipment and programs for initial cadres while systems were still in engineering design and production; it served those purposes well. The major uses of task analysis have been expanded into other applications in the design of user-system interfaces, the development of operating procedures, the specification of technical support requirements, the assessment of imposed workload, and test and evaluation.

Attempts at standardization and expansion of task analysis in the form of Instructional System Development (ISD) have revealed shortcomings that attenuate the efficiency and validity of its uses (Cream et al., 1978). The managers of training for a system have three needs that ISD is intended to address: to identify needed training and training devices; to design curriculum, course content, and instructional strategy; and to provide functional requirements and designs for training devices and simulators.

ISD procedures provide a systematic, structured approach to generating and collating task-descriptive data; however, these procedures provide little assistance in making integrative design decisions. The designer and program manager are left to their own intuitions and experience to design training and trainers.

Recommendations

A long-term research program should be initiated to provide tools for task analysis encompassing the description of operational tasks, the decomposition of task descriptions into parameters and attributes relevant to the design objectives, and synthesis of the analytical data into requirements or specifications for system design. The research should address the following objectives:

1. Codification of the Design Objectives and Decisions. Design objectives and decisions to which human factors analysis, function analysis, task analysis, and test and evaluation results contribute should be identified and classified. The data and analyses sufficient to provide the information needed to make design recommendations should then be specified for each type of decision. Examples of these objectives, decisions, and recommendations are requirements for information display, training content, instructional strategy, and test plan objectives.

2. Identification of Information Sources. Sources should be identified from which the required data can be obtained as well as the data or attributes of tasks that must be extracted or estimated in the subsequent analysis. Functional description of how a system will be used

rather than engineering design documents tends to provide more useful information for task description. This type of data is typically found in doctrinal statements, mission concepts, and the documentation of mission analysis, engineering simulation tests, and failure mode and effects analysis.

3. Development of Explicit Procedures and Algorithms for Processing the Input Task Data. Procedures and algorithms to yield the parameters, values, and estimates are required to satisfy the design objectives. The inferential processes, knowledge, and heuristics of qualified, successful analysts should be explored as a source of standardizable procedures. Emphasis should be placed on the phases of synthesis of elementary task data into design requirements and specifications.

4. Development of Automated Processing and Aiding Techniques. Automation should be provided for compiling data bases and files on task descriptions, analyzing the task descriptions, managing the analysis process, and providing "audit trails" for specific decisions and products made during the process. Automation is particularly necessary for these functions because of the numerous changes that occur during the system design process and after the system becomes operational.

Benefits

Achievement of the objectives of such a research program will significantly increase the cost-effectiveness of simulation use. The validity of the results of simulation studies and their use for training will be increased. The increased efficiency of the task analysis process will reduce the work hours required, and the explication of analytic procedures will reduce the levels of skill and experience required. Finally, the products of the task analysis will be germane to the design objectives and decisions to be made.

STRESS IN SIMULATOR TRAINING AND TESTING

Some have argued that simulators are not appropriate vehicles for training and testing because they do not cause the same levels of participant stress as do real operations. In airplanes and nuclear power plants, the pilot or operator may feel fear or arousal because of what is actually occurring. The same emotions may not be produced in a simulator because there is no physical risk. The assumption underlying such objections is that the stress associated with operational performance affects what is learned and the strength of the skills that develop, particularly those involving complex decision-making tasks. That is, it is assumed that learning is situationally specific, and operational performance will be inadequate unless the learning situation includes exposure to real stress.

Psychological stress has been defined as an unpleasant emotional state evoked by threatening environmental events or stimuli (Janis and Mann, 1977). As suggested by the Yerkes-Dodson Law, under a highly aroused emotional state, normal patterns of information processing are upset and both performance and learning deteriorate. Using flight as an example, there are at least three sources of stress that may be identified. The first, environmental stress, involves the emotions brought on by the flight itself due to the fear of injury or death, the fear of height, and the exhilaration brought on by the motion stimuli and g forces. However, most experienced pilots say that, except for early in one's flying career, this source of stress is not very important in affecting learning, pilot performance, or decision making.

The second source of stress, task demand, is the result of the attention and effort (physical and cognitive workload) needed to accomplish the flight problem itself. This source may be significant for certain maneuvers such as instrument approaches and aerobatics, for which error tolerances are small, but for most flying and flight training it is not very significant.

The third source of stress, goal conflict stress, is due to what Brecke (1981) has called the conflict between the background problem and the flight problem. The background problem refers to nonflight-related pressures to make flight decisions in a certain way. Such factors as peer pressure, family pressure, economics, company goals, and commitment to prior decisions may be very important sources of stress when placed in conflict with an operational flight problem. The level of stress from the conflicting background problem depends on the number and importance of goals that may go unsatisfied, the degree of commitment to adhere to some course, the amount of perceived risk (physical and emotional), and the amount of time to make the decision (Janis and Mann, 1977:50).

Recommendations

Although the stress effects occurring in real environments are purported by military and civilian managers to be an important factor in realistic training, most simulation specialists would agree that there exists a lack of understanding of stress that occurs or can be induced in simulators. Very little research has addressed problems in this area. The work that has come closest to this issue are the studies of workload and divided attention, although none has been performed specifically to assess simulation stress effects.

Research needed includes a review of the clinical research in the area of stress and an analysis of what these findings suggest about the control of vehicles and process plants. It should also include empirical investigations of the effects of stress on information processing, decision making, and vehicle control in both training and testing. Workload research is being conducted at Virginia Polytechnic Institute and State University by Walter Weirwille and Robert Williges; at the University of Illinois by Chris Wickens; at Wright-Patterson Air Force Base by Robert O'Donnell; and at NASA Ames Research Center by Sandra Hart.

Benefits

The ability to create realistic levels of stress in simulators would go a long way in convincing regulators, managers, and experienced operators of the validity of performance exhibited in simulators. However useful this may be, it is essential to first determine whether it is important to induce stress in some or all simulation applications. Failure to do so will simply relegate stress to the same status as physical fidelity, i.e., uncritically accepted as an essential requirement.

SCENARIO CONSTRUCTION AND SIMULATION CONTROL SUPPORT FEATURES

War games and command-and-control simulations are somewhat impeded by the difficulty of changing scenarios or scenario elements. Process and vehicle simulations could be used more effectively and efficiently if the actions of the participants were less free and more subject to the intentions of the simulation controller imposed through a structured and easily manipulated scenario. Current methods for generating and controlling scenarios are deficient and overly burdensome on the simulator controller. There are three areas in which simulation controllers need assistance: (1) constructing and compiling scenarios adequate to achieve the objectives of the simulation, (2) running the scenario, compiling the required performance data, and monitoring the simulated events for compliance with the objectives and plan, and (3) managing and adapting the scenario and simulated exercises in real time to enhance effectiveness. This last capability is especially important in training when the instructor can use knowledge of the learning process and the student's status to select exercises and variants of conditions that will maximize the student's learning.

One might wish, for example, to test the robustness of a particular finding by running the same problem with variations of some parameters and collateral variables. Or one might wish to test the generalizability of a particular decision process by running problems amenable to the same process but involving different situation-specific details. Such flexibility is currently limited to minor variations on standardized scenarios.

Designing and compiling scenarios suitable to specific simulation objectives and loading these scenarios into the computer are very time-consuming and not well-structured activities, and therefore must be done by persons who are skilled or knowledgeable in the relevant technical area, software techniques, and the methodology of simulation. Procedures and aiding techniques analogous to authoring languages are needed to simplify, organize, and make the activities of scenario generation and simulation control more manageable, flexible, and efficient.

Recommendations

A program of research projects should be undertaken with the objectives of automating parts of the processes of generation, modification, and management of scenarios and providing simulation controllers with computer aids to enhance their ability to perform these activities. These projects should encompass the following topics:

1. Description of the Activities and Processes of Scenario Generation and Simulation Control. The activities of scenario generation and simulation control should be described at several levels of detail to permit understanding of the functional flow of information, the identification of the serial and parallel sequences of decisions, the actions and discriminations required of the controller, and the knowledge and inferences on which choices and action depend. The activities described will be allocated to controller, computer, and supporting aids.

Description of these activities will start with the statement of simulation objectives by a user organization and the subsequent translation of those objectives into a sufficient set of scenario requirements. These requirements will include elements such as organizations, platforms and models needed, events and conditions required to provide data relevant to the simulation objectives, initial conditions, exercises, data collection, and data analysis. They should also include procedures for converting simulation or training objectives into strategies for accomplishing these objectives. These requirements in turn should be converted into a process for retrieving the necessary model and algorithms from a library and compiling them into the software for the simulated exercises.

2. Development of Explicitly Stated Human-Machine Procedures for Operating a Simulation. These procedures should include generating scenario requirements, compiling scenarios and exercises, conducting exercises, modifying exercises, keeping track of key events and participant behaviors, and analyzing or interpreting the results in relation to the objectives of the simulation. The interface between the controller and computer should be user-friendly; the user-system dialogue should be based on the terminology characteristic of the technical domain of the simulation and should not assume a more-than-average knowledge or understanding of computer technology.

3. Development of Computer Aids to Support the Controller in Scenario Generation and Simulation Control. The descriptions of the processes of scenario generation and simulation control should be revised to identify activities that can be simplified or reduced in difficulty by automation or supplying aids to assist the controller, increase efficiency, and increase the effective use of simulation resources.

4. Development of Simulation Controller Training Programs and Training Techniques. These programs should

emphasize not only the operation of the simulator but also the purposes of simulation in design, testing, and training. The underlying behavioral processes should be taught; use of the simulation relative to the effect of training on these behavioral processes should be covered. The need for this training is based on the premise that, although some operational or engineering knowledge may be necessary for the controller position, it is not sufficient to provide adequate and efficient use of the simulator.

Benefits

Even moderate progress on this project can greatly increase the value returned on the money invested in the development and operation of simulation and simulators. Simulators are costly to operate even though they may be less expensive than their alternatives; in some cases alternative means do not exist. However, we fail to retrieve the data and obtain the information inherent in the capabilities of the simulator and its data processing resources. Operating procedures are also inefficient, relying too frequently on manual procedures for setup, operation, and analysis. This area of research can pay off in terms of greater capability, lower operating costs, more effective utilization, and higher levels of operational proficiency.

EXPERIMENTAL DESIGN

Simulation is increasingly used to assess design and performance factors for large, complex systems that often involve many interacting human operators. Examples of these systems are air traffic control and various command, control, and communication systems. The scale required for these simulations aggravates existing problems and creates new ones. Issues arising in all phases of such simulations include simulation features and fidelity requirements, data collection and analysis procedures, and experimental design and test structuring. The simulation features and fidelity problems are the typical ones of balancing realism, comprehensiveness, and cost. For example, how can realistic scenarios be generated and implemented? Must all subsystems be simulated? Must humans play all supporting roles or can computer-based models be used instead? In the data collection and analysis area, the questions center on the choice of appropriate performance measures and data analysis methods.

Experimental and test design concerns the structuring of simulator characteristics, events, and conditions efficiently to acquire human performance information that is valid and reliable. Important objectives of experimental and test design are to allow inclusion of the important variables, control extraneous factors that may affect performance, and facilitate analysis and interpretation of performance data.

The major problems confronting systems research and development are the need to investigate simultaneously several relevant factors (often at several levels) and the difficulties in maintaining control of the many factors (both those to be varied and those to be "fixed"). The existence of a large number of interacting variables often makes it economically impractical to perform a complete crossed factorial design, i.e., every level of each factor combined with every level of all other factors.

Recommendations

The working group recommends three general actions to enhance the use of sophisticated experimental design methods in the conduct of simulation-based engineering tests and evaluations of complex systems: greater use of existing economic, multifactor techniques, training of more people in the use of these techniques, and research to develop additional procedures for designing experiments and tests for the complex situations that arise in the system development process.

1. Applications of Existing Techniques. There are existing economical experimental design procedures, although rarely used, that are quite appropriate for simulation-based research and engineering test applications. For example, Simon (1977) and Diamond (1981) summarize the use of procedures based on fractional-factorial designs as efficient means for screening a large set of independent variables to provide a smaller set of the most important, relevant variables for subsequent experimentation. Box et al. (1976) provide a detailed discussion of the use of complex experimental

design procedures such as central-composite design to facilitate the development of empirical models, which can, in turn, be used to predict human performance in complex systems. Recently, Williges and Mills (1982) discussed several of the experimental design and methodological issues related to the use of simulation in the conduct of complex systems experimentation.

Great improvement in both human factors research and engineering development could be realized through the application of these sophisticated experimental design procedures in simulation environments. Designs dealing with procedures for screening independent variables, economical selection of data points, and efficient, simultaneous investigation of multiple factors are particularly appropriate for application in simulation-based test and evaluation of systems.

2. Skills in Using Experimental Designs. Often complex experimental design procedures are not used in simulation-based test and evaluation because these procedures are not well known or understood by human factors professionals and are even less familiar to the engineers or systems analysts who may be responsible for conducting the tests. There is a clear need to institute graduate level courses, workshops, and continuing education seminars on advanced experimental design procedures for human factors applications.

In addition to education there is also a need for automated experimental design aiding. The availability of interactive, computer-based methods for the development of various design alternatives would make many of the complex experimental design procedures more readily accessible and more easily implemented. Some prototype experimental design aiding systems (System Development Corporation, 1980, 1981) have been developed for conducting screening studies using fractional factorials. However, additional work is needed to develop a complete set of automated design aids along the lines of other expert aiding systems.

3. Develop New Research Procedures. A by-product of encouraging more applications of advanced experimental design procedures to simulation environments will be the emergence of specific needs for new design procedures. These requirements will stimulate methodological research and lead to the development of new and improved research techniques.

One research need, for example, is a more detailed procedure for conducting sequential experimental designs.

Due to the extreme complexity of simulation environments, even the most economical experimental design is not sufficient to provide data on all human factors interface and system design questions. Few procedures currently exist for developing sophisticated strategies for conducting a sequential set of interrelated behavioral experiments in an efficient manner. Methodological research is needed to develop these procedures and test them in simulation environments.

Benefits

The main benefit of employing economic multifactor design techniques will be an increase in the efficiency and effectiveness of using simulators as means for investigating human-machine systems at the necessary level of complexity. The results of this work are likely to lead to the development of general, usable design principles. Likewise, increased application and development of advanced experimental design procedures also will improve the sophistication and timeliness of human factors contributions to the systems development process.

PERFORMANCE MEASUREMENT

Human-system performance is measured in simulators to provide information to aid decisions for system design, personnel selection, training, certification, and human performance research. Each use of simulation requires both common and unique performance measures.

Measures for system design should provide information about human capabilities and limits and predict human-system performance during envisioned operations for given system configurations. Measures for job sample simulation should augment other personnel selection test data and provide information to predict success in training and actual job performance. Measures for training should yield information about the learning process, diagnose performance deficiencies, provide feedback to the student and the instructor, aid decisions for training prescription and management, and predict operational performance. Measures for certification should yield information on whether an operator or maintainer can perform all routine and emergency tasks to specified levels of proficiency and safety. Measures for research should provide information to elucidate cognitive, perceptual, or response processes.

Performance measurement, while a problem in many settings (e.g., on the job, in training schools, and in behavioral research laboratories) is particularly relevant in simulation applications because of the task complexity and the frequent need for real-time, automated performance measurement in most instances. Although automated measurement subsystems are being specified as a requirement of modern simulators, there are no universal or fully validated measurement methods or measures. The need for improved human performance measurement methods is well documented (Muckler et al., 1959; Pope and Meister, 1977). A recent, large-scale study of aircrew simulator training effectiveness (Semple, 1981) concluded that most existing automated training performance measurement systems are so poorly designed as to be useless.

The principal factors impeding development of simulator performance measurement systems are: (1) user information requirements are not always defined to the degree of precision necessary, (2) performance criteria are often vague, (3) documentation to guide measurement system design is deficient, and (4) past measurement system designs have been oversimplified and are an inadequate base for new developments.

For most uses of simulation a good start on the definition of what to measure can be derived from a front-end analysis to establish the performance objectives and standards of each task. For procedural tasks for which there are a limited number of correct ways to do the task and the performance standards are well known and precise, a front-end analysis can yield a complete specification of what to measure.

As the task domain changes from simple fixed procedures requiring many specific overt actions to complex dynamic, interactive, and cognitive tasks for which the proper action is not entirely defined, what to measure tends to become more speculative. Consequently, measurement systems may include measures that are not certain to be useful; that is, researchers and test directors often record everything possible. Deciding which measures are important and how to combine them into composite performance scores or figures of merit is frequently deferred to the point at which the data are reduced and analyzed. This process commonly involves cleaning up the data by removing unwanted samples after examination, computing a variety of potentially interesting measures such as error in terms of deviation from a desired profile or sequence of tasks, and performing several statistical analyses. Simple measures showing large differences in performance usually receive more attention than more complex and subtle indicators of performance. Typically, only data recording occurs in real time. The remainder of the measurement and analysis process requires days to months to complete.

For a real-time automated performance measurement system, however, all the judgments that enter into (1) determining when tasks start and end for measurement purposes, (2) cleaning up the data (e.g. removing false starts or selecting data on outside criteria), (3) selecting measures of interest, and (4) weighting several measures to develop composite figures of merit have to be made ahead of time and implemented as algorithms that control a real-time measurement system.

If automated measurement systems are to provide data to assist the judgments of qualified instructors or evaluators, these systems must incorporate some of the knowledge and evaluation rules and assume they are validly used by humans who currently perform these functions and provide feedback to control training. Moreover, real-time measurement systems may have to scale the quality of performance in operational terms, such as the probability of mission success for design studies or a grade for training.

In short, there are human-system performance measurement problems that have been known for a long time but only partially solved. Some of the issues are development of operationally meaningful performance measures and criteria, implementation of some of the knowledge of human experts by adding intelligence to measurement systems, the need for clear and unambiguous rules for sampling the performance of interest (and nothing else that might confound the data), and organization of output to characterize the quality of performance in a way that is useful to the user.

Despite difficulties, there has been progress on performance measurement issues over the years. Some of the methods using engineering data bases for system design studies and instructional system development procedures for training have provided a basis for defining what to measure for many tasks. Studies of empirical performance measurement have developed methods for finding and weighting measures of importance in non-real time, and there have been several successes in the development and validation of operational performance measures (Brictson et al., 1973; Lees et al., 1976; Ciavarelli, 1980), and training performance measures (Brictson and Burger, 1976; Waag and Knoop, 1977; Vreuls and Wooldridge, 1977, 1981; Wooldridge et al., 1982). Solutions to real-time measurement issues have been found as well (Hennessy et al., 1979; Obermayer et al., 1982). There is much promise in the approach of integrating artificial intelligence techniques into performance measurement systems for training; performance measurement systems can be made "smarter" to function in real time with some of the capabilities of an expert observer. Progress has also been made on the kind of architectures and algorithms that are needed to control real-time measurement systems.

The efforts to date have been relatively small and isolated. A greater amount of coordinated research and development effort would facilitate development of generally applicable procedures for building useful performance measurement systems.

Recommendations

For each use of simulation there are performance measurement issues that are common across applications and other issues unique to each application. The working group recommends specific research and development to advance performance measurement knowledge and practice in the design and use of simulators:

1. Operational Performance Criteria. Operational measures and criteria of overall system effectiveness are needed for representative tasks and operating environments (Mixon, 1981). Except for a few tasks, such as weapons delivery, quantitative criteria for acceptable and unacceptable job performance are usually unknown except in very general qualitative ways. Yet operational criteria are essential to any simulator performance measurement system. Establishing operational criteria is one of the most critical needs to improve performance measurement; empirical data collection efforts are needed for representative missions and tasks performed by experienced personnel to establish these criteria.

2. Operator Goals and Strategies. Analysis is needed of the hierarchy of goals and control strategies that operators employ in the performance of real-world tasks. During training, limited goals and simplified strategies

are assumed in the solution recommended by the school, but these may not be appropriate as the basis for performance measurement of experienced operators. This issue becomes important as simulators are used to provide recurrent training for experienced operators or readiness training for military combat teams. Research is needed to derive measurement algorithms that are sensitive to which goal an operator is pursuing at any given moment and the particular control strategy being used; Connelly (1977) has demonstrated the value of measurement systems with this characteristic.

3. Performance Diagnosis. The development of measurement for performance diagnosis is a major research issue in its own right. Diagnosis becomes difficult when many minor deviations from expected performance compound into error. Considerable analysis effort would be required to provide a measurement system that can recognize patterns of deviations over time and derive the probable root causes. In addition, the architecture for such a system is likely to be very different from the basic simulator control system. The key issue is the trade-off between the value of detailed diagnostic information and the cost of obtaining it. Research is required to determine the kind and level of detail of diagnostic information required for training and system design applications of simulators (Obermayer et al., 1982).

4. Measurement of Team Performance. Most complex systems are composed of teams of individuals who have designated functions. Except for highly procedural tasks, the contribution of each person to a team effort often is difficult to define and measure (Crowe et al., 1981). Performance measurement of teams has been and continues to be one of the most important topics requiring research to improve the use of simulators for design evaluation and training of multiperson crews.

5. Automated Performance Measurement. There are reasons for automating performance measurement. Automated measurement can be based on a greater number of factors than is possible through direct observation by humans; precision and reliability can be improved. Data can be collected, summarized, and analyzed in a short period of time; adaptive feedback and automated training can be implemented; personnel requirements and thus cost can be reduced.

A related problem is simply keeping track of the tasks being performed when more than the net outcome of a simulation exercise is of interest. End goals, i.e., outcomes in terms of system parameters or effects, are relatively easy to measure. However, if information about the processes by which the goals are reached is necessary for the diagnosis of training or the evaluation of equipment and procedures, then performance measurement becomes much more complicated. The system must know how to recognize the start and the end of a task. This is not a trivial issue because many real-world operator and maintainer tasks do not start or end with easily recognized discrete events, such as alarms sounding.

Common measures of operator control describe operator-system regulator behavior during steady states (e.g., holding a vehicle on course or in a turn or holding a power plant at a given power level), but this is only one part of the continuous control task. Performance during transitions from one steady state to the next is just as important as performance during the steady states (Connelly, 1977; Vreuls and Wooldridge, 1981) but frequently is not measured because the algorithms may be complex and there is little guidance in the literature. Research is needed to develop useful algorithms that describe operator behavior during transitions.

In addition, many tasks are performed in parallel; some are executed only once and others may continue for long periods of time. Human instructors or observers usually can take these changes into account; automated systems must be programmed to handle task changes. To do so demands a substantial amount of built-in knowledge and processing capability. Research is needed to develop and validate algorithms that recognize transitions in tasks as well as to capture the essential elements of performance for concurrently performed and irregularly sequenced tasks.

6. Near-Real-Time Measurement. Research is required to develop guidelines and procedures for near-real-time performance measurement systems and to develop hardware and software architectures necessary to implement these systems. Development of an easy-to-use interface to allow an experimenter, test director, or instructor to rapidly redirect the scenario or performance measurement system is a constituent problem for near-real-time performance measurement that has not been addressed in any general way.

7. Observational Performance Assessment. Automated instrumentation and performance measurement systems are not possible in all simulations or at least for certain

tasks. There are important behavioral characteristics that can be perceived by observers that are very difficult to assess by automated systems, such as hesitations, smoothness of control, the physical position and movements of operators in a control area, such as a ship's bridge or a nuclear power plant control room, and subtle cues that indicate an operator or controller is preparing for an oncoming event or considering alternative problem solutions. In these situations, observers frequently are required to capture the performance of interest as objectively as possible.

Research and guidelines are needed on how best to use observational methods and to decide what measurement functions should be allocated among machines and humans. The value of human observers should not be forgotten in the pursuit of automated measurement methods for simulators.

8. Education in Simulator Performance Measurement. There is no single source (or even a coherent body of literature) to which practitioners can turn to obtain useful data on performance measurement methods and practice in simulation; some information is contained in reports on empirical studies, but this literature is diffuse and much of it is restricted to highly specific problems (Mixon and Moroney, 1982). A very worthy effort would be to collect and describe performance measurement methods in simulators in a form useful for educational purposes as well as a guide for practitioners.

In summary, the extensive use of simulators creates both needs and opportunities for improving human performance measurement and provides the means to automate much of the process as well. However, there is much fundamental work to be done. We must make advancements in what to measure as well as how to measure. Basic research is needed on general problems such as developing criteria, measurement when operator goals and strategies change, performance diagnosis, team performance, automated performance measurement, particularly on a near-real-time basis, and observational assessment of performance. Education in performance measurement methods in simulation is also needed.

Benefits

Good performance measurement information is the foundation for improving quality, timeliness, and cost-effectiveness of system design, training system development, certification testing, and behavioral research. The potential return on investment in performance measurement systems is vividly demonstrated by the results of a study that developed a set of empirically derived measures to automatically control advancement of instrument flight lessons in a training simulator (Vreuls et al., 1976). The empirically derived set, when used in place of the original measures, developed analytically from judgmental criteria, resulted in a 40 percent reduction in training time to achieve the same standard of performance.

TRAINING SIMULATOR INSTRUCTOR GUIDE

It is generally recognized that the validity of any simulator training program is dependent on the appropriate use of the simulator. The training program must be designed to attain specified performance objectives, and the instructor must be trained to employ the device's instructional features in a manner responsive to attainment of those performance objectives.

The instructor is a key element in the conduct of simulator training. Often, his or her qualification for the development of the training program to be used and for the conduct of that training consists primarily of skill at operation of the system simulated. Such an individual may have no training with respect to human learning mechanisms or instructional processes and techniques that can facilitate learning. In addition, the instructor seldom has information in a usable form about the various instructional features of the simulator--features that make the device a training tool rather than simply a less than perfect rendition of the operational system.

Logistically and economically it is not always possible to provide training of sufficient intensity and duration to all simulator instructors to make them fully qualified to perform their job tasks. Even when such training is feasible for a small group of instructors, instructional resource material often is unavailable or is not in a readily usable and understandable form. The absence of appropriate instructional material for use by simulator instructors during their training and as job aids during their subsequent development and conduct of training programs is a significant deterrent to more effective simulator training.

Recommendations

We recommend for development two types of instructional material and job aids for simulation:

1. General Concepts of Training. This material should describe the human as a learner and techniques for aiding him or her in the acquisition of the required skills. Topics to be addressed should include guidance, feedback, generalization, discrimination, learning set, cue development, the difference between stimuli and cues, transfer, and other concepts basic to learning (Spears, 1983). An example of a general manual that addresses many of the required topics is the Flight Simulator Utilization Handbook (U.S. Air Force, 1953). This document could readily serve as the model for development of a modern, generic guidebook for training simulation utilization.
2. Specific Simulator Features. This material should prepare the instructor for the conduct of training in a specific simulator. The contents should describe the simulator's various instructional features and provide specific guidance for their use during the process of training in the simulator. The material should serve as a job aid during the use of the simulator as well as a text during the instructor's own training in the methods and techniques of simulator instruction. An example of an instructor handbook that addresses the required topics is the Instructor's Guide for the U.S. Army's UH-1 Flight Simulator (Seville Research Corporation, 1979).

Benefits

The benefits of better trained simulator instructors will be reflected in the qualifications of the personnel they train, the increased efficiency of the training process, and, in all likelihood, in the increased morale of the instructors themselves.

COGNITIVE SKILLS

The role of the operator in modern systems is changing in the direction of supervisory control functions and away from predominantly psychomotor tasks (National Research Council, 1983). The operator in the past served as a flexible adaptive link in sensing and control systems for direct operation of a system. His functions have become more managerial, consisting of monitoring system performance for conformity to plan, assessing situations, choosing among alternatives in accordance with pre-established objectives, and evaluating events as they occur. These cognitive skills are poorly understood and not well conceptualized. New thinking in the work of Sternberg (1977) and Hunt (1983), for example, and on the nature of expertise in the area of artificial intelligence are only beginning to address this research area.

The tasks of the human as a direct control link were primarily simple procedures with minimal if any contingencies or branching. The operator had to improvise and make decisions if nonstandard or emergency conditions occurred; however, these conditions received little consideration during system design or formal training.

The cognitive functions and skills of the operator's supervisory role are semistructured activities (Keen and Morton, 1978) in emergent situations (Boguslaw and Porter, 1962) for which the sequences of specific actions are contingent on events that emerge as the operational scenario unfolds. These semistructured tasks cannot be described as fixed, invariant, deterministic sequences; rather, they must be represented as a more complex tree structure if they can be anticipated or preprogrammed at all. Operators cannot be adequately trained on these tasks by drill on a fixed scenario, and it is typically not feasible to provide training on an adequate sample of unplanned conditions. Therefore, research is needed to determine the effectiveness of training operators on component skills, knowledge, models, and rules that they use in real time to analyze specific emergent conditions and fashion procedures and actions to counter threats and maintain progress toward mission objectives.

Advances in automation and electronics have made it feasible to automate fixed procedural tasks, and they are now beginning to enter the domain of these semistructured, cognitive functions. Paradoxically, automation of these tasks tends to increase the interdependence between user and machine and to increase the complexity of the operator's workload. New system interface concepts are needed, especially in high-technology weapon systems, if they are to provide adequate support for the diversity of information processing, speed, and accuracy required for operation of these systems.

Future systems must be designed to reduce the operator's workload and support these cognitive activities.

They must provide for the integration of data from multiple sensor sources into situational information, minimize the operator's time and effort devoted to unaided mental processing support or aid tasks requiring continuous close attention in a multitask environment, and free the operator of time-consuming, repetitive, algorithmic operations that are subordinate elements of cognitive tasks.

The design of the user-system interface to be effective and efficient must also be based on and incorporate users' mental models of the systems and procedures with which they are working (Stevens and Collins, 1977, 1980; Gentner and Stevens, 1983). This is a new area of conceptualization and research, which is essential to maximizing the compatibility between system and user.

The critical deficiency for simulation in future systems is the lack of knowledge about how and what to simulate in order to elicit, observe, and train cognitive skills. An individual practitioner of the simulation arts might have good pragmatic insights into these processes, but they are not known in the sense of well-structured, articulated, and shared bodies of principles, rules, and supporting data that are necessary for a technology.

The emphasis in simulation during the last three decades of its growth and acceptance has been psychomotor skills, especially in simulation of vehicular operation and control. The emphasis in battle simulation, however, has been largely in generating a realistic scenario of events, updating force movement, and calculating the outcomes of engagements. A review of force-on-force combat models typically employed by the Army analysis community revealed that behavioral processes and human factors are considered only implicitly, even though it is well recognized that human participation and influence pervade land and air combat (Miller and Bonder, 1982).

The fundamental issues for simulator training of cognitive skills can be broken down into: (1) identifying the conditions that are necessary or sufficient for eliciting cognitive behaviors, (2) assessing the quality of performance and level of mastery in cognitive skills, (3) identifying or building a taxonomy and operational definitions of cognitive activities and skills that are adequate for describing performance of tasks with cognitive loadings, and (4) developing task analytic techniques for the decomposition of complex, multitask, time-sharing operational activities into their constituent cognitive as well as psychomotor components.

Recommendations

Research on cognitive skills should be initiated to provide the fundamental knowledge leading to design of adequate user-system interfaces for system development, evaluation, and training. This research should include the following areas as a minimum.

1. *Identify the Qualitatively Different Cognitive Functions Performed in Modern Systems*. Description of the functions should include specific actions taken, input knowledge, and output of each action, contingencies, and boundary conditions that affect the actions taken and the user-machine interaction and dependency involved in selecting exemplary systems, e.g., flight simulators and nuclear power plant simulators.
2. *Develop Operational Definitions and Measures of Performance of Cognitive Skills*. These measures must permit the evaluation of capability on basic cognitive abilities as well as provide an assessment of their effect on performance of operational tasks.
3. *Identify the Conditions of Simulation That Are Necessary to Generate Representative Cognitive Activities*. A technology adequate for effective use of simulation in system development, evaluation, and training requires that the cognitive skills and the conditions necessary for their performance must be identified in both generic form and in the domain-specific context of the system application. The skills must be formulated in terms of the scenarios and scripts typical of the application domain.
4. *Develop Cost-Effective Methods for Training Cognitive Skills Using Simulation*. Both new methods and content will be involved in training appropriate to cognitive skills. Training by drill and memorization of fixed procedures, which applies to psychomotor skills, does provide adequate training of cognitive skills. The new emphasis must consist of learning basic perceptual and response components that are combined flexibly and adaptively in real time in complex, rapidly changing, nondeterministic situations.
5. *Develop Concepts and Models Describing the Nature and Operation of the User's Mental Model in the User-*

System Interface. The user's perception, knowledge, and concepts of the equipment's operation and the job that he or she and the equipment are doing are the stuff of the user's mental models; they are critical mediators in the user's cognitive processes. The models are functionally oriented in terms of the job activities that the system performs rather than the technologies of hardware and software of the internal mechanics of devices. The mental model can be regarded as an extension of the concept of "population stereotypes" for control-display relationships in psychomotor skills.

Benefits

This research is basic to providing operationally adequate interfaces in high-technology systems and the effective use of automation in future system concepts and designs as well as methods for training and assessing cognitive skills. Knowledge of cognitive skills and their underlying behavioral processes should also enable development of adequate operator aiding to reduce complexity and difficulty, reduce ability requirements, and increase effectiveness in the use of simulator training time.

TRAINING FOR FAILURES AND OUT-OF-TOLERANCE CONDITIONS

One of the earliest uses of simulation was for emergency training. Commercial airline training focused on instrument training and accident prevention, while military aviation emphasized accident prevention plus completion of missions with failed or combat damaged systems.

The characteristics of emergencies are such that simulators are essential for training and proficiency assessment for all but the simplest of conditions. Many simulated emergencies are too dangerous to practice in the real situation, and the full scope of symptoms and consequences of the failure and out-of-tolerance conditions needed for training cannot be reproduced in operational equipment (Jones, 1979).

In some operational cases the consequence of some inappropriate actions can be catastrophic, while others can seriously degrade the operational effectiveness of a system or reduce its revenue-producing potential. Deficiencies in provisions for such training in simulators were identified years ago (Jones and Garrett, 1957), but many still persist.

Future simulator design and use must deal with the major changes occurring in advanced systems. For example, newer military and commercial aircraft will have programmable multifunction controls and displays driven by computer-multiplex bus architecture that radically change the nature of subsystems such as fuel management and weapons and flight control. They present a different set of training issues from the past in that there may be thousands of options, many automatically configured, but whose operation must be monitored and dealt with appropriately when failures or out-of-tolerance conditions occur.

There are two aspects to the problem: (1) the nature of the failure or out-of-tolerance conditions must be identified in operator-oriented terms such as cues and their patterns, decision processes, and consequences of action and (2) the explicit nature of the decision-making process must be identified and reflected in the design of the simulator or in the related instructional process.

Recommendations

A two-pronged research approach is recommended: (1) techniques must be developed for identifying the characteristics of failures and out-of-tolerance conditions during system acquisition, including multiple failures, their interactions and the consequences for the operators' related decision-making processes and (2) principles and practices for training in decision-making (problem-solving) must be developed. Studies on these problems need to be developed with particular emphasis on uncertainty and unanticipated failures for the type of conditions anticipated in future systems.

Such a research program would consist of fundamental research that addresses complex decision processes and how they are best represented and taught and applied research that takes an integrative approach to the entire problem of dealing with failures and out-of-tolerance conditions. Special emphasis should be placed on the decision-making process that will be required in the "layered" computer-driven tasks in advanced systems.

The integrative approach should address the following issues:

1. How can potential failure situations be best identified? This includes the range of failures, how they are manifest in terms of cues and cue patterns, the impact of human error by individuals and teams, the consequence of the failure, and the role of engineering analyses and operating experience in identifying these situations.

2. How can means for creating appropriate failure situations be incorporated into simulators? Designing for this purpose must take into account the necessary complexity and interactions, implications for instructor station design and aiding techniques, and providing procedures for timely updating of a device to reflect operating experience.

3. How is training to handle complex failures best accomplished? This requires research on improved training techniques drawing on fundamental research on decision-making and judgment training, particularly to respond to unanticipated events, the important issue of retention of decision skills, and its implication for the amount and frequency of training. The value of multiple complementary techniques to accomplish this training, such as computer-assisted instruction and classroom training, should be investigated.

4. How is the capability to cope with failures assessed? This is related to measures of individual and team proficiency in terms of speed, accuracy, and operational consequences. This is an especially difficult issue when more than one pattern of behavior is appropriate to solve a problem and the training is directed at classes of problems rather than particular problems.

Finally, documentation of the existing research findings and those from the research recommended above is needed to provide design guides for use by those who develop simulators and training guides for those who use simulators.

Benefits

Appropriate simulator-based training in dealing with failures, particularly those that are unanticipated, should result in reductions in accident rates, equipment damage, aborted missions, equipment shutdowns, and improvements in rates of missions successfully completed with degraded equipment.

6

FUTURE TRENDS IN SYSTEMS AND SIMULATION

Forecasting is a precarious business. However, we attempted to extrapolate some trends that are apparent for new systems, the impact of these on the role of humans, and their implications for simulation.

We expect change to be evolutionary, in that concepts and technology that are embryonic now will be exploited in the future. If one looks back on the progress in simulation during the past three decades, there is little that is radically new, with the exception of digital computer technology, which permitted the realization and exploitation of earlier ideas. It might be noted that many systems such as aircraft, nuclear power plants, command and control networks and weapons systems that are entering the inventory and being simulated today may still be in use 20 to 25 years from now.

SYSTEMS

It is not possible to project the full range of new systems and vehicles that might be simulated. We do know that the trend has been to apply simulation more broadly. We expect that newer systems will have characteristics such as greater complexity and be more highly automated and integrated and involve fewer operators or crew members (National Research Council, 1982). Systems will continue to expand the use of more capable computers, and therefore be more software-driven and have many forms of artificial intelligence implemented.

Controls and instruments will be multifunctional, with fewer special purpose or dedicated instruments. Information will undergo more processing and be integrated in pictorial formats. Control devices will affect processes at a higher level and will be more for the purpose of conveying commands and intentions than continuous psychomotor tracking or adjustment of low-level processes. Functions such as navigation, systems regulation, and target acquisition will be automated to a larger degree.

Systems will expand to include many levels and widely dispersed entities by virtue of multiple voice and data communication links. Information acquisition, analysis, synthesis, and distribution will occur with little or no direct involvement of humans except as receivers or when occasional direct conversation is necessary.

Maintenance will also become more automated, with self-diagnostic and fault identification functions built into systems. Systems will be fault tolerant, working around failed components, and degrading gracefully rather than precipitously and catastrophically.

THE ROLE OF HUMANS IN FUTURE SYSTEMS

The role of humans follows from the system design, which is a function of operational requirements, available technology, the cost of the human component, and whether the system is directly or remotely controlled. Maintenance functions for humans are driven by logistical concepts as well as system and support equipment technology.

The shift in the function of the human from a low-level system operator and continuous controller to a system supervisor, i.e., monitor and decision maker, will continue. Many of these functions might be done remotely through some sort of human interface system, several levels above autonomous self-controlling task processes. For example, this trend is apparent in aircraft such as the F-18 and its interface with the Joint Tactical Information Distribution System (JTIDS). Some of the specific implications for the future role of humans in systems are:

- Psychomotor tasks related to vehicle/weapons control will be deemphasized. Tasks requiring cognitive skills and supervisory control will be dominant.
- More system options will increase the variety and complexity of tasks.
- Greater emphasis will be placed on information assimilation and decision making.

- Fewer individuals will be required and their placement in the total system may be different.
- New technologies such as voice recognition and pictorial displays will add new types of tasks.
- Higher levels of operator/controller proficiency will be required.
- Operators/controllers will require a broader system perspective regarding how they contribute to the total operational picture.
- Workload will remain high despite automation because of the addition of new functions.

SIMULATORS

Probably the most important potential for design and training simulation is its use in the integration of complex system elements. For example, the design of any advanced military aircraft must consider not only the vehicle, but its interface with other aircraft, the C^3 system, the maintenance logistics system, and the tactical environment in which it must operate. The latter includes not only the physical features of the terrain, but also important military elements such as missiles, radar, and countermeasures. A federated simulation system augmented with models can duplicate these elements as a part of the design, development, and test and evaluation process. Not only can the human-machine elements be considered, but software and prototype equipment used in the design simulator can be transferred directly to the training simulator.

It is expected that the use of simulators will increase as a function of the economics of training and system design as well as the need to duplicate situations that are too risky or complex in actual practice. However, there may well be a proliferation of low-cost, portable devices made possible by new low-cost computer technology. At the same time, high-cost, integrated simulation systems may be developed in which many devices are linked for interactive use in real time. Or, if there is an increase in embedded simulation, existing communication links can be used for training as well as operational purposes.

It is expected that newer simulators will be more compact and reliable and that deliberate design decisions will be made to readily permit the modifications necessary to keep the simulator current with the device it represents. It might be noted that design simulators have provisions that permit the complete change of configurations in several hours. These modification concepts have been applied to training simulator design to a much more limited extent.

Some of technologies that will have greater emphasis in new devices are:

- Operator and Instructor Station Design
  - Artificial intelligence
  - Voice synthesis and recognition
  - Alphanumeric, graphic, and combination displays
- Computer Generated Imagery
  - Detailed duplication of natural environments
  - Artificial and augmenting information added to scenes

Although the trends in simulation given above will characterize all uses of simulation, there may be special considerations for specific uses.

Design Use

Design simulation for human factors purposes has only occasionally used the more complex integrated simulators that include high-fidelity environmental and situational conditions. Such uses are not only valuable for initial design, but can also extend through test and evaluation. A current example is the extensive testing of a new missile in a simulated tactical environment with projected threat aircraft. We expect to see more examples of this use for "fly offs," particularly when the C^3 elements of the system are included. These uses require objective individual, system, and mission performance measurements. We can expect to see improved measurement capability with data available to the designer and evaluator on a near-real-time basis. These measures can also serve as a source of empirically derived training requirements as by-products of the use of simulators for design.

Training Use

The trend of substitution of simulator time for operational practice and experience time will accelerate both for economic reasons and because many operational tasks cannot be duplicated in the real world. The commercial airlines and NASA have been leaders in this area; the Apollo and Shuttle programs are prime examples. However, the military services prefer to view simulators as a means to augment the value of actual flight rather than as a substitute for aircraft training.

There will be an increased emphasis on training cognitive skills to reflect the changing role of the operators. The instructional functions will introduce artificial intelligence concepts in areas such as performance assessment, feedback, and adaptive training to help improve the quality of instruction and to reduce the demands on instructors. Computer-managed instruction (CMI) may be incorporated either into the basic simulator or in supplementary devices as a way of planning and implementing the overall training process more effectively. Part-task devices will be used when appropriate and greater use will be made of Computer Aided Instruction (CAI) with improved computer graphics for lead-in or special instruction not appropriate in the larger, more expensive simulators. Simulators will incorporate better measurement systems to measure proficiency in important operational tasks. The trend toward maintenance simulation will continue, reflecting to some extent the increased use of automatic test equipment. C^3 training will reemerge as an important area, with embedded training features an integral part of many computer-based systems.

Research Use

With some few exceptions, high-fidelity simulators duplicating operational tasks have not been used for behavioral science research. However, advancements in the technology necessary to support human factors engineering is dependent on data derived from operational tasks that consider the complex and interactive effects of environmental conditions and events. The extensive use of human performance models in conjunction with simulation involving human participants has untapped potential that we hope to see realized in the future.

Licensing and Certification Use

There is little doubt that a principal future use of simulators will be for licensing and certification. At present, the principal application of simulators for this purpose is for commercial airline pilots. For more than 10 years, the Coast Guard has used simulation in certification of pilots for instrument flight proficiency. The Nuclear Regulatory Commission is studying requirements for simulator-based test and licensing of nuclear power plant operators (Ranken et al., 1984). Preliminary steps are also being taken for test and licensing of ship masters in ship handling simulators (Hammell et al., 1980). We foresee the use of many military and civilian simulators for certification and licensing of many types of systems operators and maintainers.

7

CONCLUSIONS AND GENERAL RECOMMENDATIONS

There has been a rapid growth of simulation during the past quarter of a century in both traditional and new areas. Initial uses focused on training, but research and design applications have become increasingly important. This growth is due to the considerable economic advantage and risk avoidance inherent in the use of simulators for training and design. Simulation permits situations to be reproduced artificially and examined in ways that are not practical, feasible, or affordable in the real world. There is no question that simulation is being used effectively, but, with certain technical advances and more emphasis on behavioral factors, it has the potential of making even greater contributions.

The national investment in the procurement and operation of simulators probably involves several billion dollars a year. The total spent on simulator research and development approaches $150 million per year. Most of this amount supports hardware and software developments and demonstrations; a small percentage is devoted to research on behavioral factors in simulation. Yet the working group sees behavioral research as the primary basis for improving the design and use of simulation by DoD, NASA, their supporting academic and industrial base, and other major users of simulation such as the electric power and maritime industries.

Behavioral issues and research recommendations have been covered in a number of reports going back almost 30 years. We did not treat these issues in detail--the authors of those reports made the points well enough--but simply reaffirmed that these issues are still important and the recommended research still deserves attention. We do make specific research recommendations on several topics that we think are particularly important. Most of these topics have either been neglected altogether or have not been accorded the emphasis they deserve.

Our purpose in this concluding chapter is not to repeat or consolidate the specific research conclusions and recommendations found in the literature cited or discussed in other sections of this report. Rather, we take a broad view of the concerns that persist in a variety of simulator types and applications. From this perspective we try to characterize the nature of the fundamental problems that we see to be the roots from which stem the many specific issues in simulation. We present eight conclusions that we perceive to be the problems that must be overcome to bring about general improvement in the use and design of simulators. These conclusions and their interrelationships are briefly described in the next few paragraphs since it is important to understand these relationships to appreciate the significance and implications of the conclusions as problems to be overcome.

The origin of many of the current problems is over-reliance on the belief that the degree of physical fidelity of a simulator is the principal determinant of its capability to serve its intended purpose. At the same time, the importance of the relationship between how a simulator is used and its effectiveness is not fully appreciated. As a consequence of this imbalance of emphasis, simulators are often not as cost-effective as they could be and the contributions that behavioral science and human factors engineering can make to the design and use of simulators are relatively neglected. Many serious issues relevant to stimulator effectiveness have persisted because of the failure to recognize that solutions to problems common to a variety of simulator applications must come from a better understanding of the basic behavioral processes involved rather than engineering improvements or fixes.

Although simulators could be improved by better use of existing behavioral and human engineering principles, the potential contribution of these fields is limited by the lack of adequate performance measurement methods and well-developed human performance models. Both are impediments to improving the effectiveness and efficiency of simulators as well as conducting the behavioral research necessary to solve many persistent simulator problems. Objective and automated performance measurement systems would greatly facilitate the derivation of detailed quantitative performance information useful for design, training, and research purposes. Moreover, information in this form is necessary for the further development of models of human performance that have a variety of applications relevant to simulation. For example, models can replace some human participants in system evaluation studies and training exercises. More fundamentally, quantitative human performance models provide a mechanism for accumulating and refining behavioral knowledge as well as conveying this information to system designers (including simulator designers) in a form they are accustomed to using.

This latter use of models may bring about a solution to what we see as the fundamental, overriding problem--the lack of an integrated science and technology of simulation. The contributions of engineering and behavioral science to achieving the goals of simulation are uncoordinated at best. The design and use of simulators should be based on an integrated multidisciplinary approach that draws on knowledge of engineering, behavioral science, and computer science as well as other fields that bring into balance concerns about physical correspondence between real systems and simulators and how these factors contribute to the effectiveness of simulators.

The working group has formulated three key recommendations that we believe are essential to creating the conditions necessary to solve the fundamental problems in simulation and thereby attack the roots of the many specific problems that we and others have identified.

CONCLUSIONS

1. Physical Correspondence of Simulation is Overemphasized for Many Purposes, Especially Training.

A persistent question for simulation has been how accurate a reproduction of operational functions is needed to achieve the intended purpose. Many concerns about physical fidelity or correspondence center on emulating system dynamics, visual and motion cueing, and representing malfunction or degraded mode characteristics. In the past, fidelity tended to be bounded by hardware capability. Recent increases in computer and display capabilities have made possible simulators with great complexity and realism but at high cost.

Our knowledge regarding the need for physical correspondence is limited and fragmented. Determining simulator requirements to meet behavioral objectives has been largely guesswork using analytical frameworks augmented by some research results. Most evaluations of simulators are global in nature and tell us little about the relative contribution of specific hardware and use variables. One result of this lack of knowledge has been to increase fidelity by building more elaborate equipment than may be needed. Because effective use of simulators depends on achieving the same behavioral outcomes that occur in operational situations, the concern with fidelity should shift from what is technically feasible in a hardware sense toward achieving greater effectiveness and efficiency in terms of behavioral objectives.

2. Simulators Are Often Not Used Properly.

The utility of a simulator is as much a function of its method of use as of its physical correspondence to the system or equipment simulated. While good utilization techniques can compensate for reduced physical fidelity, a simulator that is a high-quality physical representation of a system can be relatively ineffective if it is not used properly. In many cases the available capabilities of simulators are not used fully or expertly.

Some components that contribute to quality of use are scenarios, training techniques, operating and test procedures, instructor and operator knowledge and skills, proficiency assessment methods, and support features such as properly designed control consoles and instructor/test director stations. Design of these components is largely based on front-end analysis. This process requires considerable specialized effort and, for cost reasons and lack of appreciation of its ultimate importance, is often neglected. This has been the finding of many past studies and has been highlighted in a recent Government Accounting Office report (U.S. Government Accounting Office, 1983).

Physical requirements for simulators cannot be considered in isolation because they interact with the way a device is used. We need to know more about the nature of these use factors and their interactions with equipment factors as a basis for simulator design. Greater emphasis needs to be placed on the systematic derivation of these use factors to establish requirements that are more directly relevant to the processes of learning and performance elicitation.

3. Simulation Could Be More Cost-Effective.

As a consequence of the overreliance on physical correspondence and the relative neglect of use factors, simulators are less cost-effective than they could be. The drive to technically improve the realism and comprehensiveness of simulators has major cost consequences. Simulators could be more cost-effective if greater emphasis is given to understanding how factors such as physical realism and comprehensiveness, methods of use, and user acceptance influence the attainment of behavioral objectives.

4. The Role of Behavioral Science and Human Factors Engineering Simulation is Neglected.

Behavioral and physical aspects of simulation tend to be viewed separately and independently. Considerations such as perception, learning, retention of skills, performance validity, performance assessment, and human factors engineering are seldom regarded as considerations integral to the development of simulator hardware and software requirements. Equipment and functions are more tangible and tractable entities than behavioral processes and performance. In addition, costs can be more easily and directly associated with hardware products than with behavioral outcomes.

Simulator procurement specialists and users of simulators who generally are operational system experts share an understanding of hardware technology; but usually neither group is well versed in training, human performance measurement, or human factors engineering. Consequently, when procurement specialists and users cooperate to establish requirements for a simulator, hardware and functional correspondence between the simulator and the target system tend to be emphasized and behavioral considerations tend to be neglected.

Even when the procurement and user personnel are sensitive to behavioral considerations, the design, procurement, and employment of simulators are separate activities performed with little coordination and integration. The important connections among the purpose, method of use, and design of a simulator are broken. Yet it is at these connections that behavioral science and human factors engineering can have a positive impact on simulator effectiveness.

5. Many Persistent Simulation Issues are Common Across Types and Uses.

An examination of the research literature and reports of science advisory groups for the past 30 years reveals that most problems are common to most simulation contexts, have been identified repeatedly, and have persisted. Such fundamental issues as cue requirements, learning and its transfer, validity of performance, control of simulation and instructional processes, research and test design strategies, and performance measurement occur in most simulation contexts. The differences in issues from one type of application to another are superficial. That is, the system represented, the tasks required, and the purpose (i.e., design, training, research, or certification) do not substantially affect what fundamentally needs to be known or the approach necessary to solve the problems.

These problems persist because their solutions depend on a better understanding of basic behavioral processes relevant to simulation. The necessary knowledge will come largely from research that is dedicated to the discovery and development of broad principles. This sort of research requires the commitment of substantial resources over a long period of time. To date, no such commitment has been made. Most behavioral research for simulation has consisted of short-term projects dedicated to solving what is perceived to be specific application problems. This kind of research does not produce results that can be generalized to other simulator types and uses.

6. Our Capability to Measure Operator Performance is Limited.

Measurement is the keystone for design, research, and the assessment of proficiency in simulation. However, adequate capabilities do not exist to obtain objective relevant human and human-system performance measures. Although this deficiency has been recognized for some time, the interdisciplinary programs necessary to solve the problem have not been forthcoming. The lack of capability to measure performance, particularly on a near-real-time basis, impedes both the current utility of simulators for training, systems design, and licensing and the execution of the fundamental behavioral research necessary to improve future simulator design and use. Recently, the DoD Defense Science Board Summer Study on Training and Training Technology (1982) highlighted the importance of the performance measurement problem, and the secretary of defense directed the services' secretaries to support efforts ". . . to develop performance measures and criteria for use in determining performance levels and cost effectiveness of alternative methodologies" (U.S. Department of Defense, 1983).

7. The Use of Modeling in Simulation is Not Well Developed.

Human performance models both describe and predict behavior under the circumstances encompassed in the model. Human performance modeling and human-in-the-loop simulations can have important complementary relationships for research and system design purposes. An important consequence of human performance models is that they express data on human behavior in a form familiar to and usable by engineers and designers. The development of these models thus offers the potential not only to document knowledge of behavior in a rigorous fashion but also to provide a communication medium for incorporating this knowledge into the simulator design process.

Human performance models have many applications in the use of simulators as well. Modeling can be done early, be relatively economical, consider stressor effects on humans that are hazardous, and effect economies in simulation through early sensitivity analyses.

Training simulation also can benefit from models. An obvious application is to simulate team members or functions not actually present during the simulation. Models might be used in developing training curricula and paradigms of performance as well as in specifying simulator design requirements regarding dynamic response fidelity and cue fidelity. Recent developments in intelligent systems and knowledge representation will also permit modeling of the instructor's pedagogical functions, student characteristics, and the learning process for use in instructional strategies and performance assessment.

Relatively limited use has been made of these complementary relationships, especially for training; however, they should be of increasing importance in the future. Further developments needed to enhance these capabilities are currently being addressed by the working group on human performance modeling of the Committee on Human Factors.

8. The Science and Technology of Simulation Are Not Well Developed or Integrated.

Perhaps our key finding is that there is not a well-developed or integrated science and technology of simulation. Integration applies not only within pertinent disciplines but between disciplines, particularly between the engineering and behavioral sciences. Furthermore, we are aware of no academic institution that offers formal integrated engineering and behavioral science training specific to simulator design, development, and use.

The lack of incorporation of behavioral science and human factors engineering into the technology base of simulation is especially evident. A comprehensive body of behavioral principles and methods relevant to simulation does not exist. Integrative assessments of the research and operating experience in the form of books and other documents are almost completely lacking for important topics such as fidelity, performance measurement, and visual and other cueing systems. A result is that there is no history of simulation research and utilization technology in a readily accessible form that serves as a guide for the future. Much material has been lost or neglected and, as a result, many simulator studies have been repeated over the past 30 years.

The state of knowledge today can best be characterized as fragmented. At present there is not an institutional base of significance that deals with the spectrum of fundamental issues and application in simulation. These points were emphasized in the recent review of DoD laboratories, which states that the fractioning of the effort has resulted in a ". . . lack of focus on generic research, common development, maintaining a repository of information about the state-of-the-art, and, most importantly, the development of a community of skilled professionals in the simulation discipline" (Herman, 1982).

GENERAL RECOMMENDATIONS

1. Long-Range, Comprehensive, and Forward-Looking Research Plans Should Be Developed to Address Persistent and Emerging Simulation Problems.

Our study has identified the fact that most of the design and utilization issues in simulation are common to the various types and applications of simulation. Despite this fact, many agencies' research programs tend to be limited to specific applications because most users feel their problems are unique. They have not recognized that programs of fundamental research can be augmented by situation-specific applied research. The result has been that research on simulator issues during the past three decades has tended to be relatively narrow in focus with many investigations of similar problems in different contexts.

Recent progress has been noted in better integration and planning of simulation research within government agencies, particularly DoD and NASA. However, further improvements are needed along with inclusion of universities and the industrial base with its independent research and development (IRAD) program. Persistent problems should be systematically addressed in long-range, comprehensive, and forward-looking research plans and should involve all segments of the simulation community concerned with advanced hardware technology, the roles of humans in future systems, and new training practices.

On a more practical level, planning decisions are best performed with the cooperation of representatives from the prospective funding agencies and are most likely to be implemented when these agencies request such service. Moreover, it is not likely that any single plan would meet the needs of all federal agencies concerned with simulation. The best course of action we see is for the various agencies concerned with simulation to identify their specific needs and then coordinate with each other to promote complementary research and avoid duplication of effort.

A systematic look to the future is essential to planning simulation research. Too often the approach has been to use existing concepts, equipment capability, and facilities as a basis for behavioral science research in simulation. Newer roles for humans, anticipated hardware capability, evolving uses of simulation, and advanced training concepts should be considered so that research can be in a better position to influence future needs. Although the recommendation that changing roles for humans in systems and newer training concepts and equipment technology should be identified as a deliberate part of research planning may seem obvious, it is not typically followed.

We describe some of the types of projections regarding future directions that may be of use in research planning below:

1. The shifting role of the human in systems from system operator and continuous controller to supervisor can change the fundamental characteristics of simulators and how they are used. Newer operational roles will emphasize high-level decision making as in multi-operator command-and-control systems and advanced computer-driven aircraft. The operator can be either local or remote as well as have direct or indirect control.
2. Computer science and technology at lower relative cost will continue to influence the characteristics of simulators. Particular areas in which capabilities will increase include high-quality, interactive visual scene generation, integration of complex system and mission elements either as single or federated devices, and low-cost stand-alone devices.
3. Concepts such as cognitive skill development, artificial intelligence, and embedded training as well as capabilities such as computer-assisted and computer-managed training, microprocessor-based part-task devices, and telecommunications for network linking of simulators should be considered in research planning as ways of increasing the utility of simulators.

The working group did not attempt to develop a long-range comprehensive research plan during this study, since it was not within our scope to do so. However, we developed an integrated series of specific recommendations that constitute the major components of a comprehensive plan (see Chapter 5).

2. Long-Range Stable Funding Should Be Provided to Encourage the Development of Academic Bases for Simulation Research.

Funding should be provided for long-range programs of research on fundamental behavioral issues relevant to simulation. The principal object of this funding should be to foster the development of a coherent science and technology of simulation at academically based centers of excellence.* A second purpose would be to support research in other settings such as government and private laboratories.

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*Since this recommendation was written, Florida Central University has established an Institute for Simulation and Training.

A recent DoD study (Herman, 1982) identified, among other things, the need for fundamental research programs to improve the design and use of simulators and recommended that defense centers of excellence in the Department of Defense be established in several multidisciplinary areas including simulation. We believe that academic bases, complemented by industry and government research, are preferable because they fulfill as well the important traditional role of educating scientists and engineers and serving as focal points for the accumulation, integration, and dissemination of knowledge. Academic institutions also are less apt to be subject to rapidly changing priorities, thus contributing to long-term stability and continuity in the research programs.

This is not to say that currently existing government programs and facilities for simulator research are not effective, but rather that they are both limited in capacity and scope relative to the amount and kind of research required and adequate to meet the educational or information communication needs. These needs are fulfilled as a matter of course and direct consequence of the existence of research programs at academic institutions.

Ideally, academic bases for simulation would become national multidisciplinary centers for research and development in the science and technology of simulation, with human resources of high quality in the behavioral and computer sciences as well as engineering. These centers would provide a focused research program on problems of simulation, encourage formation of interdisciplinary groups of research scientists and interdisciplinary training programs focused on simulation, and attract qualified students who are prepared upon graduation to contribute to research on and development of simulation and its use. These centers would also be a resource for investigators from other institutions to visit and collaborate on research and development projects.

The educational role of these academic bases would provide training at both undergraduate and graduate levels for both practitioners and basic researchers. The purpose would be to train individuals in simulation science to teach in other universities, perform fundamental and applied research in government, industry, and universities, and apply their knowledge to simulator development and use.

However, such programs cannot begin without the incentive of adequate funding being provided initially and the prospect of its continued availability. The effort to foster a coherent science of simulation with a strong academic base requires a substantial and long-term investment that is coordinated to meet the needs of government agencies and industry.

We envision the establishment of academic centers through the process of competition for research funds based on the quality of the institutions, their faculties, and the presence and strength of behavioral science, engineering, and computer science departments, which are the foundations for the science and technology of simulation. Government agencies should invite university departments and interdisciplinary programs to submit proposals for grants to support scientific research and development in simulation. They also should include support for faculty that would enable development of new programs emphasizing scientific training in simulation problems and support for educational costs of students as well as internships and postdoctoral fellowships both for beginning and experienced scientists at active simulator facilities.

An important outcome of academic bases for simulation research would be the development and dissemination of integrated information bases in the form of journal articles, collections of review papers, and books on topics central to simulation. There are currently no complete and accessible libraries of relevant documents. Sources are far-flung and many documents have been lost or have limited availability. As a result, there has been much repetition of work in the past three decades. There are few single sources of quality information in the field. One exception is the book Man-Machine System Experiments (Parsons, 1972), which documents simulator-based research on command and control systems. Books that evaluate and integrate existing work are clearly needed in areas such as human performance measurement, visual systems, training use, and design use of simulators.

Facilities and equipment would be a major consideration in the establishment of academic bases for simulation research. We have deliberately avoided addressing the issue of facilities. Simulation research can be expensive and time-consuming and cannot be conducted only in traditional laboratory settings. While it is important that academically based research be directed to the development of principles that can be generalized to specific application needs, it is not clear, and by no means uncontroversial, that large-scale simulation facilities located at the academic bases are essential for this purpose.

On one hand, it is true that fundamental concepts can be explored and developed and educational purposes served with reasonably modest equipment; on the other hand, the complexity of operational systems, task requirements, and environments and, hence, simulators, can have major influences on performance and learning. Access to complex simulation equipment as well as to operational systems such as nuclear power plants, aircraft, and command and control centers will be needed for the development of criteria and validation.

Simple studies have limited potential. That is, the more abstract the research context is relative to the application context, the more uncertain it is that performance and learning effects found in research settings will obtain in the application context. This implies that final validation of research must occur in simulation settings at least approaching the complexity of actual systems.

Large-scale simulation facilities are expensive not only to purchase but also to maintain, change, and upgrade. And no single type of simulator will serve all purposes. Clearly, a flight simulator cannot be used for investigations of all issues relevant to a power plant simulator. At some point the unique character of fundamentally different systems must be taken into account. Whether funding agencies could justify the cost of maintaining several large simulators, even if each is at a different location, is questionable. However, just as full mission training simulators need not be used for all stages of training, all research need not be conducted in complex, expensive simulators. The most expedient approach is to fund the development of relatively modest research simulation facilities at academic bases initially and let justification for more expensive devices depend on the importance of the research product.

Finally, academic research programs could be enhanced by access to the more comprehensive simulators that exist at government and industrial facilities. The unique role of each type of organization should be recognized. The academic institution should focus on fundamental research, teaching, and information integration. Government and industrial simulation laboratories are best suited to perform applications research, validate principles developed through academic research, and ultimately do the developmental work necessary for final implementation in hardware and operations.

3. Research to Develop Near-Real-Time Human Performance Assessment Capability for Simulation is Urgently Needed.

Effective measurement is the cornerstone for cost-effective design and better use of simulators. Further progress will be limited without significant advances in human performance measurement capability. A focused, well-funded, and long-term effort is needed to develop measurement techniques that are meaningful, quantitative, and economical to use and that provide data in a usable format on a timely basis. Recent advances in computer and software technology make such advances feasible.

Performance measurement development is a demanding activity that should involve several disciplines, including systems engineering and analysis, experimental psychology, computer science, and statistics. Collection of data alone is not performance measurement. Measurement implies a definition of the performance to be measured, criteria of good and bad performance, the selection of data sources, weighting and integration of data from these various sources to form a measure, and interpretation of the measures in terms relevant to the simulator application.

Further development of performance measurement capabilities for simulator applications depends on research to develop useful conceptions of the covert behavioral processes that lead to overt actions. Such conceptions are essential to define sufficient and necessary performance measures but are likely to be a long time in coming. More immediate but limited benefits could be realized by research to establish systematic methods for development of empirically based performance measures that do not depend on conceptions of internal behavioral processes but are able to reliably distinguish among categories of performance such as stages of learning or levels of proficiency.

The developments should encompass the multiple uses of measurement in simulation to include:

1. Feedback during training;
2. Proficiency level assessment and performance prediction;
3. Research on fundamental and applied problems, including the effects of simulator characteristics

on short- and long-term retention proficiency for representative tasks;

4. Assessment of system capability during design, development, test, and evaluation; and
5. Reliable and valid assessment of capability for licensing and certification purposes.

Whether theoretically or empirically based, performance measurement for simulator applications must be implemented in a fashion to obtain useful outputs on a near-real-time basis. The need for near-real-time measurement is critical. Most of the above uses require data during or soon after a simulator session. Even in the case of research, data reduction and analysis become so ponderous and delayed that they reduce considerably the potential utility of the research. Work is needed on methods to automate all phases of the performance measurement process from data collection to final summarization in order to take full advantage of simulator capabilities.

The approach to development should be interdisciplinary and include psychometrics, software, hardware, and operational considerations. Compatibility should be sought with measurement systems planned for comparable operational equipment to permit cross-validation and follow-through assessments.

The broad context of measurement systems should be considered, including the complementary interrelationship of numerical, rating scale, audio/video recording, and physiological approaches. In addition, operationally based performance criteria are necessary and their development should be given high priority.

Research on performance measurement development should have both fundamental and application aspects. The basic core should consider concepts, techniques, classes of tasks, and the relation to modeling. The application part should be directed to specific classes of problems such as developing criteria, converting raw data into measures, and implementing the measurement systems into simulators and possibly embedding them in operational equipment.

DISSENT

Jesse Orlansky

I do not agree with General Recommendation 1, that long-range, comprehensive and forward-looking research plans should be developed to address persistent and emerging simulation problems. The working group did, in fact, recommend research on a number of specific issues that include performance measurement, cognitive skills, failure and out-of-tolerance conditions, training simulator design guides, a training simulator instructor guide, stress in simulator training and testing, and improved task analysis methodology. I agree with these recommendations. I see no reason to recommend, in addition, that long-range, comprehensive, and forward-looking research plans be developed to address persistent and emerging simulation problems until we see some of the fruits of the research we have already recommended. Moreover, I believe that a general recommendation to develop forward-looking research plans is too vague to be useful to any funding agency. It is a fact that our working group considered the possibility of doing this and decided that we did not have sufficient time. I personally believe that we did not grasp the opportunity because we did not have anything useful to say about forward-looking research plans beyond what appears in the report.

I do not agree with General Recommendation 2, that long-range, stable funding should be provided to encourage the development of academic bases for simulation research, primarily because we have not addressed, even in general terms, what the academic bases should be encouraged to do. The recommendation calls for academic bases, joint work by several departments at more than one school, large-scale simulation research facilities, and complementary support of industry and government in related areas. This is an exhilarating prospect. In our version, the recommendation proposes to spend large amounts of money to achieve obscure ends. There may be a good idea buried here, but it needs more development.

APPENDIX A

EXAMPLES OF SIMULATORS

In this appendix we present examples of specific simulators in each of five categories: (1) engineering simulators, (2) training simulators, (3) research simulators, (4) battle simulators, and (5) embedded simulation. The specific examples of simulators described within each category were chosen because they were good illustrations of one or more major aspects of simulator characteristics.

In the category of engineering simulators, the aircraft mission simulator and the part-task design simulator illustrate the complexity of simulators, ranging from multistation facilities to a functional representation of a specific subsystem.

In the category of training simulators, three kinds of simulators are described: a flight training simulator and two kinds of maintenance simulators. The description of the flight training simulator illustrates that instructional support features are important components of the simulator. That is, there is more to a training simulator than just representation of an item of equipment or system. The description of the first type of maintenance simulator (actually two versions of a simulator for the same purpose) illustrates that functional representations of a simulator can be quite disparate in cost and degree of physical similarity to the actual equipment but equally effective for training. The second type of maintenance training simulator described illustrates that a simulator can be a conceptual rather than physical representation of a system and underscores the point (described in Chapter 3) that attaining behavioral objectives and not physical emulation is the principal purpose of simulators.

In the category of research simulators, the ship bridge simulator described illustrates the use of simulators to perform fundamental research on behavioral and human factors issues and, for research purposes, that special capabilities for experimental control and performance measurement are essential to the intended purpose.

In the category of battle simulation, the examples illustrate several different points: the use of multiple small weapons simulators in the context of field exercises; command-and-control simulation, in which the essence of the simulation is information flow; and the fact that scenarios, rather than representations of physical equipment, are the predominant features.

In the category of embedded simulation, the two examples described highlight the fact that simulation can be part of operational systems, and training can be extended to the operational context.

In addition to characterizing the diversity of simulation types and uses, there is a secondary theme running through this appendix: the characteristics of simulators differ according to their behavioral purposes. While every simulator represents a particular system or piece of equipment, the comprehensiveness and form of the representation can be very different, not so much as a function of the nature of the system as the behavioral objective--that is, what the participant is supposed to do.

A final point that is important to note is that the examples of various uses and types of simulators are selective; flight simulators are emphasized, and ground vehicles and environmental simulators are not included. This selectiveness reflects the fact that flight simulation has been and continues to be the major focus for design, training, and research uses of simulators; more has been written about them than any other type of simulator. Ground vehicle simulators for automobiles, trucks, tanks, and locomotives, while showing important uses for training and research, generally reflect the technology used in other simulation applications. Environmental simulators such as centrifuges, water tanks, hot and cold rooms, hyperbaric and hypobaric chambers, and acoustical chambers are more closely associated with physiological uses than behavioral uses and we have excluded them from consideration to keep this study to manageable proportions.

It became apparent during our detailed examination of simulation that there were many common human factors issues that cut across the various types and uses. Table

A-1 illustrates this point with the issues specific to particular uses.

ENGINEERING SIMULATORS

Simulators have become an indispensable engineering tool in the design, development, and evaluation of complex military and civilian systems. Particularly in the design of new computer-driven multifunction controls and displays, radical departures in concepts have been achieved. Engineering simulators are valuable because quasi-experimental data can be obtained on crew performance for complex tasks within the time frame dictated by design and development schedules. They have been used extensively since the 1940s for aircraft systems; in the 1950s and 1960s they came into use for other systems such as command, control, and communication (C^3), weaponry, and space vehicles. The complexity of modern systems and "fly before buy" approaches to procurement also give impetus to the use of simulation for these purposes.

Some of the best examples of engineering simulators are the interactive, high-fidelity military aircraft simulators that allow performance of critical mission segments in multicrew, multivehicle environments. They can be used during each design stage from early concept phases through testing and operations.

Aircraft engineering simulators support design in several ways, including integration of avionics; development of logic, software, procedures, and tactics; design of controls and displays; and evaluation of subsystem and system performance. Pilots serve as subjects to contribute to and verify human engineering design in terms of workload, operational suitability, and estimates of training requirements.

Engineering development simulators include part-task devices for single critical functions that may be isolated such as target acquisition, multiple-task devices such as procedures trainers for crew station configuration studies, and full mission devices with visual attachments for examining mission tasks such as air-to-ground weapon delivery. Motion-base devices are used when appropriate, most typically for handling studies in transport and V/STOL aircraft, catapulting, and adverse vibration or oscillation during low-altitude, high-speed flight.

Simulation has been used very successfully at Bell Laboratories for design and development of human-machine

TABLE A-1 Common and Unique Issues for Simulator Applications

	Simulator Use or Type				
Key Issues	Engineering	Training Design	Research	Battle Simulation	Embedded Simulation
Economic, experimental, and test design	X		X	X	
Models of human performance	X	X	X	X	X
Performance measurement	X	X	X	X	X
Fidelity requirements	X	X	X	X	X
Control and support methods and features		X	X	X	X
More refined task analysis		X			
Selection and characterization of subjects		X		X	
Flexible designs, procedures, and performance measurement	X		X		
Efficient scenario construction				X	
Methods for translating training requirements into equipment and course features		X			X
Transition from operational to training status					X
Level at which simulation occurs					X
Added hardware and software requirements					X X

systems in equipment related to communication systems (Holt and Stevenson, 1977). Bell Laboratories developed the concept of functional design of an automated directory assistance system, including operating procedures and operator aids, in simulation prior to initiating full-scale engineering development. A computer-based message-switching system was also designed through simulation concurrently with engineering development. Both simulations were successful and, in addition, documentation for operating procedures and maintenance and training time were reduced.

We present below examples of engineering design and development simulators. Representative devices are described in the areas of avionics and battle simulation. Avionics systems are used to illustrate the use of simulation in the development of military platforms; descriptions of simulators for systems such as tanks, aircraft carriers, submarines, and space platforms would be quite similar.

Aircraft Mission Simulators

These devices usually represent the state of the art in simulation technology. Simulator cockpits are like a set of building blocks; configurations can be modified as system design progresses. Because of their flexibility they can be changed readily and allow high-fidelity duplication of critical crew tasks. A new cockpit can be put in place in several hours and software changes made to accommodate an evolving design.

One of the most complex simulators is the McDonnell Aircraft Company's Flight Simulation Facility, shown in Figure A-1 (Jones, 1979). This simulator has been used in the development of the F-15, F/A-18, and AV-8B aircraft. It has five domes within which removable cockpits can be placed. These spheres completely enclose the crew station and provide a projection surface for a pictorial image of the earth and sky. It has been used to define preliminary crew functions and operating procedures, to examine hardware and display symbology, to develop operational doctrine and tactics, and to establish crew performance and workload levels necessary to meet operational requirements.

An iterative process is used to develop a new crew station. Analytical results are verified empirically in the context of mission scenarios. Normal operations and

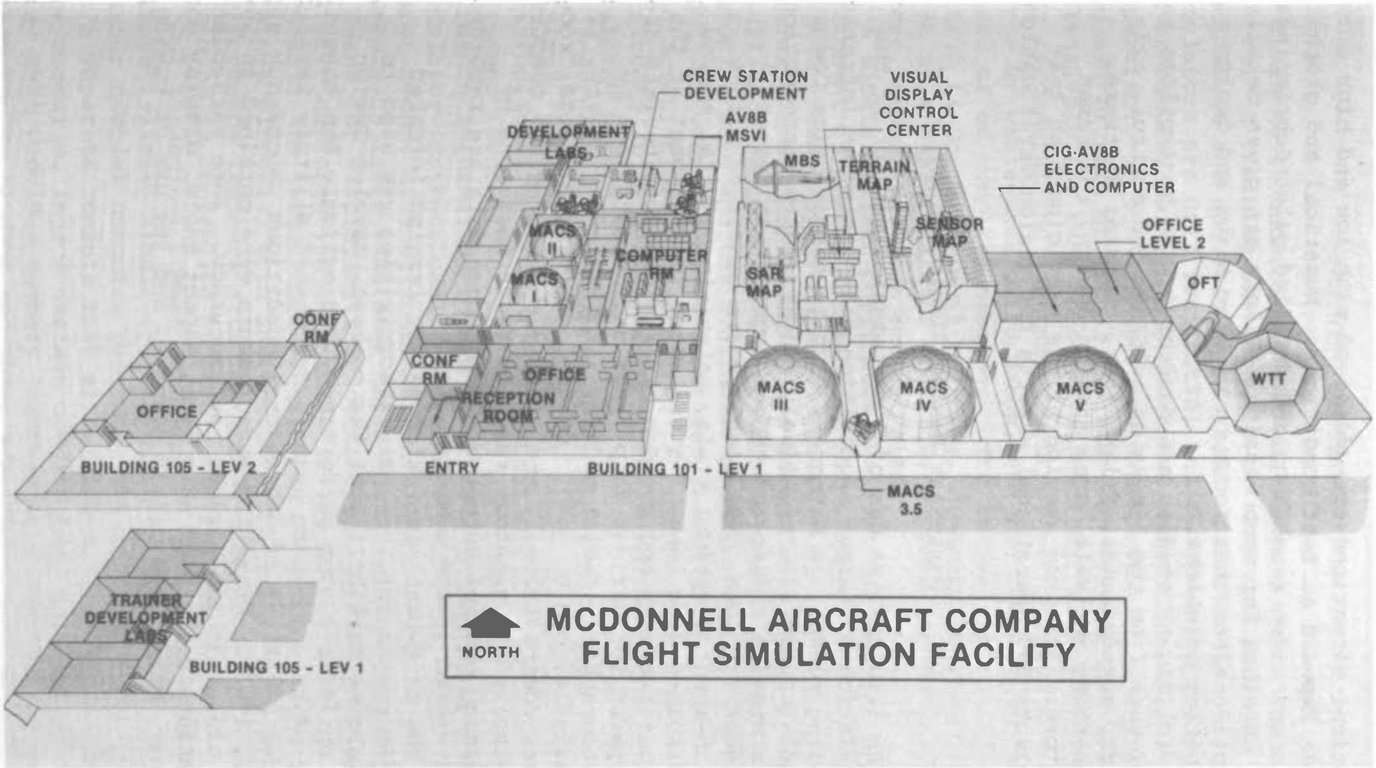

FIGURE A-1 An example of a highly sophisticated simulator complex.

tactical situations are addressed with low and high workloads imposed as test conditions. Numerical and graphic data and video recordings and detailed pilot debriefings are obtained for each mission. Pilots are given detailed questionnaires that focus on problem areas and design and operating solutions.

Preliminary studies are conducted with test pilots and engineers from the fields of guidance and control, avionics, aerodynamics, flight test, computer software, operations analysis, crew station design, and human factors. Selected service pilots participate as test subjects and operational experts for design verification.

Part-Task Design Simulators

An illustrative use of a part-task simulator is the simulation of target acquisition tasks using an infrared imaging sensor. A McDonnell Douglas Astronautics Company simulator provides relatively high-fidelity reproductions of a missile's infrared target acquisition system. Cathode ray tube (CRT) displays are generated with a bench-mounted optical train, television camera, servo-controlled zoom lens, X-Y transport for movement of the target imagery, and a video mixer. Target materials are prepared for various ship types and orientations by photographing special models, although real imagery, if available, can be used. Control of starting range, zoom rate, contrast level, and display sequencing are computer controlled. Operators register their decisions by pressing control buttons. Performance data are recorded and stored in the computer.

The part-task simulation of the imaging infrared (I^2R) system for ship target acquisition was used to determine feasibility of the concept, develop design data to optimize system performance, and estimate the capability of the system to acquire designated military targets under a variety of operational conditions (Mocharnuk et al., 1981). Criterion measurements were obtained in terms of classification, range, and accuracy. Some variables considered included ship type, aspect angle, display contrast, frame rate, field of view, and the use of cueing aids.

TRAINING SIMULATORS

Training is undoubtedly the most common use of simulators. A training simulator is an interactive device to facilitate the acquisition of skills and knowledge. Simulators are used for initial and continuation training of operators, maintenance personnel, and command and supervisory personnel. Devices duplicating or representing all or part of actual equipment or systems are used extensively for such purposes as familiarization, acquiring procedural and continuous control skills, learning part- or whole-task performance, and the practice of segments of or complete missions. The largest use of simulation is for individual training, although some devices, such as a B-52 simulator or MILES, support training of crews, teams, and even entire units.

A simulator that duplicates the function of an item of equipment or system can be used for training purposes in much the same way as the actual item. However, most training simulators incorporate instructional features to facilitate and control the training process. How a simulator is used and the availability of instructional support features can be as important as the simulation characteristics of the device. A simulator does not instruct; it is only a means to implement and support a training program.

Instructional support features usually include, as a minimum, a situational context or scenario, the means for instructional control of the simulation, providing performance feedback to the trainee, and supplying performance information to the instructor. Implementing simulator instructional features may require a small or large amount of additional hardware and software. For example, a rifle simulator may require nothing more than a means for displaying the location of target hits. The target, representing the enemy, is the situational context; the instructor observes the performance of the trainee directly, both instructor and trainee receive performance feedback from the target display, and training is controlled by verbal communication.

For a tactical command-and-control or full-mission flight training simulator, the scenario is resident in a rather complex computer program. The instructor may sit at a separate console that allows him to start and stop the scenario, inject certain conditions, and view a display that provides summary information about the actions taken by the student and their effects on the rest of the scenario. The student may receive feedback about the consequences of his actions both directly from a situation display and from certain display augmentation features, which show the ultimate consequences of the actions or an immediate evaluation of their appropriateness.

We describe three examples of training simulators: the first is a flight simulator, and the second two are maintenance simulators, one for a steam propulsion system and the other for avionics electronics maintenance.

Flight Training Simulators

Device 2B24 is a helicopter simulator for the training of instrument flight for the UH-1 series of utility helicopters. The device consists of four cockpits, each mounted on its own five-degrees-of-freedom motion base and controlled by a single computer system. The appearance and function of the cockpit instruments and controls are identical to the UH-1 helicopter.

Device 2B24 was designed with emphasis on training rather than simply reproducing the relatively inefficient learning environment of an actual helicopter. Its configuration and scope of functions were based on an analysis of training objectives and processes. Special displays for the instructor, located both in the cab of each cockpit and at the central operator station, display the position within the gaming area, the location of radio navigational aids, and time history profiles of altitude and airspeed.

As an instrument trainer, the simulator has no external visual system but does have a sound system to portray rotor noises that change with speed and load. Simulated flight can occur within a 100-by-100-mile gaming area, which is a representation of the local environment in which the simulator is located. All radio navigational aids that exist in the represented area are included in the simulation.

Partially automated instructor functions include the demonstration of maneuvers, sequencing of instruction, varying task difficulty, monitoring performance, updated scenarios, and extensive capabilities for reprogramming training situations. Feedback to the student during training is possible via real-time and slow-time playbacks of the student's control performance, video and audio recording and playback systems, on-line displays summarizing student performance over time, and hard copy printout of performance data. Provision is also made for students to exercise control over their own training.

Device 2B24 may be used in any of three modes, semi-automatic (SEMI-AUTO), automatic (AUTO), and checkride (CK-RIDE). In the SEMI-AUTO mode, the aircraft initially can be placed in any location and altitude within the gaming area, flown anywhere within the gaming area using the flight instruments and radio navigational aids, and flown through instrument approaches to several airfields. In the AUTO mode, 1 of 10 preprogrammed instrument flight maneuvers can be selected for demonstration or practice. Computer-controlled voice tapes provide a briefing on the flight profile, describe demonstrated maneuvers as they are flown, and alert the pilot to check various flight instruments during practice. In the CK-RIDE mode the pilot flies a long cross-country trip without voice alerts and basic variables of flight such as altitude and airspeed are recorded for printout at the end of the test session.

Maintenance Training Simulators

Highly skilled technicians are required to provide servicing, troubleshooting, and repair of malfunctions in sophisticated equipment such as high pressure steam propulsion systems in ships, aircraft engines, and the wide variety of complex electronic gear in ground, air, and sea systems. Maintenance training simulators have been developed to meet the need to train the large numbers of maintenance technicians required and to provide a capability to present a broad range of maintenance problems to the trainee. Maintenance trainers frequently cost less than actual equipment and are more reliable, therefore more available for training than actual equipment.

Many maintenance simulators, particularly for electronics, such as the 6883 Converter/Flight Control Systems Test Station for Air Force F-111 aircraft, the Navy A-7E Head-Up Display Test Bench, and the Navy MA-3 aircraft 12 KVA generator Test Bench, have a high degree of resemblance to, and in some cases cannot be distinguished superficially from, actual equipment. The controls, instruments, displays, and probes for testing components perform as if they were actual equipment. Components under test respond correctly to test probes, i.e., with all the symptoms of a particular malfunction. If any part of a circuit board is found to be defective, the entire board is removed and replaced.

There is, however, a real difference inside the cabinet, where electronic parts or circuit boards may consist only of photos or engravings of the real parts. The cards are connected electrically to the computer and respond correctly according to the simulated malfunction state because the computer controls the symptoms. Therein lies the basis for reduced cost and "ruggedizing" of the device for training purposes.

Maintenance simulators have also been developed that are greatly reduced in physical fidelity. These rely mainly on schematics presented on a panel board together with functional controls, switches, test points, and instruments. Some very new simulators consist solely of schematic, functional diagrams with instruments and displays drawn on a cathode ray tube; the controls and displays are addressable by touching the face of the tube or through a cursor control and keyboard. As with three-dimensional simulators, many different malfunctions can be selected by the instructor. The military services have procured more than 1,100 units of about 200 different two-dimensional maintenance simulators since 1972.

Some examples of two-dimensional simulators are: F-16 Maintenance Trainers (for avionics, electrical, propulsion, hydraulic, and weapons control systems of the Air Force F-16 aircraft), the Navy generalized Electronic Equipment Maintenance Trainer (EEMT), and the 6883 Converter/Flight Control Systems Test Station for the Air Force F-111 aircraft.

We describe two classes of maintenance simulators: the first, the 6883 Maintenance Training System, consisting of both high and low physical fidelity versions, is an electronics maintenance simulator used to train people in the use of automated test equipment for troubleshooting aircraft avionics components. The second, STEAMER, is a computer-based symbolic graphic representation of a steam propulsion system; it has little physical fidelity in terms of appearance but is accurate in its functional and relational aspects.

6883 Maintenance Training System (6883 MTS)

The 6883 MTS is a training simulator for the Air Force F-111D aircraft 6883 Converter/Flight Control Test Station. This item of automated test equipment is used in intermediate, "shop level" maintenance to test, inspect, troubleshoot, and repair faulty line replaceable units (LRUs) for the F-111D aircraft multiplexer converter and flight control functions.

The 6883 MTS is designed to permit hands-on practice of the checkout troubleshooting and repair procedures performed during maintenance of the 6883 itself and three associated F-111-D LRUs, the bank and turn assembly, the yaw computer, and the multiplexer converter. The simulator consists of four principle units: (1) a central control computer; (2) an instructor console; (3) a student station, consisting of a CRT, keyboard, and slide projector for instructional and feedback purposes; and (4) the simulated 6883 test station and LRUs.

Both actual equipment and two versions of the 6883 MTS have been used for training. The first version has high physical fidelity with respect to the actual equipment but has limited function. The second version of the 6883 MTS has lower physical fidelity than the actual equipment, e.g., a flat panel representation of the test station console, simplified cables and adapters, and a schematic panel representation of the LRUs, but can perform all functions of the real test equipment.

The instructor console permits initial setup of lessons, control of lesson flow, monitoring student progress, and recording detailed performance data. The student station directs actions of the student at the test station, provides immediate feedback on actions taken, guides students through technical material, and provides information in response to requests for help. The test station and LRUs are composites of functional components and pictorial representations of other components that are not necessary for the training purposes. For example, some of the electronic circuit boards in the LRUs are pictures, while others are three-dimensional representations of actual circuit boards.

The 6883 MTS was designed to support training objectives but not to duplicate actual equipment. This philosophy is exemplified in the emphasis on instructional support features that facilitate the instructor's initiation, control, and monitoring of training and that provide the student with easy access to routine information, guidance, and feedback that would normally require the presence of the instructor. Easily understood command and feedback statements are provided by the student's CRT. Pictorial information from the slide projector supplements technical manual information. At each step in the training sequence, the student is required to answer a multiple-choice query about what to do next. This forces the student to think about each step and also provides error information to the instructor.

The overall 6883 MTS was designed with hardware and software modularity to permit easy maintenance, change, or expansion of equipment and instructional software. A special programming language was developed to facilitate course changes or additions. In other words, the 6883 MTS was designed with the inevitable need for change and expansion of function in mind.

STEAMER

The STEAMER project is an attempt to develop and evaluate knowledge-based techniques for use in portable computer-based training systems. A prototype version of STEAMER has been field tested at the Navy's Surface Warfare Officers School. The central idea of the project is to provide a detailed, easily inspected simulation and automatic tutor in a desk-top-sized training device. The project is developing techniques for displaying and controlling simulation models and for automatically providing tutorial advice and explanations.

The project is focused on naval propulsion engineering as a domain in which to investigate these techniques. The current STEAMER system consists of a computer-based simulation of the propulsion plant of a 1078 class fast frigate, a dynamic color graphics display for inspecting and controlling the simulated plant, and a black and white display for exercising other features of the system.

A device called a mouse is used to control a cursor to designate items on the two STEAMER displays. The student manipulates the simulated steam propulsion plant by designating various components, such as valves, and then causing them to open, shut, or adjust the steam flow. Changes in the state of the components are indicated by changes in color or changes on dials, thermometers, and digital readouts (see Figure A-2).

This approach to training personnel to recognize, interpret, and adjust to malfunctions and their impact on system performance and operating procedures is particularly useful for complex systems such as nuclear power plants. It is flexible and readily adaptable to different applications through an appropriate analysis of the job to identify the required skills and knowledge and associated training objectives.

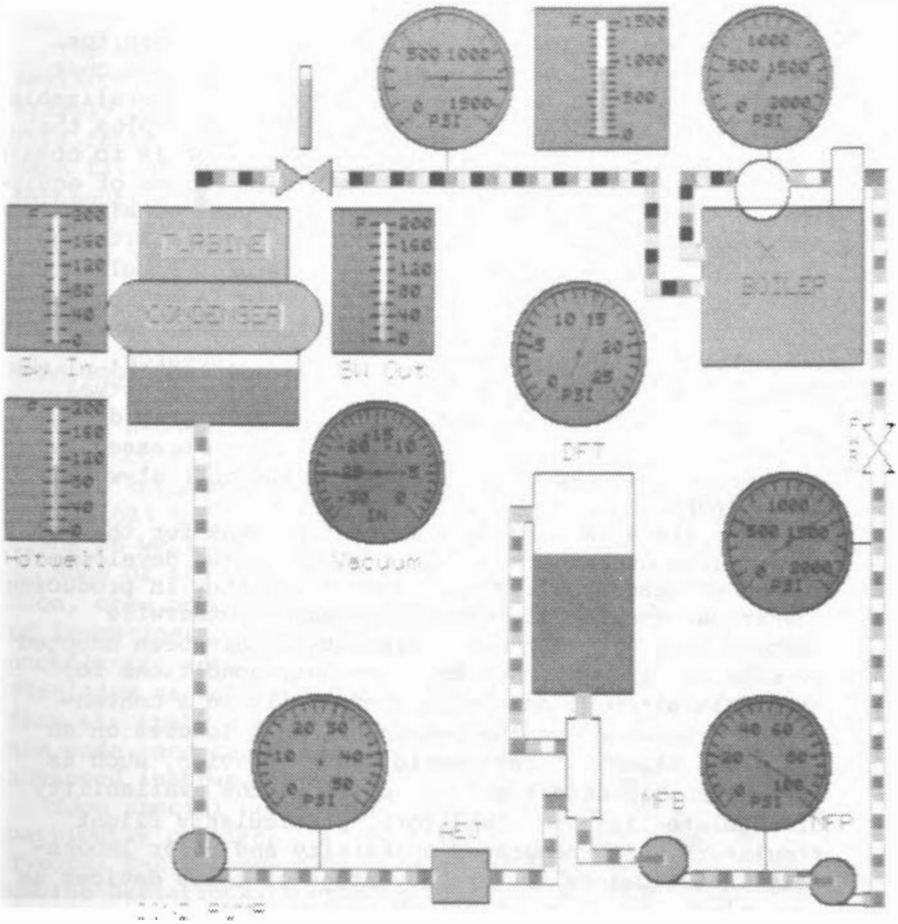

FIGURE A-2 STEAMER: A simulator with low physical fidelty and high training capability.

RESEARCH SIMULATORS

Simulators for research differ from simulators for engineering design and development principally in that the former use has the objective of gaining generalizable knowledge (i.e., discovering fundamental principles that are broadly applicable), while the latter use is to obtain specific data for the design of particular items of equipment, systems, or procedures. Research uses of simulators can focus on behavioral or engineering issues, although these are frequently interrelated. Research simulators generally must allow for greater latitude in manipulating conditions, events, and fundamental functional characteristics than engineering simulators. For research, scenarios do not necessarily have to represent actual situations; often certain features may be highly distorted or abstracted, events may be time compressed, and secondary tasks may be created that have no real-world counterpart.

There are a variety of practical reasons for the use of research simulators, such as lower system development costs, increased safety, improved efficiency in producing scenarios, and the opportunity to obtain otherwise inaccessible measurements. Simulators have been adapted to support research when the necessary conditions for experimentation cannot be created easily in a conventional laboratory or the research intent focuses on an important aspect of real-world human behavior, such as flying or ship handling. In addition, the availability of obsolete training simulators, particularly flight simulators, has encouraged university and other laboratory investigators to take advantage of these devices as convenient tools to support their research.

The extent of difference between research and engineering simulators and their uses depends a great deal on how basic or applied the research is. Clearly, these uses have much in common; both have the objective of obtaining valid and reliable human performance data, and the simulator characteristics, scenarios, and performance measurement requirements can be the same. All uses of simulation become commingled in programs of research to develop design requirements for training simulators.

We describe two classes of simulator facilities: one for aviation and one for maritime research.

Aviation Research Simulator Facility

The Man-Vehicle Systems Research Facility at NASA Ames Research Center, Moffett Field, California, is a good example of a government simulation research laboratory. This facility permits work not feasible in other existing NASA flight simulators that are intended primarily for aeronautical rather than human factors research. Its general purpose is the support of studies of the interactions among flight crews, their aircraft, and air traffic control. The facility includes a B-727 aircraft simulator, a skeletal cockpit for work on new display and control designs, and an air traffic control center. The NASA equipment supports complete simulation of a flight mission and includes a visual display capable of depicting dusk or night lighting, aircraft, fog, clouds, and other weather conditions. Experimenters can introduce problems such as turbulence, air traffic, visual obscurations, and mechanical failures to create and control visual conditions as well as operational workloads.

Much of the research focuses on cockpit instrumentation, crew procedures, and workload measurement. Topics of investigations include how decisions made in the cockpit are affected by environmental and hardware difficulties as well as by the availability of information from air traffic control and other aircraft, how errors are made, and the effects of automation, fatigue, and advanced instrumentation on human performance.

Some special measurement devices are necessary for the particular research applications of a flight simulator. Typical performance data consist of measures such as course deviations, touchdown dispersions, and pilot control activity. A great deal of human engineering effort has gone into the design and inclusion of instruments such as secondary task batteries, oculometers, and television recording systems related to particular behavioral and life-science research interests.

The instrument panels in many research simulators may be reconfigured. The controls, for example, may be moved from center pedestal to overhead location, in order to reflect differences between a conventional jet transport and a vertical or short takeoff and landing (V/STOL) aircraft. This flexibility is achieved at the expense of conformity with the anthropometric and often the geometric designs of operational aircraft.

Use of general-purpose CRT displays for the study of information display and control requirements in advanced avionics systems has become increasingly common over the last 10 years. In some cases, panel cutouts with conventional instrument identification markings are placed over the CRTs to provide an aura of realism, but in many cases these identifiers are merely inserted as text information. This procedure is consistent with the trend in the use of CRTs in transport aircraft for area-navigation and general-purpose multifunction displays.

Huff and Nagel (1975) provide an excellent review of the use of flight simulators for research as well as a list and description of many of these simulators.

Maritime Research Simulator Facility

Since 1976 the U.S. Maritime Administration has operated the Computer-Aided Operations Research Facility (CAORF) to perform research and to test and evaluate ship operations in harbor confines and open sea. The basic long-range research program includes five research areas: (1) vessel operations in ports and waterways, (2) standards for training and licensing, (3) criteria and specifications for ship's bridge design, (4) standards for watch-keeping performance, and (5) maneuvering response requirements for ships.

The core concern in all these research areas has been on human factors in maritime operations. Several maritime advanced technical developments have failed because human perceptual and control capabilities have been neglected when designing each particular system (Puglisi, 1981). These capabilities are identified with the human limitations in perception, decision making, and the control of machinery. The main area in which these functions are undertaken on merchant ships is on the bridge. The duplication of the bridge environment and the modeling of ship response in the CAORF provide a sophisticated human factors laboratory dedicated to examining the human element in marine operations.

The simulated bridge consists of a wheelhouse 5.1 meters wide and 4.3 meters deep. The equipment on the bridge is similar to that normally available in the merchant fleet and includes steering, controls and displays for propulsion, and bow and stern thrusters. The two navigation radars are capable of displaying both relative and true motion presentations plus collision avoidance information. Future capabilities will include a digital fathometer, a radio direction finder, and Loran C and Omega global navigation systems.

An external visual scene is provided by a full-color computer-generated image system, which depicts ships, bridges, buoys, lighthouses, tall buildings, mountains, etc., in a panoramic view covering approximately 240 degrees horizontally. The lighting of the visual scene can be varied continuously from full sun to moonless night and with any degree of fog or haze.

A control station is the central location from which the simulator experiment is controlled and monitored. The simulation can be initiated with the ship anywhere within the visual gaming area and any traffic configuration desired. The control station enables the researchers to communicate with the watch standing crew on the bridge, to simulate malfunctions, and to control the operating mode of the simulator. It is also possible to control the motions of other ships and tugs in the gaming area and simulate telephone, intercom, radio, and whistle contact with the CAORF bridge crew. A separate human factors monitoring station is designed to allow observation of crew behavior. Monitoring is provided by five closed-circuit TV cameras and four microphones appropriately located throughout the wheelhouse to record all activities, comments, and commands.

BATTLE SIMULATORS

Battle simulation is one use of simulators that bridges development and training applications: it is a combination of human-in-the-loop simulation and war gaming. Battle simulator uses range from system development and evaluation of systems and tactical doctrine to training and the evaluation of tactical strategies and operational capabilities. Brief descriptions of representative human-in-the-loop battle simulations from each service follow.

Army Battle Simulation

The U.S. Army has developed two kinds of battle simulations: (1) field exercises for troops operating over real terrain and (2) command post exercises for command groups using simulated forces. The field exercises, generally called engagement simulation (ES).

ES is a two-sided war game exercise played in the field. It provides realistic interactions with an intelligent adversary simulating live fire and the risks and consequences of combat. The recently developed National Training Center is an instrumented battlefield in which troops of battalion-sized organizations of combined arms can exercise with troops over real terrain. Sensor and computer systems provide realistic feedback and summary data in real-time maneuvers to the participants and the umpire/controller group. A laser-based system called MILES (Multiple Integrated Laser Engagement System) scores the effects of direct fire from small arms, missiles, and guns.

Simulated exercises for command groups at the echelons of battalion and above have the objective of exercising the planning and fighting skills of command staffs rather than the maneuvering of troops in the field. The most sophisticated of these is the Combined Arms Tactical Training Simulator (CATTS). The activities of Blue and Red Forces, tactical events, and tactical outcomes are simulated or calculated by computer; company commanders are role-played by support personnel. Practice in realistic deployment and control of forces is provided at relatively little cost.

Air Force Battle Simulation

A major Air Force facility is the Blue Flag exercise at Eglin Air Force Base, Florida. Blue Flag is a simulation of the Tactical Air Warfare Center (TAWC) of the Tactical Air Command at Hurlburt Field, Florida. The elements in Blue Flag exercises are multiple organizations within the TAWC air defense network. They direct friendly fighter aircraft to intercept hostile intruder aircraft. Both live and simulated interceptors can be directed against live and simulated tracks of hostile aircraft. The Blue Flag exercises are personnel-intensive; however, computers are being introduced to automate part of the workload of conducting the simulation.

Other multiunit war games are conducted among units subordinate to the TAWC that often include the TAWC for high-level integration. For example, the Airborne Warning and Control System (AWACS), an airborne air-intercept control center, also has embedded facilities for simulated air defense exercises.

Navy Battle Simulation

Three simulation facilities of the U.S. Navy are the Naval Wargaming System at the Naval War College, Newport, Rhode Island, the Warfare Environment Simulator (WES) at the Naval Ocean Systems Center (NOSC), San Diego, California, and the TACDEW simulators used for fleet-level training. The TACDEW is a simulation of the Combat Information Center (CIC) on surface ships. The facility is reconfigurable to permit physical representation of the CICs of the principal destroyers, frigates, and aircraft carriers of the U.S. Navy. These simulators have been used for some time and represent an earlier level of computer technology.

In its maximum configuration the Naval Wargaming System is a two-sided interactive task force simulation. Its primary purpose is to provide exercises for a task force command staff and the commands of principal force elements, both Blue and Red. Ships and aircraft of the task force are simulated in a computerized scenario. Exercises can run five days or more and range ocean-wide. Lower-level individual games can also be run, time-sharing the computer among several parallel games. These games can be one-on-one or computer-opposed.

This facility has evolved in stages from manual operation through progressive augmentations of computer support. A Multics computer system and new gaming software have been installed recently.

The major use of the Newport facility is war gaming exercises for graduate students at the Naval War College. However, it has also been used by the commander-in-chief of the Atlantic Fleet for quarterly exercises with his staff. A similar facility exists at the headquarters of the commander-in-chief of the Pacific Fleet. This simulation receives computer support from the Advanced Command and Control Architectural Testbed (ACCAT), a computer system testbed facility at the Naval Ocean System Center, San Diego.

The Warfare Environment Simulator (WES), based on ACCAT, is another facility for naval battle simulation. WES is a reconfigurable facility for human-in-the-loop simulation of command centers in which experiments in tactical communication and strategy are conducted. ACCAT is a functional representation of the Navy's Command and Control structure supporting advanced command, control, and communication experiments.

ACCAT simulates parts of the Navy's hierarchy of distributed command and control centers on land and at sea including command, control, and communication information support sites. They are implemented as a geographically distributed network with various fixed sites ashore and mobile site modules for shipboard installations.

WES is a two-sided (Blue versus Orange) real-time interactive computer-aided war gaming system with third party and neutral forces also represented. Force size can range from a single ship to an entire fleet on each side. The CRT terminals and graphic displays serve as command input terminals for issuing directives and automatic status board terminals for displaying sensor, position, fuel, and other information.

EMBEDDED SIMULATION

The presence of computers as integral elements of many complex systems has created the opportunity for including a training simulation in the operational system itself at little additional cost. This approach to simulation for training has several advantages. Little extra equipment or software is necessary. The procedural skills necessary to operate infrequently used equipment such as weapons systems can be maintained through practice. And this practice can occur in the operational context. For example, the operator of a Navy missile system could practice tactics and launch procedures while the ship is at sea. In civilian flight operations the pilot could rehearse departure and alternative arrival procedures through the flight management system and "fly" them through the autopilot while on the ground before starting the engines.

We describe as examples of embedded simulation the Demonstration Advanced Avionics System in a Cessna 402 aircraft at NASA Langley Research Center and the Integrated Flight and Fire Control system being tested by the McDonnell Aircraft Company in an F-15B aircraft.

The Demonstration Advanced Avionics System

The Demonstration Advanced Avionics System (DAAS) is essentially a computer-based navigation and flight management system. Additional hardware and software are used primarily to test the DAAS by running simulated flights through the autopilot. That is, radio navigation aids and aircraft performance parameters are simulated to drive the DAAS. The DAAS displays and controls operate on the ground as though the aircraft was actually flying. With a few modifications this same test hardware and software was found to be an effective means for training pilots, participating as test subjects, in the use of the DAAS.

Integrated Flight and Firecontrol System

The embedded simulation feature in the Integrated Flight and Firecontrol System (IFFC) for the F-15B aircraft operates in a similar fashion to allow complete pilot interaction in all IFFC weapon delivery modes, both on the ground and in flight, without the need for actual ground or air targets. The simulation used for the development test of the IFFC includes models for dynamic targets, target sensing devices, and the F-15 flight characteristics. Simulated targets can be placed at any altitude and location. Since preliminary maneuvering to approach within engagement range of the target is not necessary, repeated encounters can be flown in rapid succession and thereby allow for the maximum amount of data collection or pilot training with a minimum amount of aircraft flight time.

Aircraft displays and controls operate in the simulation mode the same as in flight with the addition of a target symbol to the head-up display to simulate a visually tracked target. A gunnery scoring routine, usable for both simulated and actual targets, supports gunnery training without the costs of ammunition and tow targets or the safety problems associated with live firing exercises.

TABLE B-1 Composition of the Working Group on Simulation

Member, Affiliation	Expertise
EDWARD R. JONES (Chair), Chief Human Factors Engineer, McDonnell Douglas Corporation, St. Louis	Systems acquisition, design simulation
SHELDON BARON, Vice President, Information Sciences Division, Bolt Beranek and Newman Inc., Cambridge, Mass.	Control systems, performance measurement
PAUL W. CARO, Program Manager, Seville Training Systems Corporation, Pensacola, Fla.	Training uses, assessment of utility
JAMES G. GREENO, Professor of Psychology, University of Pittsburgh	Learning, cognitive psychology
RICHARD S. JENSEN, Associate Professor, Department of Aviation Psychology, Ohio State University	Decision processes, research simulation
HERSCHEL W. LEIBOWITZ, Evan Pugh Professor of Psychology, Pennsylvania State University	Perception
JOHN A. MODRICK, Senior Research Fellow, Honeywell, Inc., Minneapolis	Methodology, maintenance C^3I simulators
JESSE ORLANSKY, Science and Technology Division, Institute for Defense Analyses, Alexandria, Va.	Cost-benefit analysis, maintenance simulators
JOHN B. SINACORI, President, John B. Sinacori Associates, Hollister, Calif.	Simulation engineering
DONALD VREULS, President, Vreuls Research Corporation, Thousand Oaks, Calif.	Performance measurement
ROBERT C. WILLIGES, Professor of Industrial Engineering and Operations Research, Virginia Polytechnic Institute and State University	Research simulation

APPENDIX B

BIOGRAPHICAL SKETCHES OF WORKING GROUP MEMBERS

The working group was composed of experts representing a balanced team of specialists with broad experience in simulation. The composition of the working group is summarized in Table B-1.

EDWARD R. JONES (Chair) is chief human factors engineer at McDonnell Douglas Corporation, St. Louis, where he is responsible for behavioral science research as well as human factors applications to a variety of aircraft, missile spacecraft, and C^3 and training systems. He has been at McDonnell Douglas since 1959. Previously he held research positions at Washington University, Northwestern University, and the Air Force's Air Research and Development Command, where among other activities he was responsible for human factors support of the first simulators delivered to the Air Force. He is a fellow of the American Psychological Association and the Human Factors Society and an associate fellow of the American Institute of Aeronautics and Astronautics and is currently a member of the Advisory Council of the Institute of Nuclear Power Operations and of the U.S. Army Science Board. He received an A.B. in biology and psychology and A.M. and Ph.D. degrees in psychology, all from Washington University.

SHELDON BARON is vice president and assistant director of the Information Sciences Division at Bolt Beranek and Newman, Inc., in Cambridge, Mass. He was a pioneer in the application of modern control and estimation theory to the analysis of person-machine systems and, in particular, to the development of human performance models. His current research interests are focused on the application of such models to supervisory control tasks and to the assessment of flight simulator requirements. Prior to joining Bolt, Beranek and Newman, he was employed by NASA, where he directed and conducted research in advanced aircraft and spacecraft control and was directly involved in simulation for many person-in-the-loop studies (including studies of the X-15 and the Mercury spacecraft). He is a fellow of the Institute of Electrical and Electronics Engineers and a member of the American Institute of Aeronautics and Astronautics. He was cochairman of the NASA-University Conference on Manual Control in 1977 and in 1980. He served on the Scientific Advisory Group of the Army Missile Command in 1975 and was president of the Harvard Society of Engineers and Scientists from 1976 to 1978. Currently, he is secretary treasurer of the IEEE Control Systems Society. He received a B.S. degree from Brooklyn College, an M.A. in physics from William and Mary College, and a Ph.D. in applied mathematics from Harvard University.

PAUL W. CARO is program manager with Seville Training System Corp. in Pensacola, Florida, and a member of the U.S. Air Force Scientific Advisory Board. Previously he was a senior staff scientist with the Human Resources Research Organization. He has directed research on training simulator design, utilization, and evaluation. He has been responsible for the design of flight simulator training systems for the U.S. Army and the U.S. Coast Guard and has participated in simulator design and evaluation efforts for other U.S. and foreign agencies and industrial organizations. He is a fellow of the American Psychological Association and a member of the Human Factors Society, the American Institute of Aeronautics and Astronautics, the American Nuclear Society, and Sigma Xi. He received B.A. and M.A. degrees from Florida State University and a PH.D. degree in industrial psychology and psychometrics from the University of Tennessee.

JAMES G. GREENO is a professor of psychology at the University of Pittsburgh. He was a visiting scientist at the University of Oxford in 1974 and a member of the National Research Council's Committee on Fundamental Research Relevant to Education in 1976-1977. He is a member of the Psychonomic Society and was chairman in 1980. He is a fellow of the American Psychological Association and of the American Association for the Advancement of Science. He was president of the

Federation of Behavioral Psychology and Cognitive Science in 1982-1983. His research interests include the psychology of learning, problem solving, and thinking, mathematical psychology, and the philosophy of psychology.

RICHARD S. JENSEN is associate professor in the Department of Aviation Psychology and the director of the Aviation Psychology Laboratory at Ohio State University; he also holds an appointment in the Department of Industrial and Systems Engineering. He received a Ph.D. in engineering psychology from the University of Illinois in 1979. His primary interests are in the development of display symbology and dynamic algorithms for cockpit CRT displays and in pilot judgment training and evaluation. He is also involved in developing low-cost simulation techniques for pilot training.

HERSCHEL W. LEIBOWITZ is the Evan Pugh professor of psychology at Pennsylvania State University, a consultant with the Veterans Administration, and consulting editor of the Journal of Experimental Psychology and the International Journal of Vision Research. He has a Ph.D. in experimental psychology from Columbia University. He is a member of the National Research Council's Committee on Vision and has been a consultant to various government agencies. His technical interests include behavioral psychology, visual perception, visual system and image perception and evaluation.

JOHN A. MODRICK is senior research fellow in the Man-Machine Sciences Group at Honeywell's Systems and Research Center, Minneapolis. He has been at Honeywell since 1972. Previously he has held research and teaching positions in several academic and industrial organizations, including Colorado State University, Washburn University, and the Air Force's Aerospace Medical Research Laboratory. His technical interests include training, cognitive functions, and system design. He has the degrees of B.A., M.A. and Ph.D., all in psychology from the University of Michigan.

JESSE ORLANSKY is a member of the technical staff in the Science and Technology Division of the Institute for Defense Analyses. He received degrees from City College of New York and Columbia University.

JOHN B. SINACORI is an aeronautical technologist operating as both an engineering consultant and a principal investigator at John B. Sinacori Associates, Hollister, Calif. His experience in aerospace firms includes flight dynamic and aerodynamic analyses, the design of aircraft, rotorcraft, and spacecraft, research on pilot-vehicle dynamics and all aspects of flight simulation, including their conduct for training and vehicle development, simulator design and simulator research. As the head of his own firm, he has been active in the design and development of advanced simulation equipment, research on simulator cueing, and particularly the determination of motion and visual cueing needs for training and engineering development simulation and the design and development of advanced astronomical telescopes. He holds a B.S. in aeronautical engineering from Rensselaer Polytechnic Institute and has performed numerous additional studies in electronics, optics, physics, mathematics, engineering. He is also a rated commercial pilot.

DONALD VREULS is president of Vreuls Research Corporation, Thousand Oaks, Calif., where he directs applied research and development in human-system and team performance measurement and assessment, intelligent information systems, and instructional technology and simulation. He cofounded Canyon Research Group, Inc., in Los Angeles, where he directed research and development in simulator performance assessment, automated and adaptive training, and flight simulator visual system requirements. He has performed both flight simulator and in-flight experiments on aircraft control, display, flight management and fault warning system design requirements, and field studies of human visual performance with passive night vision sensors. He is a member of the Human Factors Society and has authored over 60 technical reports and publications. He received a B.S. degree from the University of Illinois and an M.S. degree from Trinity University.

ROBERT C. WILLIGES is professor of industrial engineering and operations research as well as professor of psychology at Virginia Polytechnic Institute and State University. He is a fellow of both the American Psychological Association and the Human Factors Society. He is a former editor of *Human Factors* and is a past-president of the Human Factors Society. He was also president of the Division of Applied Experimental and Engineering

Psychologists of the American Psychological Association. He was on the faculty at the University of Illinois with appointments in psychology and aviation and served as the associate head for research of the Aviation Research Laboratory and assistant director of the Highway Traffic Safety Center at the University of Illinois. He received an A.B. degree in psychology from Wittenberg University in 1964 and M.A. and Ph.D. degrees in engineering psychology from Ohio State University in 1966 and 1968, respectively. His research interests include human-computer interactions, computer-based training procedures, and human factors research methodology. He has authored or coauthored over 100 technical reports, scientific papers, book chapters, and journal articles. In 1974 he won the Jerome H. Ely award for the best paper published in Volume 15 of Human Factors.

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The increasing importance and pervasiveness of simulation are due to several factors including cost and time savings that can be realized in system design and training, the ability to reproduce and examine situations that would be unsafe using actual equipment, the control and measurement of human-machine performance in a benign environment, and the capability to investigate conditions that would be impractical to arrange otherwise. Shortcomings in the use of current simulators are described and recommendations are made for research needed to enhance the value and use of simulators.

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