

FIDELITY OF SIMULATION AND TRANSFER OF TRAINING: A REVIEW OF THE PROBLEM

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FIDELITY OF SIMULATION AND TRANSFER OF TRAINING

I. Introduction

In 1957, Jack A. Adams, who was at that time with the Air Force Personnel and Training Research Center at Lackland Air Force Base, Texas, wrote a chapter about "Fidelity of Simulation and Transfer of Training" in an article entitled "Some Considerations in the Design and Use of Dynamic Flight Simulators".¹ Although he dealt primarily with flight simulators used by the USAF at that time, his report deals with fundamental knowledge and, therefore, has a much wider application.

Results of a number of piloted simulator investigations were critically reviewed by Sadoff and Harper in 1962.² Comparative appraisals, obtained in various ground-based simulators and in flight, were used by the two authors to determine the degree of simulator sophistication required for the evaluation of handling qualities and specific control problem research on conventional and advanced vehicles.

In 1964, Westbrook reviewed the development of piloted simulators, primarily that in the United States, and he gave 273 references on this subject.³ He listed 68 ground simulators, which do not include the simple cockpit-computer simulators and the so-called "iron bird" simulators used in the development of the flight control systems of a given vehicle. The number of in-flight simulators given by Westbrook was 32. Figure 1 shows a logical grouping. There are certainly more flight simulators of various degrees of sophistication available in the United States today. Twelve different types alone are described in the new NASA Ames brochure.

In this review, some of the results obtained from newer studies will be presented. The examples and studies which will be discussed are mainly from investigations conducted within the

civilian sector of simulator research that is, within the FAA and NASA. Nevertheless, they are so closely related to operational problems that they equally apply to Air Force and other weapon systems problems.

II. Definitions

In order to establish a common basis of understanding, in particular with those not familiar with the terminology used in this discussion, the key expressions of this subject will be defined:

Fidelity—Fidelity is defined in this context as the degree to which a device accurately reproduces a specific effect.

Simulator—A simulator is a device or a facility which represents a machine, system, or environment and their functions under certain—mostly well specified and controlled—conditions. Examples of the various types of simulators are equipment simulators (e.g., the F-111 simulator and other piloted simulators in which a human operator performs a control task); environment simulators (e.g., the lunar surface simulator); situation simulators (e.g., simulation of turbulence, attack, approach, or landing); condition simulators (e.g., IFR, VFR, night or daylight, zero-G); and procedure or mission simulators (e.g., for combat, space flight, SST flight profile).

Simulators have been categorized as "part-task" and "whole-task" simulators. A part-task simulator is defined as a device which represents only specific characteristics or functions of the task, such as radar observation, navigation, or fire control. An illustration of a part-task simulation is the pilot's job to position a target return in the center of a radar scope. In contrast, whole-task simulation has been defined as the "deliberate effort to achieve complete representation of equipment characteristics and in-flight mission factors". The latter include the environmental factors which are thought to be important.

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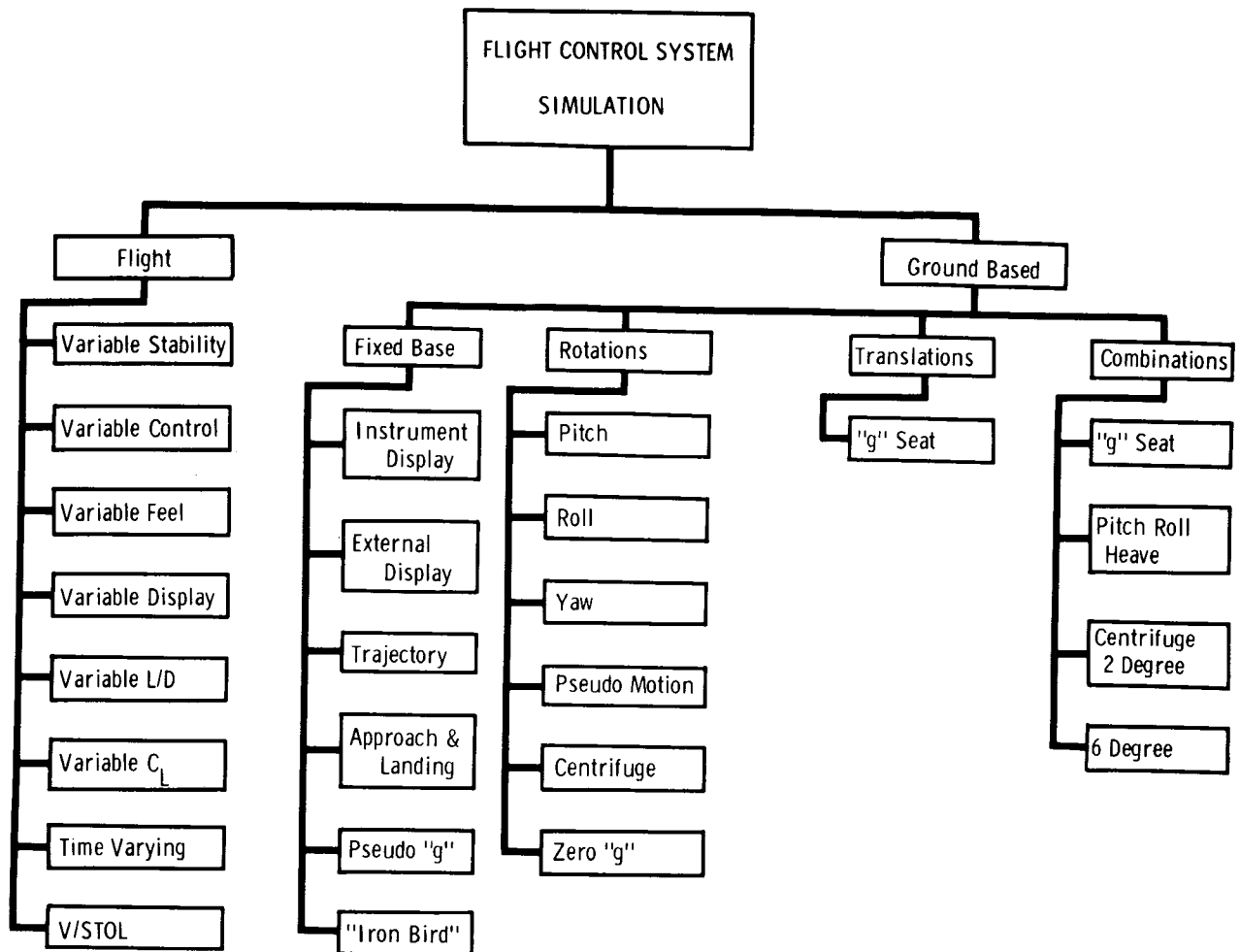


FIGURE 1. Flight Control System Simulation

Examples of whole-task simulators are the space flight simulators which were used by the astronauts for the simulation of the Mercury, Gemini, and Apollo missions.

Another grouping of simulators is that in fixed-base or stationary and moving-base or dynamic simulators. The first group mostly consists of cockpits of aircraft or facilities, in which a pilot or an aircrew can familiarize itself with the flight instruments, their arrangement, and certain operating procedures in the absence of dynamic and motion cues. These cues are available in the moving base simulator. In order to obtain dynamic responses of the pilot or the vehicle, cockpits of aircraft and entire space capsules have been placed on wheels, gimbals, pulleys, or air bearings. Needless to say, a simulator does not produce tasks or environmental conditions which are identi-

cal to that encountered in the "real world", it merely represents them to a degree necessary for the intended purpose. There is a certain type of dynamic simulator, however, which approaches reality in aviation as closely as possible, namely, the in-flight flight simulator. The variable stability aircraft is a most realistic flight simulator when properly used. An example of such a device is the T-33 variable stability airplane operated by the Cornell Aeronautical Laboratory in Buffalo, New York.⁴

Transfer of training—Transfer of training is a concept which derives both from learning theory and from practice. In both instances it has been shown that skills acquired in a particular situation can be successfully transferred to a similar situation. A well-known example is to practice each hand separately

before playing both hands together on the piano. In this process, the student learns a part of a task to a specified level of accuracy and then is required to integrate the previously learned tasks into the final entity. This principle has long been applied to flying training. Although Link Trainers, which were first used to this end, are rather crude devices for instrument flight training, they proved useful for practicing navigation owing to the positive transfer of learned behavior patterns from one situation to the other. If the learned functions disturb each other, negative transfer occurs. On the basis of present evidence it appears that flight simulators generally are very useful, but that the amount of transfer of skill from the simulator to the aircraft depends upon a variety of factors which are still subjects of experimental investigations.

III. The Purpose of Flight Simulators

In the course of this presentation, the topic will be limited to the discussion of flight simulators. Today, the use of flight simulators to economize training and to cope with situations which are difficult or impossible to reproduce is recognized. Ground-based simulators are generally less expensive, easier to handle and to maintain, independent of weather, and more suitable for proficiency measurements than aircraft. A simulator which reproduces the aerodynamic response of an aircraft with enough realism is not only a valuable tool for practicing newly acquired skills, but can also be used for the study of man-machine relationships, stress factors, human tolerances, and fatigue effects. Proficiency measurements under realistic conditions are necessary to determine the effectiveness of man-machine links. Periodic checks are made to evaluate proficiency in each of the many aircrew activities for the purpose of detecting shortcomings in the system and of pinpointing performance decrements due to overload of its components. However, airborne measurements of aircrew performance are limited by the extent to which the aircraft can be equipped with recording devices. Even if adequate criteria are established and automated or computerized techniques are available for recording and measuring performance in flight, their application very frequently appears inopportune because of interference with the actual crew duties. In addition,

the installation, maintenance, and calibration of the instruments used in field tests or in combat operations pose almost insurmountable difficulties to the investigator. The impossibility of exposing the astronauts to space conditions, for example, left the simulator as the only means for assessing their performance before the planned missions in space and on the moon could be undertaken.

In addition to meeting the training requirements, simulators have played an important role in proficiency measurement. In studying the possibility of using man as a backup for the Mercury system, failure mode analyses were conducted in order to determine the critical tasks of the astronaut during the standard three-orbit mission. The results of these analyses were then checked by tasks in various simulators—the procedure trainer, the centrifuge and the aircraft—and systems as well as procedure changes were based on these test results.

The development of analog computers was instrumental for the construction of our present day flight simulators; and computer technology will further advance the improvements in simulation. One of these advanced devices recently on display is a fixed-base fighter/interceptor simulator developed by the General Electric Company, which shows the computer-generated pictures of two aircraft on television. One of the two aircraft is taxiing out of the hangar, taking off, and flying on a programmed course, while the other one can be controlled by a joystick to follow, intercept, or overtake the other aircraft. The programs can be changed to meet various mission requirements of these types of airplanes.

The activities in aeronautics closely related to simulation include several steps, namely, research, training, and operations (see Table I). In the hardware research field, various models are manufactured which simulate the characteristics and functions of the final vehicle. Later, the flight and handling characteristics of advanced systems and its major components are determined through simulation. The last step includes operational use; and it is in this phase that the human element in the simulation process becomes of prime importance. Simulators are being used to determine the dynamic characteristics of the human operator as a servo element. There are significant implications as to man's capabilities to evaluate, control, and improve the

efficiency of complex systems—including his own—under normal or the most unusual circumstances.

Specifically, our problem boils down to asking how accurately any simulated task element, interaction, function, or situation should represent that encountered in the real world. In order to obtain a maximum return, or transfer of training, the following questions should be answered:

1. How “true” should be the visual input which is presented to the pilot in simulated situations?

2. How closely should the feedback from the controls in the simulator resemble that of the aircraft in order to elicit the desired response?

3. Are motion cues necessary for the simulation of the operational characteristics of a control system?

4. What environmental factors should be included in order to obtain valid results?

5. What measures are available to determine quantitatively the effect which fidelity of simulation has on the transfer of training?

FLIGHT CONTROL SIMULATOR USE IN DESIGN CYCLE

	DESIGN REQUIREMENTS DATA ON SPECIFIC PROBLEMS	FINAL DESIGN REQUIREMENTS PROOF OF DESIGN ACCEPTABILITY EQUIPMENT DEVELOPMENT PILOT TRAINING	PILOT TRAINING PILOT PROFICIENCY DANGEROUS REGIMES RESOLUTION OF PROBLEMS	CREW TRAINING PROCEDURAL TRAINING NAVIGATION ALL WEATHER OPERATION
RESEARCH	PRELIMINARY DESIGN	DETAILED DEVELOPMENT	FLIGHT TEST	OPERATIONAL USE
		TIME →		

TABLE I. Flight Control Simulator Use in Design Cycle

IV. Influence of Fidelity of Simulation on Pilot Performance

1. *Visual Input in Simulation.* The fidelity of the visual input required for simulation depends to a large extent on the pilot's task. For IFR simulation, the flight instruments are the more important components of the simulator, since they may provide the pilot with more accurate information than obtained from the ex-

ternal visual field (Cooper 1963).⁵ For example, rate information can hardly be accurately perceived by the pilot. If flight instruments are designed to combine, integrate, or compute information, the pilot may find himself engaged in a more or less complex tracking task. Thus, care must be taken to present instrument information with high fidelity; otherwise, the purpose of the simulation task may be defeated. The

results of a recent study concerning general aviation cockpit display and control simulation, made by FAA personnel at NAFEC in Atlantic City, New Jersey, show that the use of improved cockpit display and aids are especially beneficial at an early stage of instrument training in the simulator as well as in the aircraft.⁶ If visual noise is present in the system, operator performance is temporarily disturbed. However, Briggs, Fitts and Bahrick⁷ in 1956 established experimentally that the degradation of performance is not relevant for learning the visual task required for proficiency. This was recently confirmed by Hopkin, Poulter, and Whiteside⁸ for a flight simulator task performed by pilots with a blinded retinal area. Since VFR provide the pilot with continuous general orientation and a feeling of security, it is only natural that the critical maneuvers which are performed close to the ground, namely, takeoff, approach, and landing, should be done VFR in the simulator.

In 1967, Chase⁹ evaluated a simulator display system at the NASA Ames Research Center by measuring pilot performance during landings. He also compared the visual qualities of the TV picture with "real world" conditions. Owing to the limitations of the TV system used, the simulation was not of high fidelity. Nevertheless, the approaches were flown very similar to that in actual flight, and the pilots even included the so-called "duck-under" maneuver. Touchdown distance was about the same as during aircraft landings, but the simulated approach was made at a higher rate of descent.

In order to provide systematic information about the value of TV displays for research and training, another study was initiated by the Man-Machine Integration Branch at Ames using a color TV system (General Precision Instruments, Ltd.) in a fixed-base simulator. The task consisted of simulated approaches and landings of a DC-8 type aircraft by experienced airline captains. Performance measures included rate of descent, flight path variations, and touchdown accuracy in addition to the evaluation of the fidelity of simulation by the pilots.

Some preliminary results, made available by Mr. Sadoff, Chief of the Man-Machine Integration Branch, are shown in Figures 2 and 3.* From Figure 2 it appears that the rates of de-

scend were better controlled with the color display than with the black and white picture.

The pilots then rated the various displays according to the fidelity of simulation on a subjective scale from 1 (real world) to 5 (poor fidelity). The results obtained from four pilots are shown in Figure 3. There is a progressive increase in fidelity of simulation through the addition of color and with the collimated visual image display. The pilots also commented that color reduced visual workload, made it easier to line up with the runway, and that the collimated visual image system facilitated altitude estimates during the flare.

The implications of these findings are straight forward. If we are training for IFR, the information obtained from instruments should have high priority. Visual noise may or may not be a factor, depending upon the criticality of picture clarity at the moment of decision. For VFR operation, the ultimate goal is the "real-world" display. Advanced TV display systems, used in conjunction with properly designed collimated visual image, should approach "real-world" quality. There was subjective agreement on this point by experienced airline pilots, and it was quantitatively reflected by their performance. Collimated TV pictures of this sort eliminate the need for expensive projector systems, and they can be used equally well for crew training.

2. *Control and Kinesthetic Feedback.* The main problem in control simulation concerns the precision and exactness with which the basic form of the input-output relationship must be reproduced. Pertinent experiments on this subject have shown that even a low fidelity in part-task simulation provides for positive transfer of proprioceptive feedback (see Ref. 1). This means that the basic control movements can be learned in a simulator, although the control sensitivity may be altered, the direction of an indicator may not exactly correspond to a specific control movement, or the mathematical function specifying these relationships may differ. However, it must be emphasized that these conclusions are based almost entirely on continuous psychomotor responses and cannot be extended to apply to whole-task procedural simulation.

If the control system characteristics are under study, the situation is different. Because of the close relationship between control system characteristics and handling qualities, the vehicle con-

* Personal communication (1969).

COMPARISON OF TOUCHDOWN RATES OF DESCENT FOR COLOR AND BLACK AND WHITE DISPLAY CONFIGURATIONS

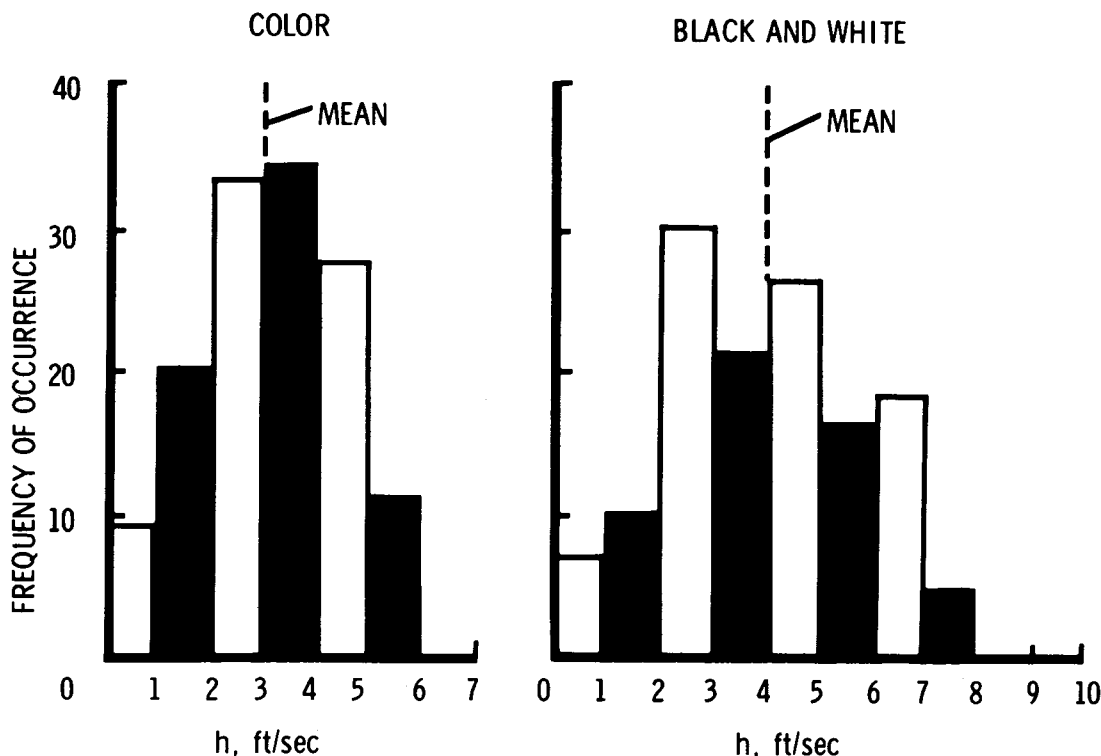


FIGURE 2. Comparison of Touchdown Rates of Descent for Color and Black and White Display Configurations

trol system should be simulated with high fidelity. This will reveal the actual balance or lack of balance between control sensitivity and control power input. If the actual control system cannot be simulated, a variable feel system should be provided. At least, the simulator control system should have no adverse characteristics, such as friction, lag, or dead band. While the simulator should accurately represent the short period vehicle dynamics and the essential control system characteristics, it has been found that its value is not a direct function of the degree of sophistication (see Ref. 5). However, experience with the Aero Flight simulator by Perry and Naish (1964) suggests that kinesthetic cues used for control may be at least as important as the visual cues (McPherson 1968).¹⁰

An outstanding example of the use of the simulator for studies of proprioceptive feedback is the turbulence experiment which was conducted by Ragland¹¹ in 1963/1964 on the human

centrifuge at Johnsville. The purpose of the experiment was (1) to determine whether physical events, which led to a 25,000-foot dive of a United Airlines 720 and which were retained on the flight recorder, could be reproduced by the centrifuge, and (2) what effects detrimental to the safe control of the aircraft were experienced by the pilots. The turbulence produced accelerations ranging from +3.5g to -2g at a random frequency of about 1 Hertz. The pilot and copilot of the United Airlines aircraft participated in the experiment. They pronounced the fidelity of simulation excellent. Eight more pilots who also took part adjudged it realistic, based on their own experience of turbulence.

The most interesting finding of the study was a "kinesthetic illusion" of climb or dive after rapidly changing G-forces, which sometimes causes the pilot to move his controls in the wrong direction. By responding to a strong kinesthetic illusion of climb or dive after correcting from

FIDELITY OF SIMULATION (4 PILOTS)

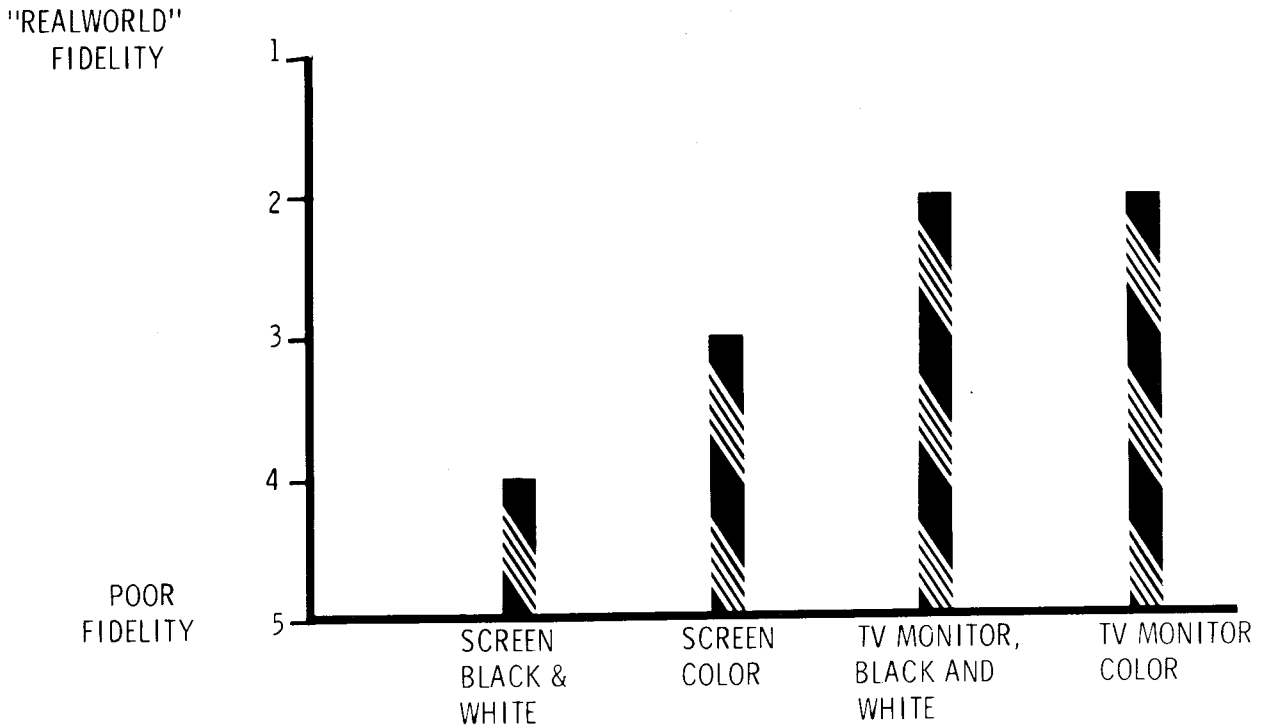


FIGURE 3. Fidelity of Simulation (4 pilots)

an unusual nose-up or nose-down position, pilots may increase the deviations from normal attitude alternately and thus induce uncontrollable oscillations. Some of the pilots indicated that the "involuntary control movements" which occurred were reflexes largely resulting from what they had learned in transport flying training and through experience. All of the pilots thought that the two centrifuge runs improved their performance. In general, the simulations were much more realistic than the pilots had thought; in particular, the negative G-portion was especially realistic and the turbulence conditions seemed real. A comparative evaluation of the centrifuge simulation and fixed-base motion system is shown in Figure 4.

3. Motion Simulation. The importance of providing motion information for the specific ranges of vehicle dynamics has long been recognized. From the pilot's point of view, motion adds realism and either helps or hinders the execution of his task. Motion becomes distract-

ing when it disturbs the pilot physically, as is the case during high G-forces on the centrifuge (see Fig. 5). Useful cues produced through motion do assist the pilot and improve his performance. An example, which illustrates how the motion cues help the pilot to control a simulated aircraft following abrupt asymmetry due to engine failure, is shown in Figure 6. Marked improvements can be seen in the excursions of bank angle, sideslip, rudder, and side force (see Ref. 5).

The rotation simulators of the Link Trainer type have limitations due to rotational travel. By incorporating an initial movement into the simulator and then "washing out" the motion but continuing it on the instruments, a very effective simulation of motion is obtained. In order to understand better the effects of motion inputs on the pilot, a study was conducted by Systems Technology, Inc., using the Ames Six-Degree-of-Freedom Simulator.* The purpose of the

* Personal communication (1969).

Comparative evaluations of the centrifuge simulation and fixed-base motion systems.

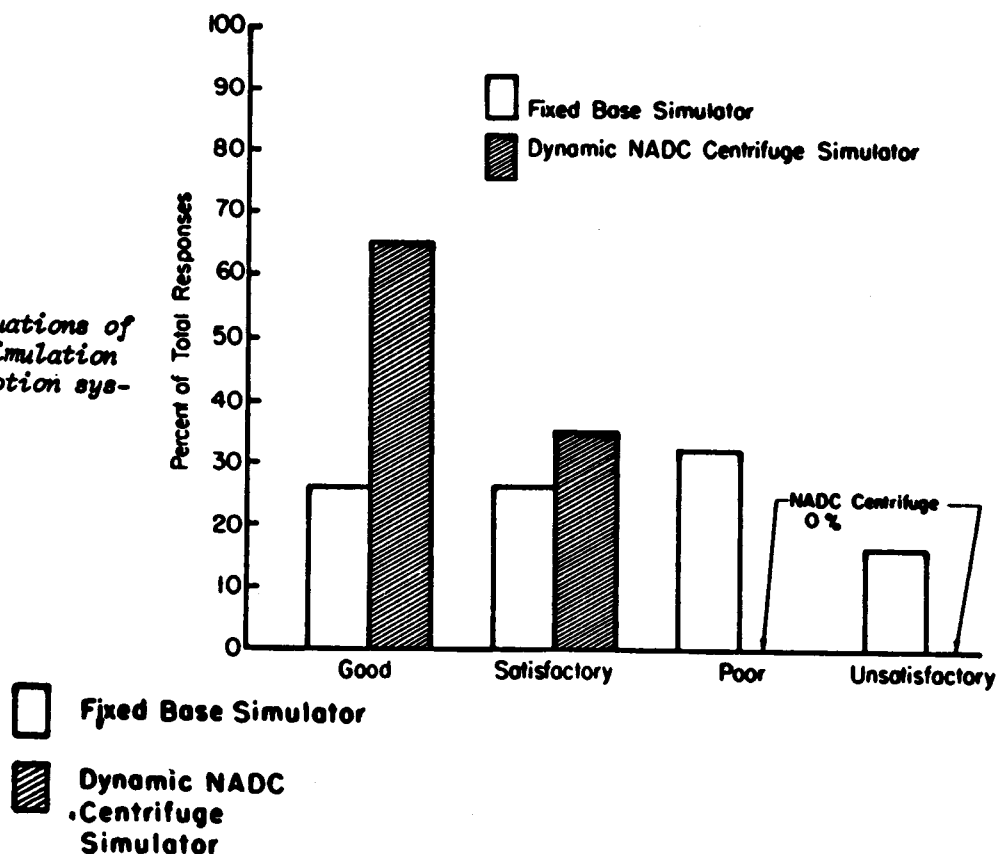


FIGURE 4. Comparative Evaluations of the Centrifuge Simulation and Fixed-Base Motion Systems

experiment was to establish a two-modality pilot function, which would allow predictions of the effects of motion, motion washout, and simulator fidelity. The initial phase consisted of a simple hover task: the pilot had to roll-stabilize the craft in the presence of disturbance input. The experiment was so designed that the effects of visual input as well as angular and linear acceleration on pilot performance and dynamic response could be determined. Figure 7 shows the block diagram for this experiment including the three feedback loops. The position of the pilot's head was varied to change the ratio of linear to angular acceleration feedback. Three sets of vehicle dynamics were used: $K/S(S+10)$ =good, $K/S(S+1)$ =moderate, and K/S^2 =no roll damping. In addition, washout time constants for both roll and lateral motion were varied from 0.5 to 2 seconds.

One of the most important findings of this experiment is presented in Figure 8 which shows results from analysis of the two-input (disturbance and command) data. The fixed-base data

are for the visual cues alone. As indicated, the pilot operates with greater gain in the visual mode but with less lead, and he utilizes the motion channels to develop the required lead. This result quantifies previous intuitive notions and observations regarding the beneficial effects of motion cues.

4. *Environmental Factors.* The simulation of environmental factors primarily concerns the aerodynamic forces which act on the aircraft. An experiment similar to that mentioned before was conducted on the centrifuge simulating a sweptwing transport in severe turbulence; and its results were released in 1969.¹² Several of the pilots who participated noticed that the centrifuge did not realistically represent such factors as the pitch changes and the associated control forces, the lack of trim stabilization, and the representation of normal G-forces, although the simulation generally was authentic. Moreover, the noise level in the cockpit was not realistic and the lighting was sometimes disconcerting, particularly when pictures were taken

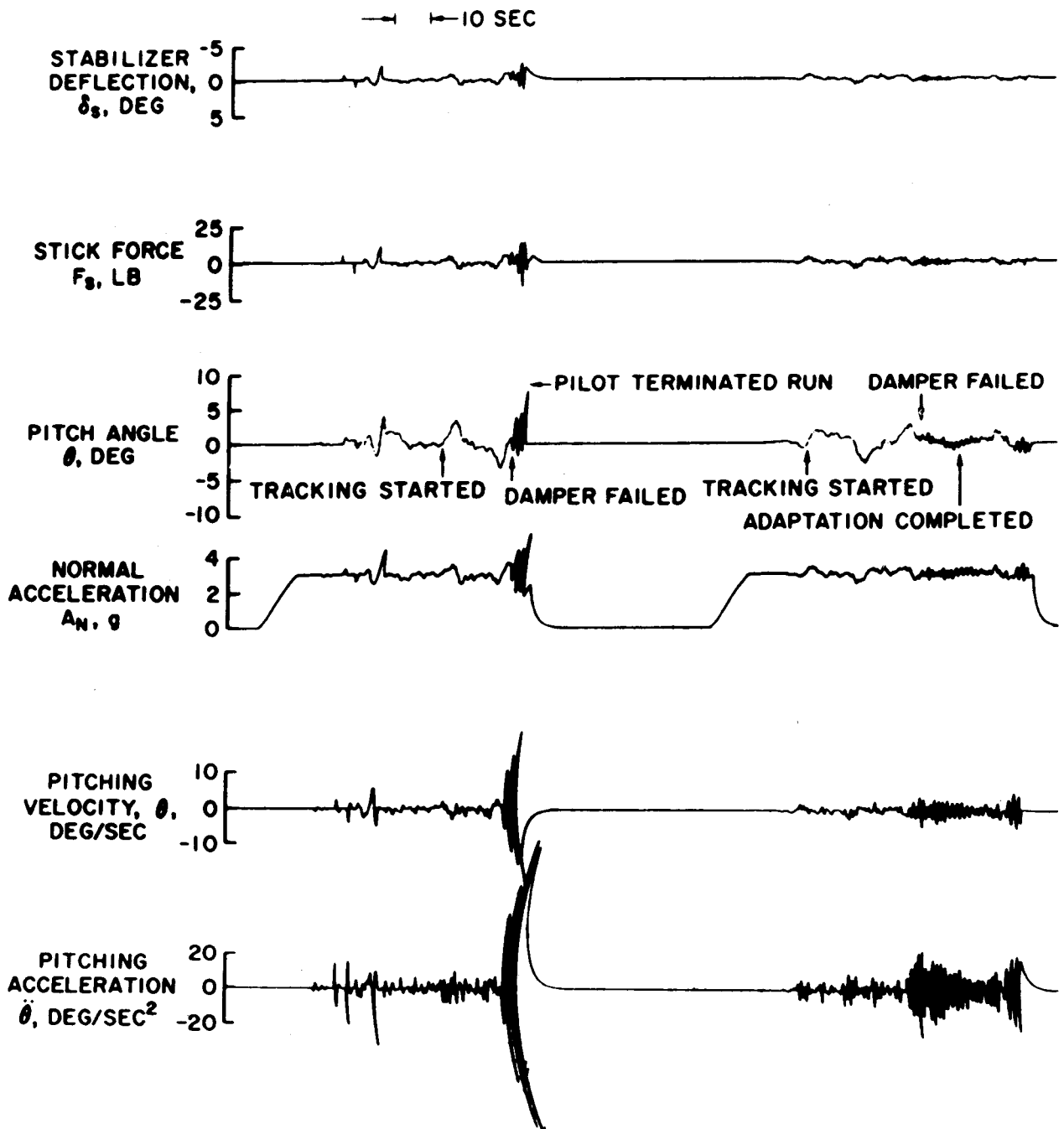
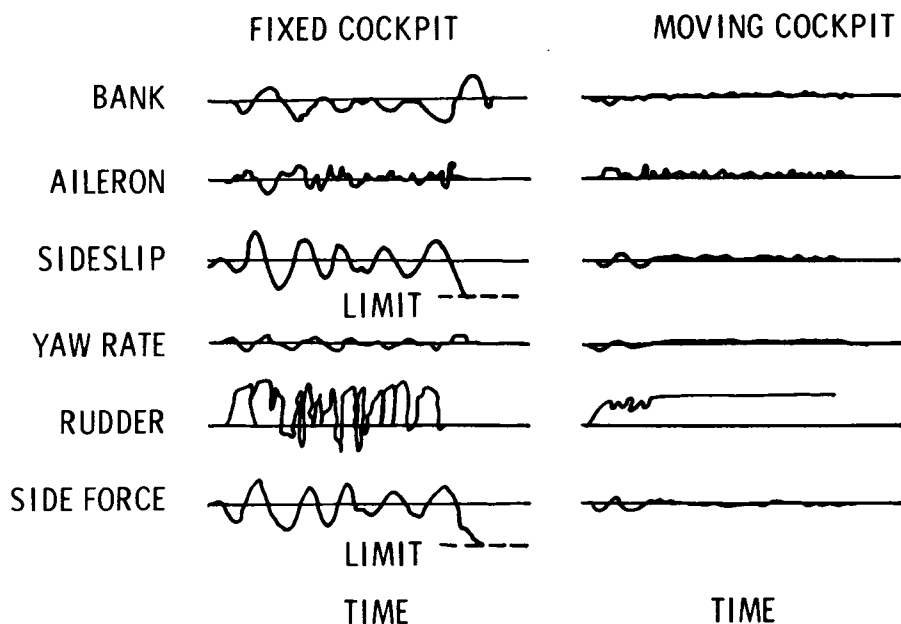


FIGURE 5. Example of Pilot Loss of Control in Centrifuge (damper failure)

inside the cab. Experiments with the Ames Five-Degree-of Freedom Flight Simulator also indicated that, as the number of degrees of mo-

tion increased, it became more difficult to maintain a natural flight environment (see Ref. 5).

One of the problems is to keep the simulation



EFFECT OF COCKPIT MOTION ON PILOT CONTROLLABILITY FOLLOWING ABRUPT ENGINE FAILURE

FIGURE 6. Effect of Cockpit Motion on Pilot Controllability Following Abrupt Engine Failure

free of unwanted motion because of the restrictions imposed by the physical dimensions. The actual displacements in flight can be in the order of hundreds of feet, whereas those in the simulator are in the order of a few feet. Therefore, the Flight Simulator for Advanced Aircraft at Ames has a side-to-side displacement of ± 50 feet in order to simulate yaw in case of outer engine failure, and the designer still considers this marginal.* But even under normal flight conditions there are shortcomings due to inaccuracies in aerodynamic representation. Although the pilots were able to fly the six-degrees-of-freedom. Aero Flight research simulator, which represents the Handley-Page 115 slender-wing aircraft, they particularly disliked the "normal acceleration" cue and felt it reduced the realism of the simulation (see Ref. 10). With the cockpit fixed or with pitch attitude and sideslip motion, the simulator did not feel like the real HP 115, regardless of the other features available to the pilot. When the motion cues were realistic, the nature of the external visual

background was not very important. Of the six degrees of freedom of motion simulated, pitch and roll attitude cues proved most pertinent, although there always was a spurious sensation of side force during the bank, which is not present in actual flight. Roll washout (by gradually restoring the cockpit to wings-level position) was used to overcome this particular deficiency.

One of the difficulties of the realistic presentation of the environment concerns the size of the objects on the ground. Ideally, they should be presented at a scale which allows a large enough area to be pictured without loss of detail. Normally, a scale of the order of 1:2000 is used for most models which are suitable for take-off and landing studies. This means that a house on the model needs to be made only 0.2 of an inch high. The total size of the area and the scale depends primarily on the purpose of the experiment and the variables under study, since the eye is able to fill in details so that some kind of perceptual equivalent exists (Corkindale and Benson 1968).¹³ For the simulation of three-dimensional objects in space, the use of holograms may prove more realistic.

* Personal communication (1969).

BLOCK DIAGRAM OF MULTIMODALITY PILOT MODEL AND SIMULATION EXPERIMENT

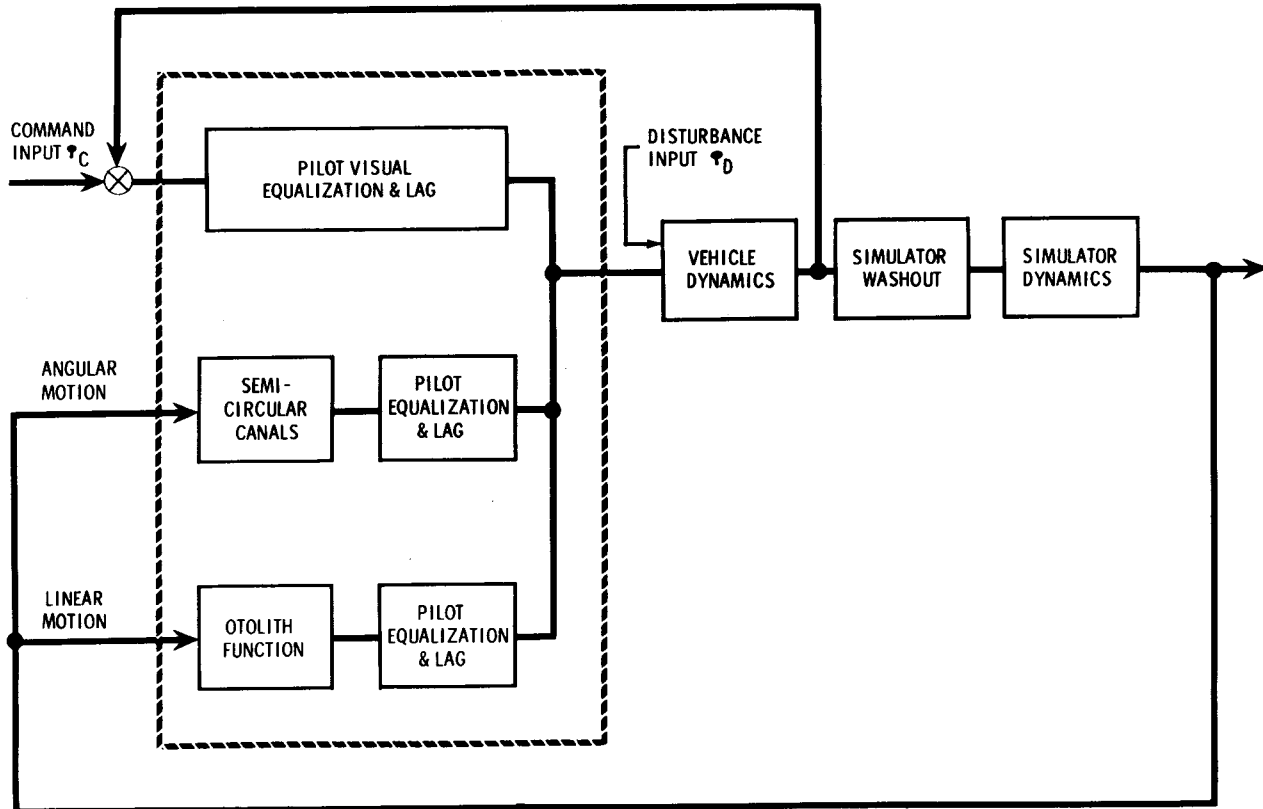


FIGURE 7. Block Diagram of Multimodality Pilot Model and Simulation Experiment

Another “environmental” factor, namely danger, cannot be simulated on the ground. It is present, however, with the inflight flight simulator.

By and large, it can be stated that whole-task and inflight flight simulators provide the greatest variety of factors in regard to the aerodynamic and the ground environment. They have their real potential in the fidelity with which they can be used to represent the environmental conditions in the area of greatest interest. Some shortcomings—such as spurious motions, lack of gross movements, high washout and reduced dimensions—must be accepted even in modern ground-based simulators. Naturally, the inflight flight simulator provides the highest fidelity of the aerodynamic environment.

5. *Quantitative Assessment of Fidelity.* Although simulators are widely used for research, development, and training purposes, quantitative information about the degree of fidelity needed

to produce the desired amount of transfer is scarce. Training simulators are employed today with the assumption that if the trainer accurately reproduces the characteristics of the aircraft, and if the task of operating the trainer resembles that in the air, enough transfer of training will occur. The validity of this assumption is known as “face validity” which may not be dependable. A better estimate of the validity of a training device can be obtained by quantitatively assessing the fidelity of the simulator and the resulting transfer effect.

A valid evaluation technique of simulation should employ means for measuring those aspects of a situation which are relevant to the set of responses involved in the system being simulated. Moreover, the evaluation of fidelity necessary for simulation should apply measures for the extent to which a simulator elicits behavioral and physiological responses or sets of responses otherwise produced by the operational environment.

VARIATION OF ERROR WITH MOTION CUES AND VEHICLE DYNAMICS

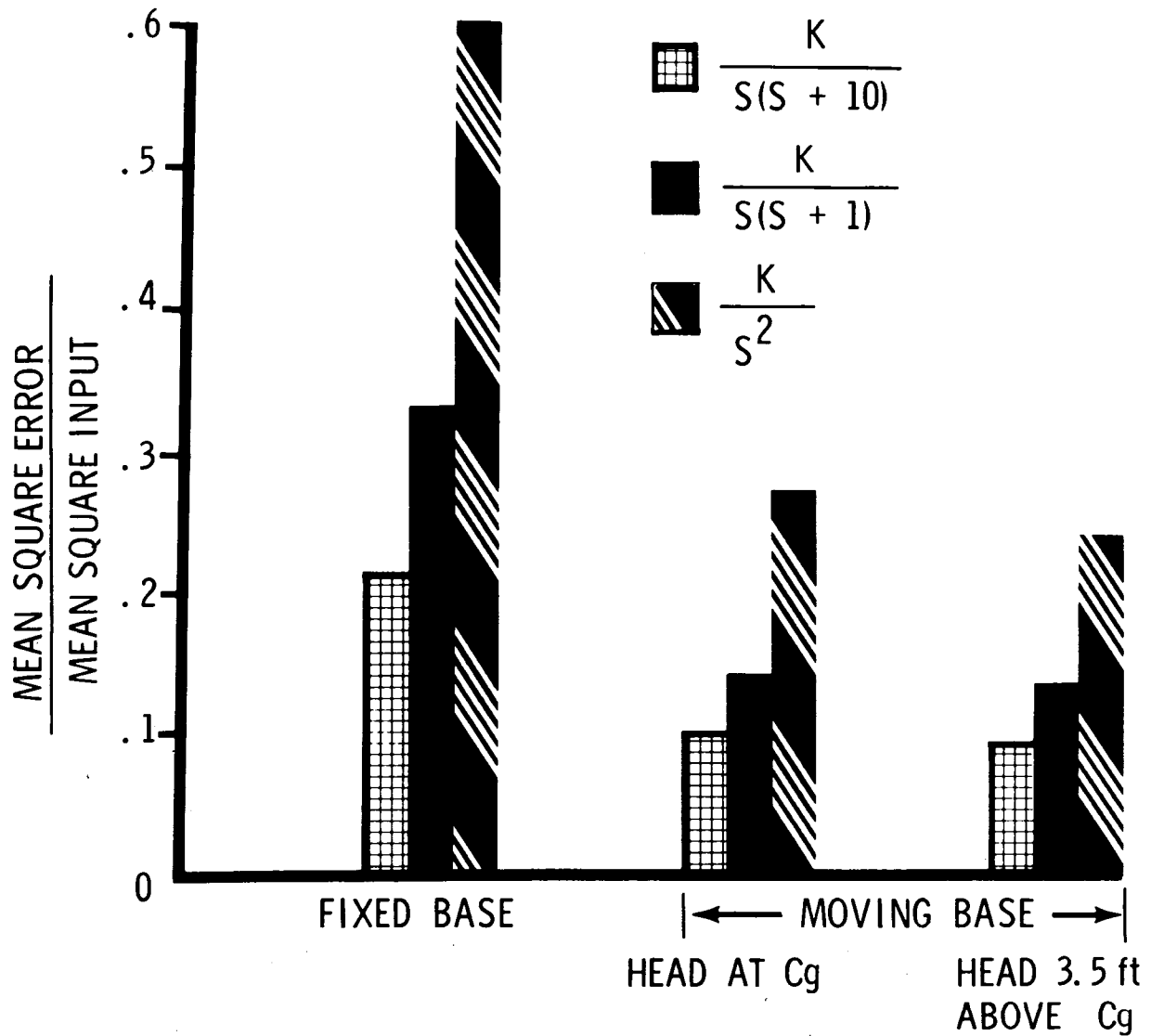


FIGURE 8. Variation of Error with Motion Cues and Vehicle Dynamics

If similarities or differences between the two types of responses are specified and determined, the degree of simulation fidelity or cue deficiency, respectively, can be established. There are four different techniques available which may be useful to the assessment of fidelity of simulation and transfer of training:

(a) *Pilot ratings*—Subjective pilot evaluation is still an accepted technique of assessing the interactions between a pilot and his aircraft, particularly, in determining the handling qualities of the vehicle, pilot performance, and the suitability of an airplane for the mission. An example of this technique, which employs a 10-

point numerical rating scale, is the so-called Cooper-Scale developed by G. E. Cooper at the NASA Ames Research Center.¹⁴ As a general rule, each pilot judges the suitability of any set of aircraft characteristics in terms of his own skill and experience, and in terms of the required operations and circumstances as defined in the experiment. Correspondingly, the pilot's usual approach to the assessment of simulator fidelity involves the judging of accuracy of simulation by means of pilot comments and ratings. Empirically, a simulator is thought to have high fidelity if the pilot ratings are satisfactory and comments favorable. Although the pilot makes his judgments in quantitative terms, his ratings are obviously subjective and predominantly based on face validity. It has therefore been suggested that a confidence factor be added, which determines the ratio of information available to the pilot in the simulation situation to the information required to derive a realistic pilot rating (see Ref. 13). Useful as it may be for judging fidelity, a strictly subjective method does not provide the type of information required for measuring transfer of training.

(b) *Pilot transfer functions*—The success in correlating handling characteristics of aircraft with human response characteristics has resulted in adequate human transfer or describing functions. These functions are mathematical expressions of the input-output relationship of the human operator in a control system.^{15 16 17 18} An example of a simplified model of a flight control system transfer characteristic is shown in Figure 9. Y_p is the pilot describing function made up of pilot gain (K_p), his reaction time delay ($e^{-\tau}$), and his lead (T_L). S indicates the Laplace transform operator. In one study of this kind, the parameters K_p (gain) and T_L (lead) have been related quantitatively to pilot opinion concerning aircraft landing performance ranging from "satisfactory" to "unacceptable."¹⁹ This concept calls for a model-matching procedure, in which the dynamics of a given vehicle are represented in the form of equations of motion to be matched or approximated by the simulator. Analytically, a simulator is considered to have fidelity to the extent that the simulator model generates an output that falls within standard engineering tolerances of the parent model. Mudd²⁰ (1968) has amended this approach by proposing an adaptive control system

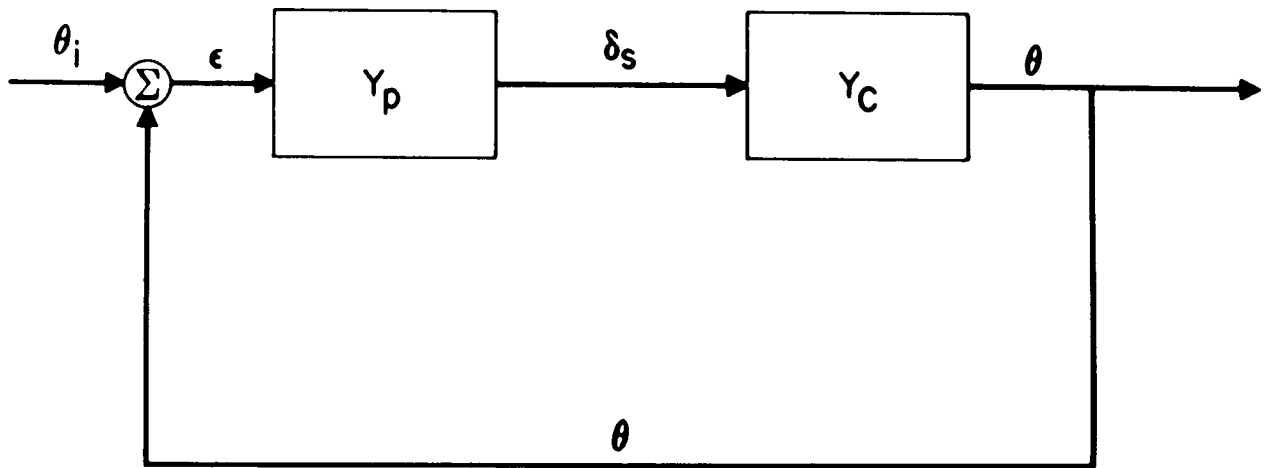
for immediate discrepancy recording. The basic concept of his theory is that pilots can evaluate the fidelity of dynamic flight simulators in terms of psychomotoric responses. If a means for recording such responses can be provided, deficiencies of simulation in terms of specific aircraft motion can be objectively determined. The "control-recorded discrepancy technique" would generate a subjective error signal in a form suitable for analysis by control system methods, particularly those developed for model reference self adaptive systems. The relative magnitude of the error signal generated by the pilot would then provide a direct measure of simulation fidelity.

(c) *Physiologic measurements*—There is a possibility of determining simulator fidelity by comparing physiologic data obtained in the simulator and during flight. Among others Rolfe and coworkers²¹ used heart rate and respiratory rate to compare pilot response during flight in the Hunter T-7 aircraft and in the simulator with and without pitch motion. Of the two criteria used, heart rate was more indicative of the similarities and differences between tasks and conditions. In addition, control performance data were valuable in comparing simulator and flight response. By and large, there were no significant differences for either heart rate or respiratory rate between simulation and the various types of flight involved in this study.

During the past years, Ruffell Smith and coworkers²² studied airline captains charged with the conversion training of pilots for Comets, Tridents, Vanguard, and Viscount type aircraft. The investigators compared physiologic responses recorded in regular line flying to stress produced by three kinds of training; namely, simulator training, involving all phases of "flight", base training involving takeoff and landing, and line training which followed the simulator phase and included base work.

The heart rate was considered a stress index and recorded in 12 training captains. The highest heart rates were found during base training, followed in descending order by simulator work, line flying, and line training.

The human centrifuge has long been used as a flight simulator to study physiologic functions under acceleration stress.²³ Now Melton (1969) has proposed that the aeromedical factors associated with stress flying and flight training,



$$Y_p = K_p e^{-\tau s} (1 + T_L s)$$

$$Y_c = \frac{C_0 + C_1 s}{s(s^2 + 2\zeta\omega_n s + \omega_n^2)}$$

FIGURE 9. System Block Diagram

previously studied on the centrifuge and in flight, be studied for comparative purposes in the Link GAT-1. It is thought that the physiologic functions may be sensitive to the amount of stress provided by the GAT-1 and that the change of the physiological functions due to the stress may reflect the degree of fidelity present in this type of flight simulator.*

Recently, Gabriel, Creamer, Carpenter, and Burrows²³ used the U.S. Navy S-2 Operational Flight Trainer, a rather realistic weapon system simulator, to investigate the behavioral and physiological effects of workload on the flight crew. In all, over 70 different variables were measured in 16 volunteer subjects during exposure to low and high workloads. While the psychological functions and performance were affected but slightly, most physiological parameters including heart rate, respiration rate and basal skin resistance yielded statistically significant differences between high and low workloads. The experimenters believe that the equipment and methods used for the acquisition and interpretation of their data seem promising as tools in the investigation of fatigue.

(d) *Proficiency measurements*—Finally, it is suggested to use proficiency measurements for the

assessment of simulator fidelity. The assumption is that if one succeeds in objectively measuring pilot performance during actual flight, the results can then be related to the simulator. In order to do this, one first has to record actual pilot performances during parts of the mission, such as preflight checkout, taxiing, takeoff, cruise, etc., and for the entire mission; and one must then “construct” an “ideal” mission based on zero error scores and minimum deviations from an idealized pilot describing (transfer) function. It is not quite clear, however, how accurately this can be done today, but it appears that “proficiency” comparisons of this sort will be helpful in assessing the fidelity of simulators. The main problems yet to be solved are to agree upon the essential criteria measures, to develop precise measuring scales and systems which do not interfere with cockpit duties, and to apply meaningful standards of determining pilot proficiency equally valid to the flying and to the simulated condition. Six years ago, Obermayer and Muckler²⁴ summed up the dilemma as follows:

“Unfortunately, in the case of the selection of performance measurement for flight simulation studies, all of the measurement decision problems remain unsolved.”

Undoubtedly, progress has been made since then particularly through the use of advanced

* Personal communication (1969).

PHASE	CY 1969				CY 1970				CY 1971				CY 1972				CY 1973			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
T-33 Oklahoma City, FAA																				
Qualification	▼	▼			▽								▽							
Proficiency					▽								▽							
F-102/106, USAF																				
Qualification (Perrin) - 15 hrs.	▼				▽								▽							
Proficiency & R&D			▽			▽														
TB-58, USAF																				
Flight - 10 hrs.		▽				▽							▽							
Concorde (Schedule)	●	Development Testing			○	Pre-production		○	Production		○	Certificate of Airworthiness		○	Air Service					
Flight			▽			▽				▽				▽						
TIFS, Cornell, USAF						▽	▽	USAF Flights												
Ames - Simulator, NASA		▽	▽	▽	747	Concorde	U.S. SST													

FAA SST PILOT TRAINING

FIGURE 10. FAA SST Pilot Training Plan

flight recording, computing, and data processing systems. Moreover, the elements, components, and functions to be measured have been defined, and it is known how to do it. In its most complex mode, the pilot's task of flying or "flight management" is characterized by the integration of information gathering, communicating, decision making, and direct control. If one eventually succeeds in measuring the functions which determine pilot proficiency in the aircraft, it will be possible to provide for the degree of fidelity required for its true simulation.

V. Summary and Conclusions

In general, it can be stated that the amount of transfer expected to occur in flight simulator application seems to be proportional to the degree of fidelity provided. Although part-task simulators are usually less expensive and of lower fidelity than whole-task simulators, they can be very useful for the learning of specific tasks.

However, their shortcomings, as clearly demonstrated by Adams²⁵ can be traced back to the lack of fidelity, particularly in simulating motion.

It seems that the whole-task flight simulator derives its advantages as a training device primarily from the incorporation of motion cues, if the addition of complex motion vectors increases the fidelity of the simulation and does not result in spurious stimuli. The various perceptual phenomena, physiological effects, and performance changes observed in complex simulators indicate that it is the psychological, physiologic, and operational realism which determine fidelity in simulation and not face validity based on physical similarity of the devices.

There are two additional factors which must be mentioned in this context, namely, motivation and danger. Elsom²⁶ has pointed out that a certain degree of stress is necessary in order to motivate the pilot who works in the simulator.

Physical identity alone is not enough to generate motivation and acceptance. The question whether danger must be involved in order to produce fidelity is not easy to answer. Experience in the training of the astronauts seems to indicate that danger is not a necessary prerequisite for the transfer of training.

In closing it is recommended that an *optimum* degree of fidelity be provided in order to obtain a *maximum* amount of transfer. In certain instances, this can be achieved simply by part-task simulation; in most cases, however, the use of whole-task or even inflight flight simulators may be optimal. This latter device can provide for

the highest degree of fidelity, but it is generally the most complex, complicated, and expensive type of simulator. For certain types of training, for example SST pilot training, a combination of ground-based whole-task and inflight simulators will be used (Fig. 10).²⁷ This approach is straight forward by proceeding from the aircraft which is apparently easier to handle than the more difficult one. It is based on the best judgments of qualified test pilots and on face validity. A general scientific theory which accurately predicts the optimum degree of fidelity needed to achieve the maximum of transfer in flight training has still to be developed.

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