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TECHNICAL REPORT

SIMULATOR COCKPIT MOTION AND THE TRANSFER OF INITIAL FLIGHT TRAINING

ROBERT S. JACOBS

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Institute of Aviation

University of Illinois at Urbana-Champaign
Willlard Airport
Savoy, Illinois
61874

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BACKGROUND

The acquisition of complex flying skills through practice in a simulated, as opposed to actual, operating environment is hardly a new concept. During the First World War, Grahame-White and Harper (1916) suggested that student aviators practice positioning flight controls as appropriate to various flight conditions in a parked aircraft prior to flight. However, ground-based flight trainers were not widely used until the Second World War when the need to train pilots quickly with few training aircraft led to rapid advancements in simulation technology and more efficient training.

Smode, Hall, and Meyer (1966) note that by the end of the war, an appreciation had been gained for the flight simulator, not only as a primary training aid, but also for transitioning from one airplane to another and training for specific missions. It was realized, as Adams (1957) points out, that economic factors favored the use of the relatively inexpensive-to-operate simulator rather than the parent aircraft, that the simulator was useful in teaching skills too complex, expensive, or risky to practice in the air, and that the simulator provided the ability to isolate and practice particular segments of the overall task. Further, simulator operation is independent of weather conditions, and single place aircraft simulators allow supervised practice impossible in the aircraft itself.

Transfer of Training

The value of a flight training simulator in a particular training curriculum is expressed quantitatively by its transfer and cost effectiveness. Where flight safety is not a consideration, the determination of whether such a training system should include a training simulator turns upon whether time spent in the device reduces the need for aircraft training time by a sufficient amount to offset the cost of the simulator use. As long as simulator practice pays for itself in this way, it is cost effective and economically justified. The amount of time saved in aircraft practice by prior simulator exposure is dependent upon the relative learning efficiency of the two environments.

For any particular curriculum, this efficiency can be experimentally determined by the measurement of the time spent in each device by experimental and control subjects, as shown in Figure 1, and the calculation of the transfer effectiveness ratio (Roscoe, 1971).

The transfer effectiveness ratio is expressed quantitatively by:

$$TER = \frac{Y_o - Y_x}{X},$$ where

Y_o = performance to criterion in the transfer task for the control group,

Y_x = performance to criterion in the transfer task for the experimental group(s), and,

X = performance on the practice task by the experimental group.

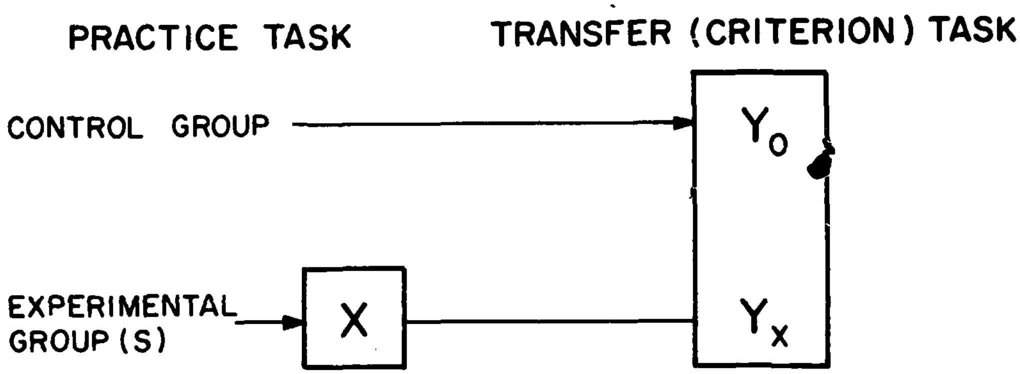

Figure 1. Schematic representation of the transfer of training experimental paradigm.

These performance variables may be quantitatively defined by any dimensionally consistent and meaningful measures of student achievement in the respective tasks.

In the evaluation of the cost effectiveness of a flight training simulator, the practice task refers to simulator training activities. The criterion or transfer task is the operation of the aircraft. The quantitative measures may be time spent in practice, number of attempts required for mastery, or number of errors made in meeting training objectives in each curricular segment. While the latter two alternatives are of interest in the case of training in hazardous skills, time is the more usual basis for computation of the transfer effectiveness ratio because of its direct relationship with cost of simulator and aircraft operation.

Simulator Training Effectiveness

More than a dozen reported investigations have demonstrated positive transfer of training from flight simulators to airplanes. For example, Williams and Flexman (1949) found that non-pilots could be trained to perform a series of contact maneuvers using a Link SNJ trainer and an aircraft in an alternating practice sequence with 61% fewer trials and 62% fewer errors than a group trained entirely in a North American SNJ/T-6 airplane. Flexman, Matheny, and Brown (1950) reported similar findings in terms of a reduction in time required to reach private pilot proficiency. Povenmire and Roscoe (1971; 1973) investigated the transfer benefits of a Singer-Link GAT-1 trainer used in the University of Illinois' primary flight training program, confirming not only that transfer was positive to a Piper Cherokee 140B airplane, but disclosing diminishing returns associated with successive increments of practice in the simulator.

It can be stipulated, in view of this evidence, that the simulator does constitute a basic training aid and that this is generally recognized is evidenced by the wide use of such devices in basic flight training. The demonstrated transfer effects apparently are sufficient to justify the outlay of funds for procurement, operation, and maintenance of training simulators by both small and large schools in the highly competitive flight training industry. Transfer effects are not, however, uniform across the entire spectrum of skill categories required for pilot certification.

Ornstein, Nichols and Flexman (1954) found that the simulator is most effective for teaching procedure-loaded flight exercises, presumably because such tasks are primarily cognitive. Simulators are somewhat less effective for teaching dynamic perceptual-motor tasks that are generally more difficult to reproduce faithfully. Ornstein, et al. discuss the relationship between the transfer effectiveness of the device and the fidelity, or verisimilitude, of reproduction of the aircraft's procedural and environmental cue structure. They suggested that by extending the range and fidelity of the simulation transfer is maximized. This would follow logically by analogy from the Osgood (1949) transfer-surface concept in which increasing both stimulus and response fidelity facilitates positive transfer. Negative transfer can only occur when similar stimuli require opposite or antagonistic responses in the transfer situation.

Motion Cue Fidelity

Advancements in simulation technology during the present decade, particularly in the simulation of visual scenes and cockpit motion dynamics, make extremely high stimulus and response fidelity possible but at very high procurement and operating costs. Motion systems have been refined to provide a cue structure that is highly realistic in all dimensions with the exception of sustained linear acceleration cues accompanying turns.

The discrepancy arises here because of the physical impossibility of artificially creating centripetal acceleration experienced by a turning aircraft and its occupants. The resultant forces of gravitational and centripetal accelerations are perceptually combined by the aircraft pilot's vestibular system, so that in a properly coordinated turn, the sensation is one of increased weight in addition to the rotational accelerations associated with roll into and out of the bank. There is no side force because the resultant force summation of gravitation and centripetal accelerations is kept perpendicular to the pilot's seat and the cabin floor.

In the simulator, any cabin tilt for the purpose of generation of rotational acceleration cues tends to displace gravitational force from the cabin vertical axis. Thus an unrealistic tendency to slide across the seat is perceived. This cue to the change in aircraft bank angle is unavailable in actual flight. Dependency by the simulator pilot on this cue for attitude information is unrealistic, and less positive transfer to the aircraft may result.

The most realistic simulation of airplane motion cues resulting from turns is provided by "washout" roll motion. By introducing roll acceleration cues via simulator cab tilt, the sensations accompanying initation of turns are provided. As the simulated airplane assumes a steady state of bank, the cab is returned gently to horizontal with subliminal acceleration. In this way, the side forces are avoided during sustained banked attitudes. However, because linear accelerations of the magnitude experienced in flight can only be generated by translation through great distances, and even by this means such accelerations can be sustained only briefly, washout motion systems, at best, provide imperfect representations of the flight environment.

An interesting new method for the presentation of acceleration related cues to simulator pilots makes use of a form fitted pressure suit and the so-called 'G seat'. The subject wears an inflatable rubber flight suit. The suit can be made to exert pressure on the arms and legs by selective inflation under control of a computer. During periods of simulated high acceleration, the subject's body is squeezed by this technique to create the subjective impression of whole body response to high acceleration. At the same time, the segmented inflatable seat cushion built into the pilot's seat can be differentially inflated to simulate force and acceleration cues. These devices have received favorable evaluations where tested, and are under consideration for augmentation if not replacement of motion cue generation systems.

Simulator Cockpit Motion, Performance, and the Transfer of Training

Adams (1957) identified three primary application areas for flight simulators: research, evaluation of performance, and training. Recent research has demonstrated that simulator motion cue structure is a determining factor of pilot performance in simulators in each of these applications. Ince, Williges, and Roscoe (1975) compared flight attitude displays in a simulator under three motion conditions. Overall performances in the simulator under washout banking and sustained pitching motion were reliably better and more representative of actual flight performance than performance without motion cues. The order of merit of the experimental displays, in terms of disturbed attitude tracking performances, also corresponded most closely to their order of merit in flight when the simulator was operated with washout motion, thereby clarifying earlier findings by Jacobs, Williges, and Roscoe (1973).

However, recoveries from unknown attitudes incurred fewest control reversals when subjects had the benefit of the gravitational cues of absolute attitude afforded by the sustained banking and pitching mode. An intermediate frequency of reversals occurred with no motion, and the highest frequency with washout motion, which corresponded most closely with the acceleration cue structure encountered in flight. Furthermore, the high reversal frequency associated with washout motion corresponded most closely with the frequency of reversals in flight.

The first experiment bearing directly upon the transfer of training from a simulator to an airplane as a function of the kind of simulator cockpit motion was recently conducted for an entirely different purpose;

the apparent finding of differential transfer was incidental but nonetheless historic. Major Jefferson Koonce (1974), USAF, was concerned with the reliability of instrument flight checks given in a modified Singer-Link GAT-2 simulator and their predictive validity to performance in a Piper Aztec airplane. Independent groups of 30 instrument pilots were tested on Day 1 and Day 2 in the simulator and then on Day 3 in the airplane with the results shown in Figure 2.

The three groups of pilots were treated identically except that one group was tested in the simulator with the cockpit motion system turned off; for the second group, the motion system of the GAT-2 was operated with its normal sustained banking and pitching; for the third group, the motion system was modified to provide subliminal washout of banked attitudes during turns. An experimenter in the right seat and a second observer in the rear seat (both in the simulator and in the airplane) scored each subject's performances independently to allow calculation of reliability and validity coefficients, all of which were quite high.

Group performances revealed the usual finding that either type of cockpit motion makes a simulator easier to fly as indicated by the successively better flight check scores by the sustained motion group and the washout motion group. Clearly, pilots make use of whatever cockpit motion cues are provided in a simulator. Furthermore, the two closely spaced flight checks of approximately 1.5 hours each resulted in statistically reliable improvement by all groups from Day 1 to Day 2, indicating that the flight check performances of all were refreshed by practice in the simulator ($p < .001$).

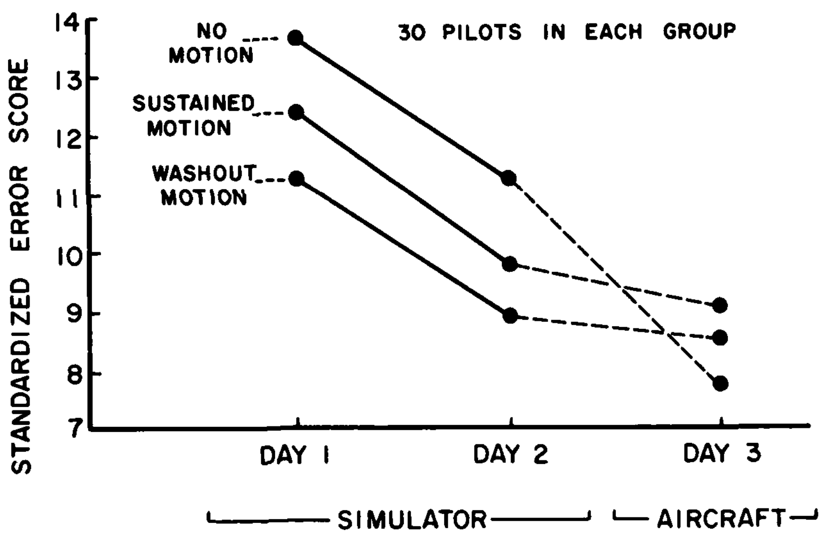

Figure 2. Transfer of refreshment of instrument skills in a Singer-Link GAT-2 to flight check performances in a Piper Aztec airplane.

In the transition to the aircraft on Day 3, a remarkable turnabout occurred. There was a statistically reliable interaction between group performances in the simulator and in the airplane as a function of the presence and type of cockpit motion in the simulator ($p < .001$). All groups showed further improvement on Day 3 in the air, indicating either that it is easier to fly the airplane or that there was transfer from the three hours of refreshment in the simulator during Days 1 and 2. However, the reliably disproportionate improvement by the group tested with no cockpit motion in the simulator strongly suggests differential transfer.

PROBLEM

Any of three possible explanations, or some combination thereof, may account for Koonce's unprecedented finding. Because the differences among group performances observed in flight fell short of accepted statistical reliability ($.10 > p > .05$), they may have occurred by chance, and the reliable interaction between performances in the simulator and in flight could reflect only the differential difficulty of flying the simulator with and without motion. Alternatively, differential transfer may indeed have occurred, in which case the apparently greater transfer from fixed-base simulator training might be uniquely associated with the refreshment of instrument flight skills, or it might reflect a general training benefit.

In each example, performance differences between groups of subjects operating the simulator with washout motion and those operating the simulator without motion suggest that motion-aided subjects achieve better performance in the simulator. Holding (1965) distinguishes between "learning feedback" and "action feedback" in the learning process. He concludes that the "intrinsic, concurrent, and immediate" nature of such cues as motion feedback of control inputs facilitates performance more than it facilitates learning. Certainly cockpit motion provides acceleration cues useful to the student in his performance of practice tasks, but do these cues improve transfer?

Koonce's experiment dealt with the refreshment of the instrument flight skills of experienced pilots in various states of currency and non-currency. It has been speculated by many that the effects of cockpit motion interact with pilot experience level. More specifically, some believe that faithful cockpit motion is more important for experienced pilots (Briggs and Weiner, 1957; Flexman, 1966), while others have suggested that motion combined with contact cues is more important during the initial stages of learning (Muckler, Nygaard, O'Kelly, and Williams, 1959).

Koonce found motion cue structure to be an important performance determinant for pilots with considerable experience in both flight and simulators with cockpit motion characteristics other than those in which they were tested. Such experience may have cause differential habit interference among his subjects. To provide comparative data at the lower extreme of flight experience, and thereby avoid markedly differential habit interference, original learning by flight-naive students was investigated as a function of simulator cockpit motion conditions.

The present experiment addressed two issues:

1. Whether simulator cockpit motion facilitates transfer of basic flight skills during initial pilot training,
2. Whether cockpit motion cues play a directing or merely an alerting role in training student pilots to cope with the visual and vestibular cue conflicts encountered in flight.

To resolve the first issue, one group of student pilots received simulator training with normal washout cockpit banking motion, and a second group was trained with no cockpit motion. To resolve the second issue, a hybrid, directionally random, washout banking motion group was included. In each case, pitch attitudes were presented by sustained motion. After completing a fixed schedule of practice in the simulator, each group commenced an aircraft training sequence during which performance was carefully monitored. A control group received all training in flight.

Although suprathreshold angular accelerations provide both alerting and directing cues, it has been speculated by many that it is the alerting function that makes moving-cockpit simulators easier to fly than their fixed-base counterparts. By retaining the alerting cues from the onset of motion but making the direction of roll acceleration an undependable cue, the beginning pilot might be taught to depend more completely on flight instruments as he must learn to do in the air.

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METHOD OF INVESTIGATION

When attempting to quantify the effects of external influences on the rate of acquisition of complex skills such as flying an airplane, the researcher must not overlook internal differences among subjects which may also affect this rate. Most important among possible differences of this sort is the subject's aptitude to learn the skill. Whether the result of variation in inate ability or differential experience with similar skilled operations, aptitude differences across the subject population increase the variability of the dependent measures. If not accounted for, this increase can only dilute the apparent strength of the effects of independent variables of interest.

Traditionally, investigations of the transfer among similar complex skills have dealt with this problem by random assignment of subjects to treatment conditions and by using sufficient numbers of subjects within each treatment condition to equalize the average aptitudes of treatment groups to an acceptable degree. Even when this is accomplished however, the typically wide range of aptitudes within groups is reflected by wide variation in individual learning rates, rendering the differences among experimental treatments less conspicuous statistically.

A more sensible approach is to accept the existence of aptitude differences among subjects and attempt to neutralize the effects of these differences by approximating and removing the variance they create. This implies the ability to measure the aptitude by some independent and objective means, and to the extent that this aptitude estimator is in error, the efficiency of the variance removal process suffers. However, even an imperfectly correlating measure increases the discriminating power of statistical analyses. A statistical procedure that allocates dependent variable variation to treatment effect versus subject sources is the analysis of covariance as described by Tatsuoka (1971). That procedure was adopted for the present research.

Aptitude Estimator Measure

The problem of developing a valid aptitude estimating measure for basic flight students has, fortunately, received considerable research attention. Recently, Gopher and North (1974) have developed a system for measuring time-sharing abilities as reflected by concurrent task performances. Using an adaptive compensatory tracking task and a digit cancelling task both singly and in combination, Gopher and North tested a large number of students in the University of Illinois' primary flight training course. A number of measures reflecting individual and combined task performances were compared with student performances in the flight course as rated by their individual flight instructors.

Four measures that jointly accounted for a large proportion of the rating variance were selected as components of an aptitude measure for the present study. Single task performance in the component tasks, as measured by acceleration percentage in the adaptive tracking dynamics and digit processing latency, were used along with proportions of tracking accuracy and correct digit response interval maintained during concurrent performance of the two tasks. Subjects for the present study were tested, and their scores standardized against the population used in the task development. The standard scores were then added to produce a combined aptitude estimator for use in the subsequent analysis.

Subjects

Flight naive students were solicited by means of an advertisement in the Daily Illini, the campus newspaper. To obtain research findings that might apply to the military flight training process, subject selection criteria were designed to yield students representative of Air Force undergraduate pilot trainees. From approximately 500 applicants, a subject pool of 100 males between the ages of 18 and 26 was selected, with no previous experience in controlling airplanes and sufficient interest and availability to contribute the required time and effort.

Flight experience backgrounds were verified by checking subject names and addresses against FAA listings of flight certificate applicants. None of the selected individuals had ever applied for a student pilot license, a step normally undertaken prior to formal flight instruction. Each subject selected for participation in the study was required to obtain a third class FAA medical certificate and student pilot license. These could be obtained only by passing a medical examination administered by an FAA designated flight surgeon.

Experimental Group Assignment Strategy

The four experimental groups were formed by assignment of subjects as needed to keep a running average of the group aptitude estimator scores approximately equal. Although not a random assignment technique, the approach was justified by the long duration of the data collection which precluded assignment of all subjects from those in the initial pool. A period of over 18 months elapsed between the commencement of flight instruction and the achievement of criterion performance by the last subject tested. This occurred because of the limited capacity of the program for concurrent training of students. Many potential subjects who professed availability at the beginning of that period found that demands upon their time had changed and precluded participation as the experiment progressed. A running subject selection strategy proved to be necessary.

Assignments were made to maintain approximately equal numbers of subjects active in the various experimental groups as the training progressed. Delays and disruption of training due to bad weather and equipment breakdown could not be predicted or controlled, nor could their possible differential effects upon transfer be assessed. Balancing numbers of participants from treatment groups in training at a given time tended to subject them to these influences to an approximately equal degree and thus to leave experimental measures minimally disturbed.

An examination of the distribution of aptitude predictor component measures by means of a discriminant analysis among treatment groups, as finally constituted, failed to show any reliable difference among groups either for individual measures or the linear combination of the four component scores (Bartlett's $\chi^2 = 16.925$, $\underline{df} = 21$). Selection of the more apt among potential subjects as being more representative of military pilot trainees (and also for the practical purpose of completing the experimental program at minimum cost and with least risk of having a subject fail to achieve criterion performance) tended to displace the aptitude estimator scores of all groups in the positive direction from zero. Group aptitude predictor statistics are presented in Table 1.

Equipment

The transfer study was conceived to evaluate the benefit of simulator practice upon subsequent aircraft criterion learning for various conditions of simulator motion fidelity. A Singer-Link GAT-2 twin-engine aircraft training simulator (see Figure 3) was modified to:

1. provide the motion conditions of interest,
2. provide a faithful representation of the handling qualities and procedural characteristics of the aircraft used for the transfer task.

The fixed-base condition was simulated by simply leaving the motion generation system inoperative during the simulated flight. The design of the simulator is such that instrument indications and control dynamics are provided by motion-independent computation; thus, except for the physical motion of the simulator, all groups were furnished with equivalent flight cues.

Washout motion was created by making the simulator cab's roll accelerations proportional to the simulated aircraft roll accelerations within the acceleration limits of the motion base. The initiation of a turn caused the cab to tilt in the direction of turn. Once a steady state of turn was achieved, and a constant bank angle maintained, the cab was brought back to a level condition with roll accelerations below the pilot's threshold of perception. Rolling out of the turn to simulated straight flight was conveyed by a bank in the opposite direction, then a

TABLE 1

Aptitude Predictor Component Data

TREATMENT GROUP	SUBJECT RANK 1	2	3	4	5	6	7	8	9	M	σ
AIRCRAFT (1)											
ACC%	.849	-2.708	.198	.135	-1.073	- .344	.693	- .917	- .219	- .376	1.088
D. L.	1.133	1.035	-4.685	- .168	.965	- .364	.741	- .056	.042	- .151	1.794
P (T)	.628	.637	2.936	1.066	.096	.371	- .766	- .710	- .578	.409	1.152
P (CRI)	.159	1.220	2.355	- .608	- .138	- .320	-1.543	- .050	-1.453	- .042	1.226
TOT	2.769	.814	.804	.424	- .150	- .656	- .875	-1.732	-2.207	- .090	1.507
WASHOUT MOTION (2)											
ACC%	1.370	1.230	- .719	1.370	- .266	- .234	.964	.063	.891	.519	.807
D. L.	.545	.910	.196	-1.133	.323	.476	-1.524	.392	.797	.109	.850
P (T)	1.181	.638	1.415	1.170	- .096	- .140	.814	- .957	- .138	.432	.800
P (CRI)	.196	-1.094	.761	- .167	.754	.408	- .263	- .659	- .101	- .018	.621
TOT	3.292	1.684	1.653	1.240	.715	.509	- .009	-1.161	-1.501	.714	1.489
FIXED-BASE (3)											
ACC%	.391	.583	.839	- .443	.460	.443	1.100	- .708	- .766	.211	.680
D. L.	.140	- .294	.727	.629	.517	- .028	.224	1.483	.615	.446	.517
P (T)	1.330	1.426	- .617	1.362	.277	- .181	-1.043	- .447	- .862	.138	1.000
P (CRI)	.761	.232	.870	- .399	- .268	0.000	- .109	-1.609	- .746	- .141	.758
TOT	2.662	1.947	1.819	1.149	.986	.234	.172	-1.281	-1.759	.659	1.474

TABLE 1 (continued)

RANDOM WASHOUT MOTION (4)											
ACC%	.370	.135	.615	.505	1.359	.339	- .672	.073	.320	.338	.534
D. L.	1.497	.811	1.343	.769	.909	.098	.741	-2.168	-1.566	.270	1.283
P (T)	- .032	2.489	-1.064	1.351	- .979	- .415	1.819	.885	- .404	.406	1.278
P (CRI)	1.065	- .232	.768	-1.297	- .348	.906	-1.790	.420	.355	.430	1.08
TOT	3.900	3.302	1.662	1.328	.941	.928	.098	- .290	-1.795	1.119	1.747
Aptitude Predictor Composite (Across all groups)										.6004	1.5545

KEY:

ACC% is the standardized proportion of acceleration to rate dynamics in the adaptive tracking task.

D.L. is the digit cancelling latency observed during single-task performance of that task.

P(T) is the proportionate RMS tracking error maintained from single-task to dual-task performance.

P(CRI) is the proportionate correct digit-cancelling response interval maintained from single-task to dual-task performance.

Figure 3. GAT-2 simulator in which students in the three experimental groups performed fixed numbers of trials on the various practice tasks.

Figure 4. Piper PA 28 R-200 Cherokee Arrow in which all students were trained to criterion performance levels on the transfer tasks in flight.

sub-threshold return of the cab to a level attitude as the simulated flight attitude stabilized once again.

Random washout motion was generated in a similar fashion except that when the simulated flight roll attitude remained close to level for a short time, the momentary value of the output of a random noise source was compared to a threshold value to determine whether the cockpit motion for the following turn would be in the direction corresponding to or opposed to the direction of the turn. Thus, the direction of cockpit rolling motions was random, but their amplitudes and onset dynamics were the same as in the conventional washout condition.

Simulator dynamics were adjusted to approximate the handling characteristics of the counterpart aircraft as judged by several flight instructors with experience in that aircraft. Although the Singer-Link GAT-2 simulates a light twin-engined airplane, the paired engine controls were mechanically linked and one set of engine instrumentation masked for the purpose of preserving procedural commonality. Power sensitivity of the simulated engines was adjusted so that equivalent power settings in the simulator and aircraft produced similar performance. Control response of the simulator was considered to be representative of the aircraft with the exception of the pitch trim, which was overly sensitive in the simulator, and could not be adjusted to a sufficient degree. Motion cues were realistic within the limitations of the simulator's capabilities, as presented in Table 2.

TABLE 2

Singer-Link GAT-2 Limits of Motion System Capability

Axis	Position	Velocity	Acceleration
Pitch	-13^{o} to $+8^{o}$	$\pm 13^{o}$/sec	$\pm 100^{o}/sec^{2}$
Roll	$\pm 13^{o}$	$\pm 25^{o}$/sec	$\pm 300^{o}/sec^{2}$
Vertical Translation (at pilot's seat)	+7.16 to -4.36"	±7.16"/sec	±0.6g

The aircraft used for the transfer learning was a Piper PA-28R-200 Cherokee Arrow (see Figure 4). It is a four-place single-engine medium performance light aircraft with retractable landing gear and a constant speed propeller. It is powered by a 200 horsepower fuel-injected Lycoming engine and is equipped with operable wing flaps. As defined by the Federal Air Regulations, Part 61, the airplane is classed as a complex aircraft. Although not typical of primary training aircraft employed in the general aviation sector, the Arrow may be taken as representative of basic military training vehicles such as the twin-jet Cessna T-37 in terms of operational complexity. For this reason and because the aircraft provided greater flexibility in power and drag configuration, which jointly alter handling qualities and increase the procedural/cognitive components of the flight tasks to be learned, the Arrow was chosen in preference to a more typical civilian primary flight trainer.

An audio intercom system was installed to facilitate communication in the cabin in the presence of engine noise and the replay of audio instructional cassette tapes to the student while in flight. The system provided three headset outputs, one each for the student, the experimenter in the right front seat, and the observer in the rear. Both the student and experimenter were provided with microphones; the observer was not. Only the experimenter's microphone could be used for radio transmission. Switching capability was provided to enable the experimenter to speak to the observer privately.

Experimenters and Observers

Eleven Institute of Aviation staff members served as experimenters or observers. All were licensed flight instructors. The five experimenters were Aviation Research Laboratory staff members with extensive flight instructional experience. Experimenters were responsible for the administration and conduct of the individual instructional sessions and also scored student performances, as was done independently by the flight observers. The experimenters gave the students practice directions and narrated required demonstrations through the intercom set. All landings and extra-curricular flight segments were made by the experimenters who also navigated, handled communications with air traffic control, and watched for and avoided other airplanes.

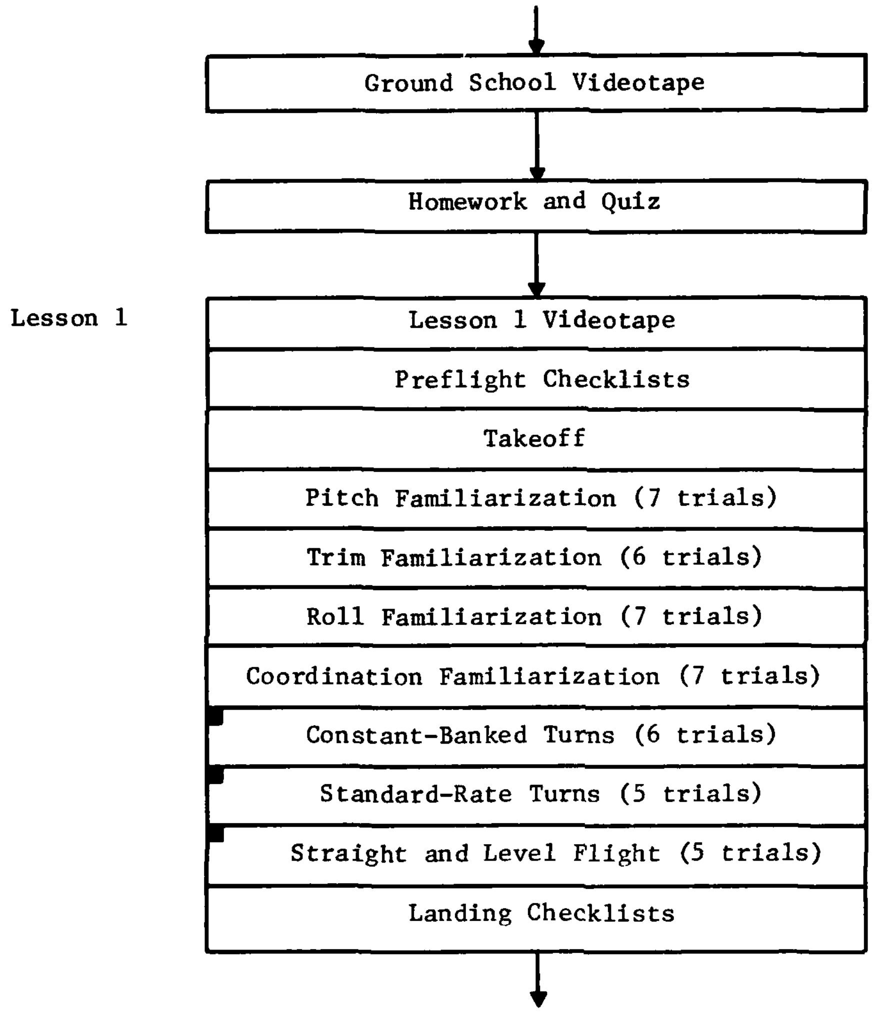
Experimenters and flight observers were familiarized with the curriculum and scoring system as part of a training sequence. Each experiementer was given the opportunity to act as a student for selected segments of the curriculum and to learn all maneuvers that required demonstration according to standardized procedures. Observers were required to act as third scorers for several flights with an experienced observer prior to assumption of flight observer duties. During this time, they accustomed themselves to the performance scoring techniques used and were encouraged to ask questions to resolve any interpretation problems.

Curriculum

The decision to investigate initial learning to avoid the bias introduced by uncontrolled prior exposure to aircraft motion cues constrained the training exercises to basic maneuvers appropriate to beginning flight students. The objective in the selection of training exercises was to develop a sequence of challenging but achievable tasks that could be taught using a building-block teaching strategy and that sampled a broad range of skills required of the private pilot. The FAA's building-block approach to flight instruction involves the sequential introduction of new and slightly more complex practice exercises as the student masters each in turn. The exercises should be sequenced in such a way that the transfer of learning from one exercise to the following one is reasonably high; thus each new task taxes the student's capabilities, but he has a background of skills to facilitate its rapid mastery.

A sequence of 11 maneuvers, along with supplementary introductory and review exercises, was abstracted from the primary flight training course at the University of Illinois' Institute of Aviation. The sequence used in both the simulator and the airplane is shown in Figure 5.

Simulator trained groups were exposed to the entire curriculum in the GAT-2 prior to beginning practice in the airplane. Progression in the simulator was based strictly upon completion of a predetermined number of trials for each maneuver and was independent of performance observed; thus, all simulator students practiced virtually equal amounts on any given maneuver in the simulator. Consequently, differences in transfer performances would depend only upon the transfer effectiveness of the different practice environments. Since these environments



■ symbol denotes those exercises practiced to criterion performance level in the aircraft

Figure 5. Curricular task sequence.

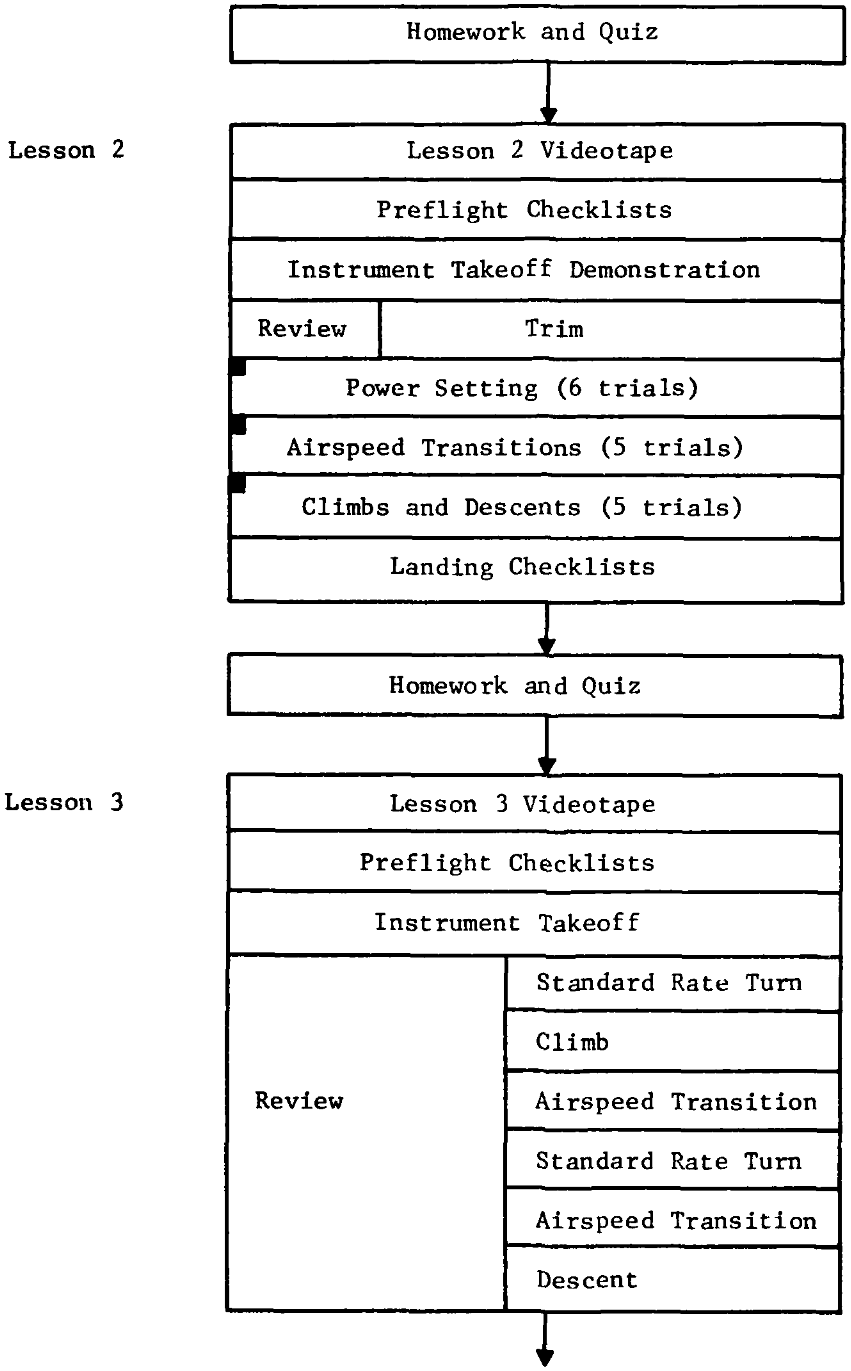


Figure 5 (continued)

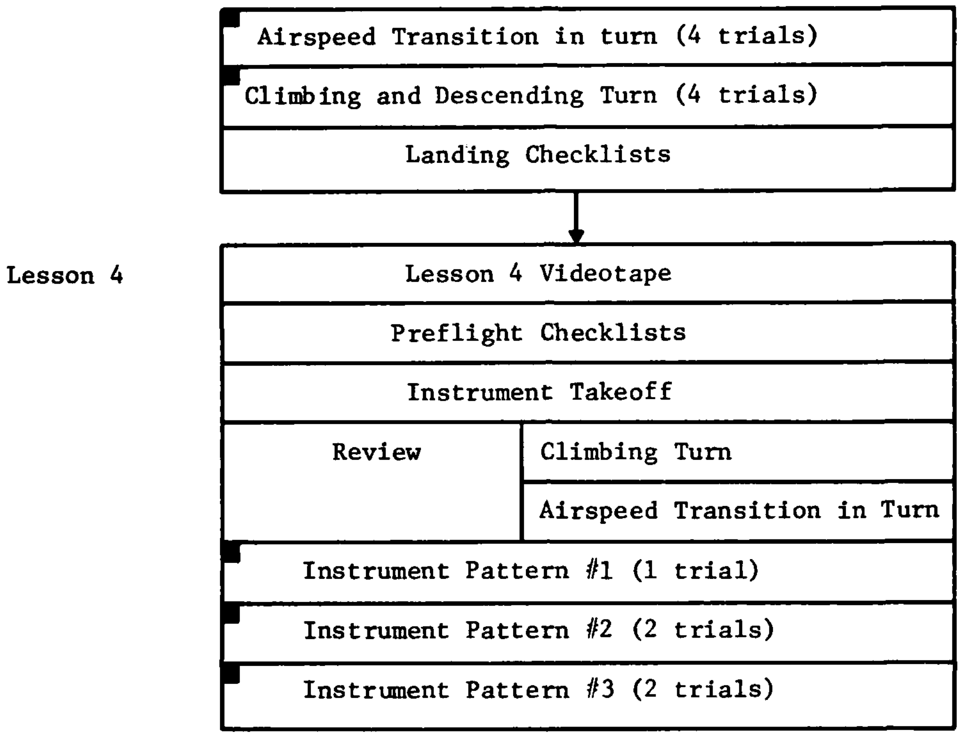


Figure 5 (continued)

differed only in terms of motion cue structure, differences in student skill level induced by differences in cockpit motion fidelity would be brought to the airplane.

The instructional sequence was divided into four 'lessons' by the introduction of major new skill components at three points. The first lesson was concerned with developing an understanding of and skill at basic aircraft attitude control. Independent pitch, pitch trim, roll, and yaw (coordination) exercises were given to familiarize the student with aircraft control response. The student was required to maintain an assigned bank angle through a given heading change while maintaining altitude by pitch control. Following this, standard rate turns were introduced which were simply constant-bank turns at a specific bank angle that produced a 3^{o} per second heading change. The maintenance of a standard rate of turn requires attention to the rate of turn indicator in addition to the gyro-horizon instrument and thus forces a faster and more efficient instrument scan. Straight and level flight is simply the maintenance of heading and altitude by noting and compensating for errors on the flight instruments.

Each of the exercises in the first lesson group was performed at cruise power setting and therefore at nearly constant airspeed when altitude was properly maintained. The handling qualities of the aircraft change markedly with changes in airspeed; thus, practice at various airspeeds is an important part of learning to control the airplane. Further, power adjustments, as required either for changes in speed while in level flight or for climbs and descents, are made according to a set of procedural rules. Thus the concurrent manipulation of power and aircraft attitude brings cognitive/procedural skill components to the flight task.

The introduction of power management was the objective of the exercises in the second lesson. Following a brief review of lesson one maneuvers, power changes during straight and level flight were made. These required that the student set certain memorized combinations of RPM and manifold pressure while maintaining heading and altitude and retrimming in pitch to stabilize the aircraft. Changes in power of this type produce changes in airspeed. The second criterion exercise of the lesson involved selective power changes and landing gear and wing flap extensions and retractions according to prescribed procedures while seeking to stabilize the aircraft at assigned airspeeds and on the assigned heading and altitude. Finally, changes in altitude while maintaining heading were introduced through climbing and descending flight. These are both highly procedural and involve standardized power manipulations.

During the third lesson, students were asked to make specified changes in heading, airspeed, and altitude with specified concurrent changes in landing gear and wing flap positions with appropriate compensations in power. These exercises demanded a more efficient instrument scan, greater memory span, and more rapid performance of procedures for successful accomplishment.

To the basic flight management skills introduced in the previous lessons, the fourth lesson added navigation, orientation, and additional memory burdens to the student's workload. Three instrument navigation practice patterns of increasing complexity were assigned in sequence. These patterns required the students to conceptualize the position of the aircraft along a memorized closed course composed of straight and level and level turning segments. The lengths of the straight and level portions of the patterns were defined by the passage of one minute of flight, thereby introducing the element of timing. Turning segments were defined in terms of magnitude and direction of turn, requiring the student to perform mental arithmetic to determine desired headings at the end of the turns.

The instrument navigation practice patterns were all variations of the closed course depicted in Figure 6. In each case, the straight segments were flown on cardinal compass headings starting with East, and the sequence of turns was invariant, starting with a 90° turn to the left, then a 270° turn to the right, a second 90° turn to the left, and finishing with another 270° turn to the right. All turns were to be made at a constant altitude and a standard rate of 3° of heading change per second. In each case the pattern required 8 minutes to complete.

The first practice pattern consisted of simply navigating around the course while maintaining altitude. Next, the student was asked to repeat the pattern with a transition from cruise to approach configuration at point B, and a transition back to cruise configuration at point D. These transitions involve changes in power setting, airspeed, landing gear and flap positions, and pitch trim setting. Pattern three was

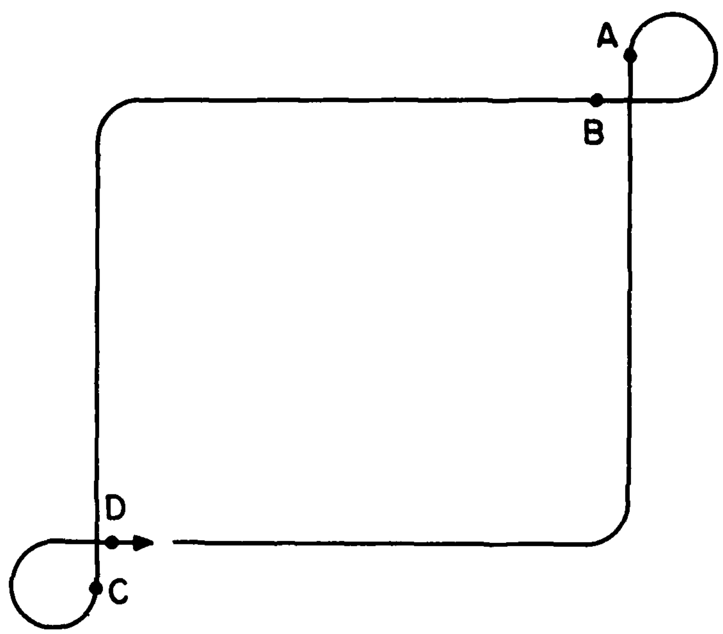


Figure 6. Instrument navigation practice pattern.

similar but required that the transitions be made at points A and C, in the turns. Satisfactory performance in flight consisted of two sequential executions of each pattern with 3 or fewer errors.

Instructional Approach

A source of variation in flight training effectiveness is instructor technique, and a number of individuals were necessarily involved as experimenters. To avoid contaminating student learning rates by the effect of possible differences in instructional skill among these individuals, the instruction was automated. Prior to the first simulator or aircraft flight, the student was shown a videotape presentation that explained basic aeronautical principles. At that time, a textbook of aviation fundamentals was given to the subject, and assignments that included reading and written response questions were distributed. A supplemental handout described the objectives of each maneuver and required techniques of performance.

At the beginning of each of the four lessons, students were shown additional videotaped material introducing the maneuvers to be covered during the lesson. A quiz was administered prior to each of the first three lessons to establish that the student properly understood the taped instructional materials prior to practice in the simulator or the airplane, as appropriate. Failure to achieve a satisfactory score on the quiz required remedial study before proceeding.

During the practice flights in both the simulator and the aircraft, the student received instruction from audio cassette tapes. These tapes reviewed performance procedures for each exercise in detail prior to practice. The experimenter assigned practice trials individually by reading prepared instructions printed in the scoring booklet. These instructions could not be presented by the audio cassette because of the need for flexibility in headings and altitudes used due to changing weather conditions. Experimenters were restricted from suggesting how student performance could be improved from trial to trial other than to point out in the most general sense the nature of the student's failure to meet performance standards. "You failed to maintain your assigned altitude" would be permissible, as an example. Experimenters were not permitted to discuss performance during the practice trial.

This open-loop instructional technique involved a tutorial compromise in that students were denied normal instructional guidance to maximize the rate of learning, but that was not the objective here. The purpose was to provide each student with an equivalent instructor interface regardless of experimental group, student aptitude, or experimental personnel aboard at the moment. By employing this open-loop procedure, inherent differences in the training effectiveness of the different types of cockpit motion could not be compensated for and thereby masked by differential instructional remediation.

Students wore instrument hoods in the aircraft at all times during lessons. These are devices that restrict the student's vision to the aircraft instrument panel, obscuring his view through the cabin windows. The instrument hood guarantees that all attitude information is being abstracted from the aircraft instruments as must be accomplished in the simulator; thus, the simulator and aircraft training tasks involved close stimulus correspondence in the presentation of flight information.

Performance Scoring

Student practice maneuvers were scored independently by the experimenter and the rear-seat observer. Performance criteria for each maneuver were abstracted from published Federal Aviation Administration private pilot flight check standards. These error tolerances are presented in Table 3. The recording of student performance consisted of noting violations of these tolerances or of specified procedures at predetermined points in each maneuver. Each such event constituted an "error." While failing to distinguish between smooth steady performance and erratic performance which happens to fall within limits at the scoring points, this method imposes a manageable workload on scoring personnel and provides an objective framework for scoring compared with a necessarily more subjective continuous scoring strategy.

Each curricular maneuver was assigned an error budget. Student performance within that budget was the behavioral criterion that indicated readiness to progress to the next maneuver in sequence in the aircraft. Table 4 presents the allowable error for each of the maneuvers in the curriculum. In the simulator, although error scores were recorded, advancement from one exercise to the next was based solely on the number of practice trials as has been noted.

Experimenter and observer scoring records were kept independently; however, some coordination was required to confirm that both scorers observed that criterion performance had or had not occurred. After each

TABLE 3

Performance Standards for Various Exercises

Error Type	Standard for Correct Performance
Checklist Procedure	No deviation from checklist provided
Bank Angle	Assigned angle $\pm 10^{\circ}$
Coordination	Turn and bank ball centered $\pm$ 1/2 ball width
Altitude	Assigned altitude $\pm$ 100 feet
Heading in Flight	Assigned or appropriate heading $\pm 10^{\circ}$
Heading on Ground	Assigned or appropriate heading $\pm 5^{\circ}$
Turn Rate	Standard rate of turn $\pm$ 1/2 turn needle width
Power Setting Procedure	No deviation from prescribed procedure
Airspeed	Assigned or prescribed airspeed $\pm$ 10 mph
Pitch/Power Sequence	No deviation from prescribed procedure
Parking Brake Release	Not omitted
Power Application Technique	No deviation from prescribed procedure
Rotation Speed on Takeoff	80 mph $\pm$ 5 mph
Pitch Attitude After Takeoff	3 horizon bar widths up $\pm$ 2 bar widths
Trim Setting	"Hands-off" level flight
Landing Gear Retraction Altitude	950 feet $\pm$ 150 feet
Climb Power Setting Altitude	1150 feet $\pm$ 200 feet
Fuel Pump Operation	Not omitted
Timing During Instrument Patterns	1 minute legs $\pm$ 20 seconds
Orientation in Patterns	No incorrect turns
Destination Altitude After Climbs/ Descents	Assigned destination altitude $\pm$ 100 feet

TABLE 4

Allowable Error Budget for Criterion Maneuvers

Maneuver	Criterion Performance Standard
Constant Bank Angle Turn	Two successive error-free trials
Standard Rate Turns	Two successive error-free trials
Straight and Level Flight	Two successive error-free trials
Straight and Level Power Changes	Two successive error-free trials
Straight and Level Airspeed Transitions	Two successive error-free trials
Climbs and Descents	Two successive error-free trials
Airspeed Transitions During Turns	Two successive trials with one error or less each
Climbing and Descending Turns	Two successive trials with one error or less each
Instrument Navigation Pattern I	Two successive trials with three errors or less each
Instrument Navigation Pattern II	Two successive trials with three errors or less each
Instrument Navigation Pattern III	Two successive trials with three errors or less each

trial on which the experimenter judged performance to be within the allowable error tolerance, he would glance back toward the flight observer. The flight observer would signal his vote using silent hand signals.

A performance recording system was devised to preserve error by trial information. Scoring booklets (see Appendix B) were used by the experimenter and the flight observer to record the date and duration of each actual or simulated flight and their independent scoring of a student's performances on each trial of each maneuver or procedure throughout training. The booklets contained error standards for each maneuver along with lesson sequence directions for the experimenter. A grid was printed beside each maneuver, with each box in the grid representing a particular error type made on a particular trial attempt. A mark in the box indicated that an error had occurred. A marking code was established that permitted up to five passes through the grid with distinctive notation for each pass. Details of this code are presented in Appendix C.

RESULTS

Almost incredibly, not one of the subjects who flew the simulator with randomly reversed banking direction commented on this characteristic during training, and when questioned specifically at the conclusion of simulator training, none could recall any instance in which the cockpit motion had seemed strange. No subject was told about the hybrid motion, or any other condition, either before simulator training or before proceeding from the simulator to the airplane, and care was taken to conceal the fact that the simulator was capable of motion from the fixed-base group. There was no indication at any time during the experiment that any subject realized that cockpit motion was an experimental variable.

Because the population distributions for such measures as time, number of trials, or number of errors made in performing a specific task are positive integers only, they are necessarily truncated at zero, and are therefore unsymmetrical. The application of statistical tests based upon the assumption of symmetrical population distributions to samples drawn from such distributions may be inappropriate. The transformation of the data prior to statistical analysis to produce a more symmetrical distribution is an accepted procedure that makes possible the use of such tests with less risk of misleading conclusions.

In the case of positively skewed population distributions, transforming the data by means of the substitution of the log of the sample values reduces the skewness and produces a more symmetrical sample distribution. Unfortunately, where a sample value of zero might be obtained, a simple log transformation cannot be applied because of the negatively infinite value of the log of zero. In such cases, the appropriate transformation to apply is the substitution of the log of 1 plus the sample value; a sample value of zero thus leading to a transformation of the log of 1 + 0 which equals 0. Thus, all tests for statistical reliability were applied to the transformed scores, and all graphs show the regression of transformed performance scores on aptitude predictor scores. However, to make the results more meaningful for the reader, tables of raw scores and raw scores adjusted for aptitude effects are given untransformed.

Simulator Training Performance

Because each transfer subject received a fixed and equal schedule of trials on maneuvers in the simulator, practice time was nearly invariant and the only measure reflecting differences in performance among transfer groups was error count. Table 5 presents actual and aptitude-adjusted time and error-count data for the simulator training sequence.

Figure 7 presents individual linear regression line fits for transformed total simulator times as a function of pilot aptitude for each experimental treatment group. An analysis of covariance failed to demonstrate reliable differences in the goodness-of-fit of the slopes or intercepts of these regression lines adjusted for aptitude effects (p_{slope} = .71; $p_{intercept}$ = .73). The negative slopes are indicative of a slight tendency for the more apt subjects to finish the simulator practice sequence more quickly than the less apt. However, the small absolute magnitude of the slopes (-0.0128, -0.0065, and -0.0062 for washout, no motion, and random washout motion groups respectively) suggests that this effect is not strong and that all subjects regardless of aptitude within each group tended to take approximately equal amounts of time to complete the practice tasks.

TABLE 5

Simulator Performance Data

Treatment Group	Average Simulator Time	Average Total Errors	Average Adjusted Simulator Time*	Average Adjusted Total Errors*
Washout Motion	442.2 min	95.5	441.6 min	95.5
No Motion	442.2 min	126.7	441.3 min	125.6
Random Washout Motion	428.6 min	118.4	430.3 min	120.9

*Adjusted to reflect group aptitude differences

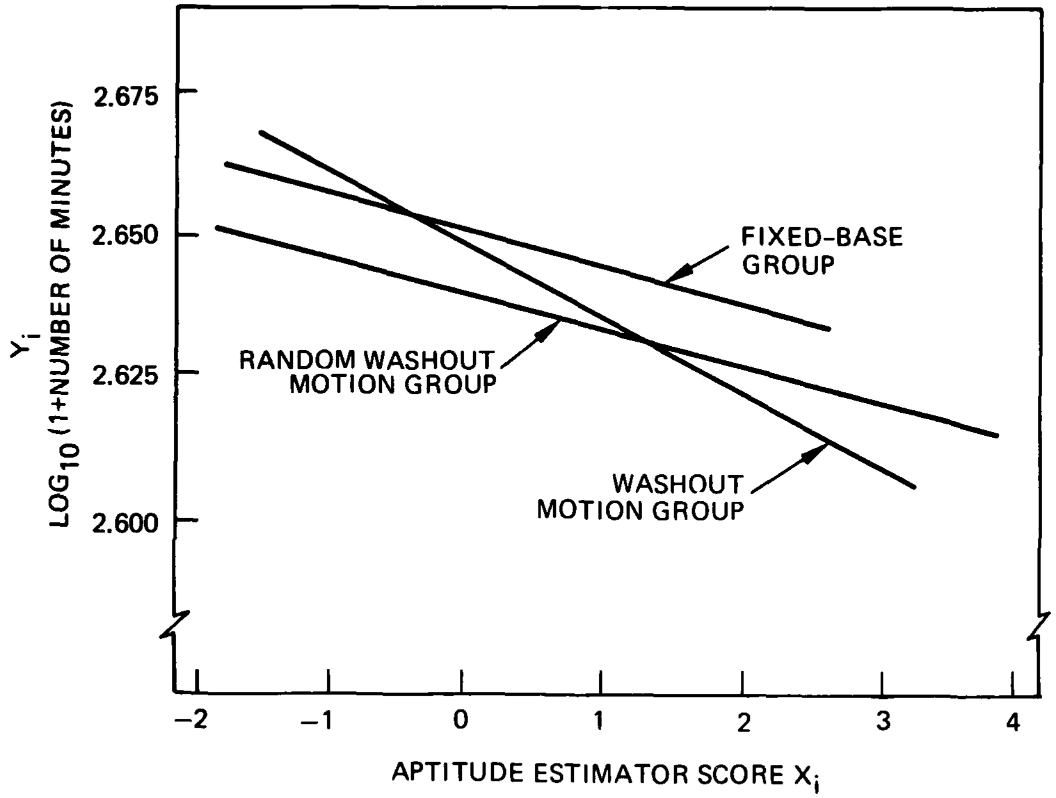


Figure 7. Regression lines showing best-fitting linear relationships between time required to complete simulator training sequence and aptitude predictor scores for independent groups of nine subjects in each of three experimental conditions.

A similar analysis of covariance to remove aptitude effects from the total simulator error count records was based upon the regression relationships shown in Figure 8. Although the three-way comparison showed no reliable difference, (p_{slope} = .82; $p_{intercept}$ = .16), paired comparisons yielded a reliable intercept difference between the washout motion and no motion groups, ($p_{intercept}$ = .02). The error total for the washout motion group, adjusted for aptitude differences, was lower than that of the random washout motion group, and lower by a reliable margin than the error total of the group trained without motion. The relatively flat slope of the regression line for the normal washout motion group suggests that, regardless of aptitude, these subjects tended to make small and equal numbers of errors during simulator practice compared with counterpart subjects in the other groups whose error frequencies showed greater dependence upon aptitude.

This difference in regression slopes between the washout motion group and the other two treatment groups might be interpreted as indicating that all subjects trained with normal washout motion advanced in transferable skills to the practical limit in the simulator prior to performance in the airplane, whereas students of decreasing aptitude in the random washout and fixed-base groups might have gained additional benefit from continued practice in the simulator. If subjects in the normal washout motion condition were to receive somewhat less practice in the simulator, their performances likewise might be expected to depend on aptitude. Furthermore, the more apt student would still be expected to gain maximum transfer benefit, and the less apt student would not.

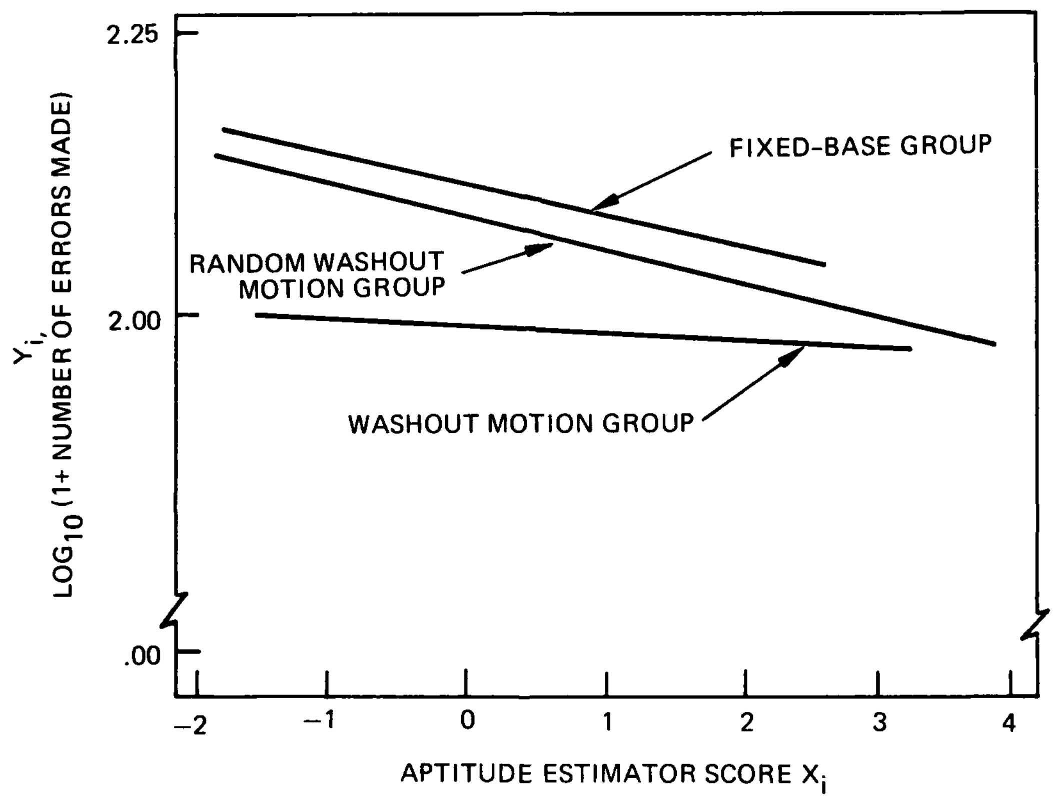


Figure 8. Regression lines showing best-fitting linear relationships between total errors made in the simulator and aptitude predictor score for independent groups of nine subjects in each of three experimental conditions.

Errors made in the simulator were analyzed by type and by maneuver to reveal patterns of occurrence. It might be expected that those flight skill components such as altitude and airspeed maintenance that are heavily dependent upon pitch control precision would show a strong reaction to the presence or absence of pitch motion cues. This relationship was evident in the comparison of washout motion and fixed-base group performances. Washout motion subjects made fewer altitude errors (33.6) than did the fixed-base trained subjects (43.1); the analysis of covariance showed this difference to be reliable ($p_{intercept} = .01$). Similarly, airspeed errors for the washout and non-moving simulator groups (0.67 and 12.90 respectively) were reliably different ($p_{intercept} = .007$). The presence or absence of pitch motion cues also produced a reliable difference in slope for the regression of frequency of takeoff pitch attitude errors on aptitude across all groups ($p_{slope} = .04$).

Although the normal-washout motion students made reliably fewer errors in airspeed and altitude, there is no indication that the lack of pitch motion caused the fixed-base group to make a greater proportion of its errors on pitch dependent skills. Airspeed and altitude errors constituted 43.1% of the errors made in the simulator by the normal-washout motion group and 45.3% of the errors made there by the fixed-base group.

With random washout motion, subjects made altitude and airspeed errors at a frequency between those of the normal washout and fixed-base groups and group performances did not differ reliably on either measure. The stability of these performance rankings suggests that performance for the random washout motion group suffered, although the nature of the pitch cues delivered by the simulator was identical for them in every respect to those provided by normal washout motion. Although unaware of the random nature of the roll motion cues with which they had to deal, it is apparent that these subjects, who made 43.9% of their errors in altitude or airspeed control, were affected in pitch performance by this difference in the total motion-cue environment.

For a number of tasks that are primarily procedural as opposed to perceptual-motor in nature, performance was observed to deteriorate under the fixed-base condition. Climb power setting altitude ($\underline{p}_{intercept}$ = .07), power setting procedure ($\underline{p}_{slope}$ = .04), and checklist ($\underline{p}_{slope}$ = .07) errors all were made in greater numbers by subjects trained under the fixed-base simulator condition. This may have occurred because attitude control for the fixed-base student is a more consuming activity, leaving less attention capacity for procedure recollection. Since the aptitude estimator used to adjust performance in this analysis reflects naive attention sharing capabilities directly, the evidence is strong that this systematic difference in total task performance must be related to the absence or presence and type of cockpit motion rather than to individual subject differences.

Errors observed in the simulator were analyzed as a function of maneuvers giving rise to them. The first curricular maneuver requiring students to control attitude with simultaneous attention to pitch, roll and yaw was the constant-banked turn. Washout motion students made fewer (72 vs 97) errors during practice of constant-banked turns than did the students without the benefit of motion cues, and this difference corrected for aptitude differences between the groups approached reliability ($\underline{p}_{intercept}$ = .07). When power management was added to the task of controlling attitude, this trend persisted.

An aptitude by performance interaction indicated by a reliable slope effect ($\underline{p}_{slope}$ = .03) for the three-way comparison of groups in the power-setting task was caused principally by the relatively uniform performance of the washout motion subjects regardless of aptitude while the fixed-base subjects tended to make more errors at lower aptitude levels, ($\underline{p}_{slope}$ = .008). Perhaps the students trained under the washout motion condition had sufficient environmental cues to perform the task acceptably well at all aptitude levels, while only the more apt among the fixed-base subjects were able to cope with the task without motion cues.

The trend of the students trained with washout motion to perform better than the fixed-base students continued to be evident in the simulator as the maneuver complexity was increased still further. When students were asked to perform airspeed transitions while making turns, washout motion students made a total of 68 errors while fixed-base students made 87 errors. Random-washout motion students erred 74 times. Corrected for aptitude, these scores were reliably different in the three-way comparison of groups ($\underline{p}_{slope}$ = .01; $\underline{p}_{intercept}$ = .04), and in the paired group comparisons of washout group versus fixed-base group ($\underline{p}_{slope}$ = .02; $\underline{p}_{intercept}$ = .02), and washout-motion group versus random-motion group, ($\underline{p}_{slope}$ = .01).

TABLE 6

Errors Made by Each Simulator Motion Group During Practice of the Three Instrument Pattern Maneuvers in the Simulator

Treatment Group	Instrument Pattern 1	Instrument Pattern 2	Instrument Pattern 3
Washout Motion	15	53	37
Fixed-Base	32	102	81
Random-Washout Motion	30	96	70

The addition of timing and orientation in the instrument pattern tasks produced similar results. Washout-motion students performed best, followed by random-washout motion students, who were followed in turn by the fixed-base students. Table 6 presents error totals for each of the motion groups in each of the three instrument practice pattern maneuvers. These scores, corrected for aptitude, show reliably better performances in the simulator by the washout motion group than by the fixed-base group on each of the three pattern exercises.

Transfer to the Airplane

Group means for practice time and trials prior to criterion performances and total error counts during the aircraft training sequence are presented by treatment group in Table 7. By any definition of the measure, it is clear that large positive transfer of training occurred as a result of the simulator practice.

Time to criterion scores. An analysis of covariance was performed to adjust for individual aptitude effects and to test for reliable differences in flight training time required for the 11 maneuvers. The basis for the analysis is the time required in practice exclusive of time spent in demonstrating that criterion skill had been achieved. The covariant relationship between practice times to achieve performance criteria and aptitude predictor scores for each treatment group is represented graphically in Figure 9 by the four regression lines.

Covariance analysis revealed highly reliable differences among intercepts for groups ($p_{intercept} = .005$). Pairwise comparisons showed reliable transfer to the airplane for normal-washout and

TABLE 7

Mean Times, Trials, and Errors to Reach Performance Criteria in the Airplane, Adjusted to Eliminate Individual Aptitude Effects, for a Control Group and Three Transfer Groups of Nine Subjects Each

	Control Group	Cockpit-Motion Transfer Group		
	Airplane Only	Normal Washout	Fixed Base	Random Washout
Time in min.	182.4	69.8	80.0	111.2
Trials	38.5	16.1	17.1	22.2
Errors	90.0	46.5	56.4	59.9

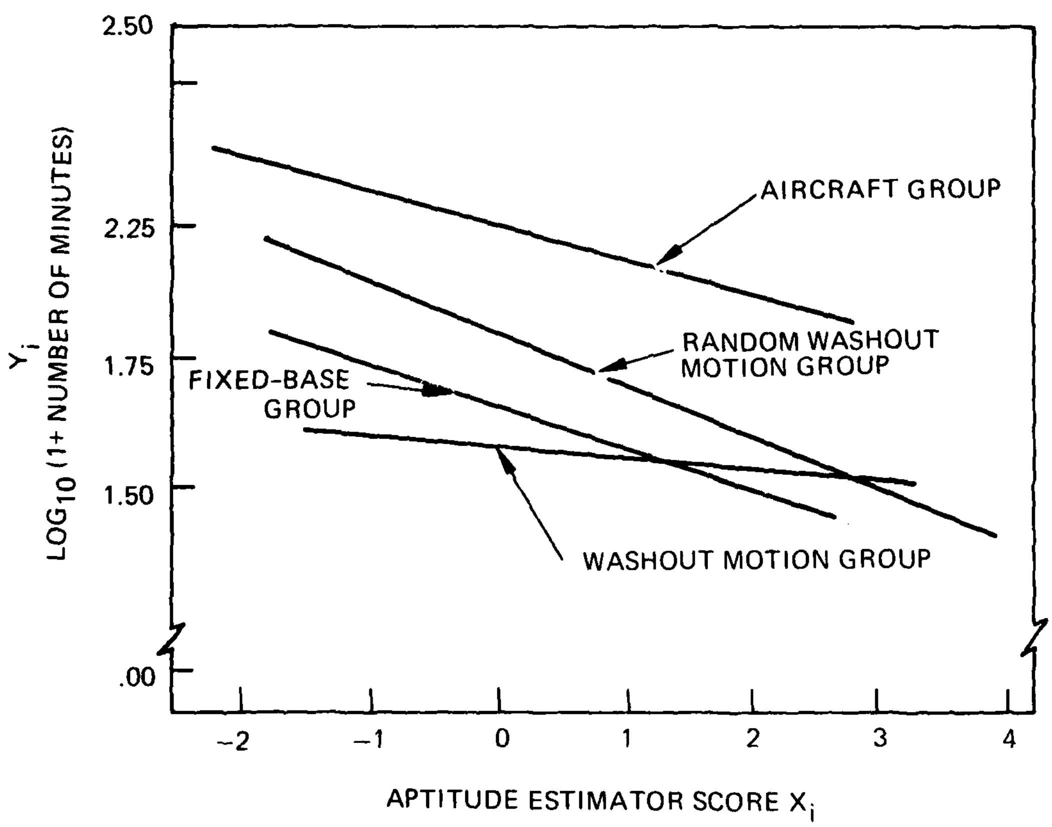


Figure 9. Best fitting linear relationships between flight time to performance criteria and aptitude scores.

fixed-base groups ($p_{intercept}$ = .001 and .005, respectively) while the random-washout motion group approached a reliable level of transfer ($p_{intercept}$ = .097). Transfer groups were not found to differ reliably from one another in time scores in the air. Transformed time to criterion scores were found to correlate reliably with the aptitude estimator measure ($r = -.404$, $p < .05$)

Trials to criterion. A similar highly reliable difference among groups was observed in the number of practice trials required prior to the demonstration of criterion performance ($p_{intercept}$ = .004). Each simulator treatment group differed reliably from the control group ($p_{intercept}$ = .003, .003, and .05 for normal-washout, fixed-base, and random-washout motion conditions respectively). Furthermore, there was a reliable difference in the lack-of-fit to a common slope of the regression lines between trials and predictor scores for the normal-washout and fixed-base treatment groups (p_{slope} = .04). Figure 10 presents regression lines for trials prior to achieving criterion performance as a function of subject aptitude predictor scores for each of the four treatment groups. The correlation between the transformed number of trials to criterion and the aptitude estimator measure was equal to -.445 which was reliable ($p < .01$).

Errors in the airplane. The covariation between error frequencies in flight (including those errors made during review and criterion trials and those made during practice on maneuvers prior to criterion performances) and the aptitude predictor scores for subjects in each group are presented in Figure 11.

Analysis of the covariance between total error counts and aptitude predictor scores showed reliable overall transfer ($p_{intercept}$ = .02).

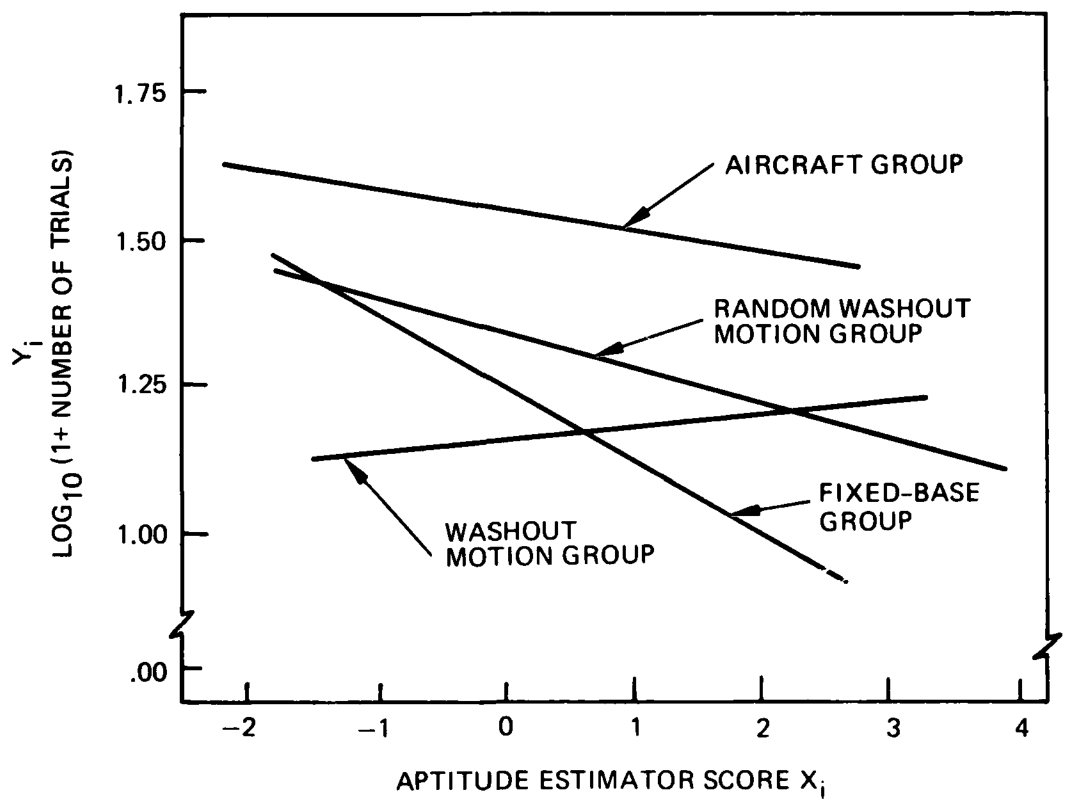


Figure 10. Regression lines showing best-fitting linear relationships between number of trials prior to criterion performances and aptitude predictor scores for four treatment groups.

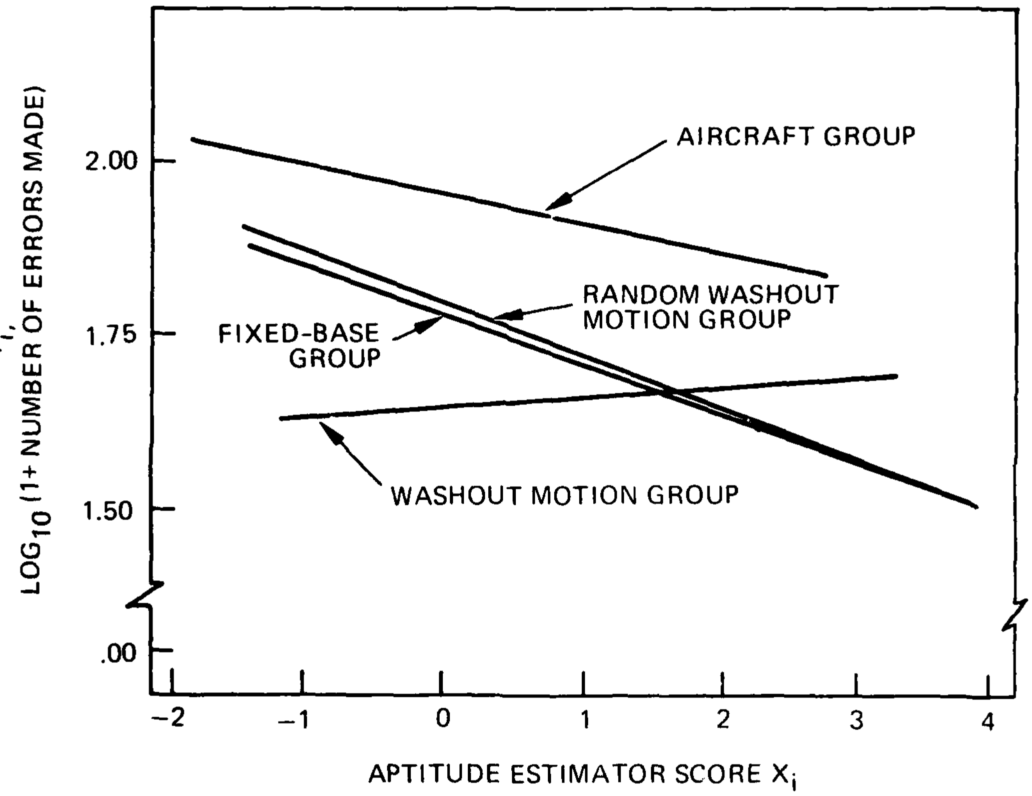


Figure 11. Regression lines showing best-fitting linear relationships between transformed total error counts, including errors made during review and criterion trials, and aptitude predictor scores for a control group and three transfer groups of nine subjects each.

Transfer was also reliable for normal-washout and fixed-base groups taken individually ($\underline{p}_{intercept}$ = .001, and .02, respectively), and approached the reliable difference threshold for the random-washout treatment condition ($\underline{p}_{intercept}$ = .08). No reliable difference was found among simulator treatment conditions compared pairwise. The aptitude estimator measure was found to reliably correlate with total error count, ($r = -.471$ $\underline{p} < .01$).

The relative flatness of the regression line for the normal-washout motion group on error counts, as on time and trials, indicates that all subjects, regardless of aptitude, tended to gain maximum practical benefit from the simulator prior to performance in the air. In clear contrast, the times, trials, and errors prior to criterion performances for the random-washout and fixed-base groups indicated that while the more apt students gained full benefit from practice in the simulator, the less apt did not.

Error totals reflect overall performances but offer no basis for explaining the interaction between simulator motion conditions and the formation of the component skills required in the various maneuvers. For that information, it is revealing to analyze the errors tabulated by error category and by maneuver during which they occurred, as was done for simulator pratice. In that discussion, it was noted that a large percentage of simulator errors were pitch-related altitude and airspeed errors, and that reliable differences in the numbers of these types of errors occurred among simulator treatment groups. Table 8 presents the altitude and airspeed error counts observed in flight for each treatment group.

Although there were no reliable differences in the absolute numbers of altitude and airspeed errors made by the three transfer groups (as there were in the simulator), their percentage contributions to the

TABLE 8

Altitude and Airspeed Errors in Flight

Treatment Group	Altitude Errors	Airspeed Errors
Aircraft (Control)	236	94
Normal-Washout Motion	110	53
Fixed-Base	135	54
Random-Washout Motion	134	63

total error counts were remarkably similar from group to group (aircraft, 38.7%; normal-washout motion, 38.9%; fixed-base, 37.6%; and random-washout motion, 39.9%). The four-way statistical comparison among groups indicated reliable transfer of altitude control skills ($p_{intercept}$ = .05). This reliable transfer was supported by a strongly reliable transfer of skill for the normal-washout group ($p_{intercept}$ = .007). Probabilities of borderline reliability were observed for the normal-washout and fixed-base groups in airspeed control ($p_{intercept}$ = .08 and .05, respectively).

Differences in the characteristics of simulator roll motion cues might be expected to affect the acquisition of bank-associated flight skills differentially. However, heading and bank-angle maintenance skills were not found to be sources of reliable differences among group performances in the simulator. In the air, the transfer/aptitude interaction differed to a marginally reliable degree among all four groups (p_{slope} = .07) in the frequency of bank-angle errors. These differences in performance relative to aptitude were primarily among the simulator treatment groups. A comparison among simulator groups revealed reliable differences (p_{slope} = .007). Individual comparison of the normal-washout motion and fixed-base groups (p_{slope} = .03), and of the normal-washout and random-washout motion groups (p_{slope} = .003), also exceeded chance probability.

This difference in ability to maintain a constant bank angle as a function of aptitude and the type of cockpit motion in the simulator is not evident in the scores for heading precision errors, reflecting poor turn execution. Figure 12 presents the regression representation of the relationships between transformed heading error frequencies and subject aptitude predictor scores for each group.

Although bank angle maintenance is important in heading control, the simulator trained groups did not reliably differ from one another in numbers of heading precision errors. Transfer from the simulator to the aircraft as measured by heading error frequency was quite pronounced; overall group transfer was reliable ($p_{intercept}$ = .008) as were transfer effects for each simulator group taken individually ($p_{intercept}$ = .005, .007, and .02 for the normal-washout, fixed-base, and random-washout motion groups, respectively). Strong transfer effects were observed based upon certain of the individual maneuver error totals. Table 9 presents error totals for three striking examples of the value of the simulator in reducing airborne error frequency.

Constant-banked turns were introduced first in the transfer task sequence. Thus performance on this maneuver is a sensistive indicator of the level of skill brought from previous experience in the simulator. Clearly the simulator was an effective transfer learning environment; overall transfer was reliable ($p_{intercept}$ = .0001) as were the individual transfer levels of each treatment group ($p_{intercept}$ = .001, .0002, and .006 for normal-washout motion, fixed-base, and random-washout motion groups, respectively). Again, no reliable difference was demonstrated among transfer groups.

Standard rate turns were not attempted until constant-banked turns had been mastered to a standard of two errorless performances. Even so,

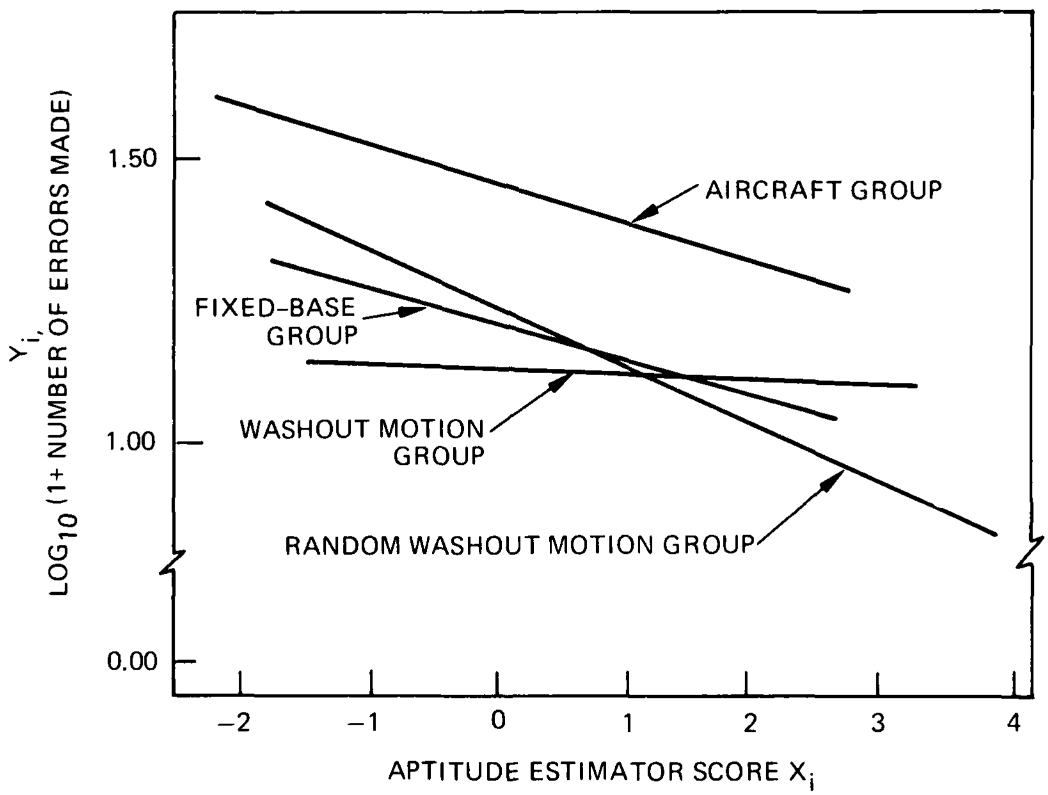


Figure 12. Regression lines showing best-fitting linear relationships between transformed heading error count and subject aptitude for each of four treatment groups.

TABLE 9

Error Totals in Flight by Maneuver and Experimental Treatment As Observed in Flight During Practice to Criterion Performance

Maneuver	Aircraft Group	Normal-Washout Motion Group	Fixed-Base Group	Random Washout Motion Group
Constant-Banked Turns	53	7	4	10
Standard-Rate Turns	83	3	5	12
Power Setting (S & L)	99	8	20	43

the additional demand introduced by the turn and bank instrument reinforced the value of simulator experience as demonstrated by a continuing strong overall transfer effect ($\underline{p}_{intercept} = .00006$) and reliable individual transfer levels for each simulator trained group ($\underline{p}_{intercept} = .0004$, .001 and .01 for the normal-washout motion, fixed-base, and random-washout motion groups in turn). Among simulator groups, no reliable differences were noted.

Figure 13 presents the set of regression lines constructed for the analysis of covariance of errors made during pre-criterion practice of the power-setting task. More than any other single measure, this error total differentiated among treatment groups and demonstrated strong transfer effects. The power-setting task increased the subject's workload because it demanded that the aircraft be kept on a straight and level course while intermittently diverting student attention away from the primary flight instruments. Aircraft attitude had to be controlled on the basis of sampled rather than continuous flight data; thus for the first time immediate flight performance goals had to be memorized. Overall transfer for task was remarkably high and reliable ($\underline{p}_{intercept} = .00002$). Among the simulator groups, differences were in each case reliable ($\underline{p}_{intercept} < .05$). Individual simulator treatment group transfer to the aircraft was reliable at very high levels except for that of the random-washout group which achieved marginal transfer and a dramatic decrease in error frequency.

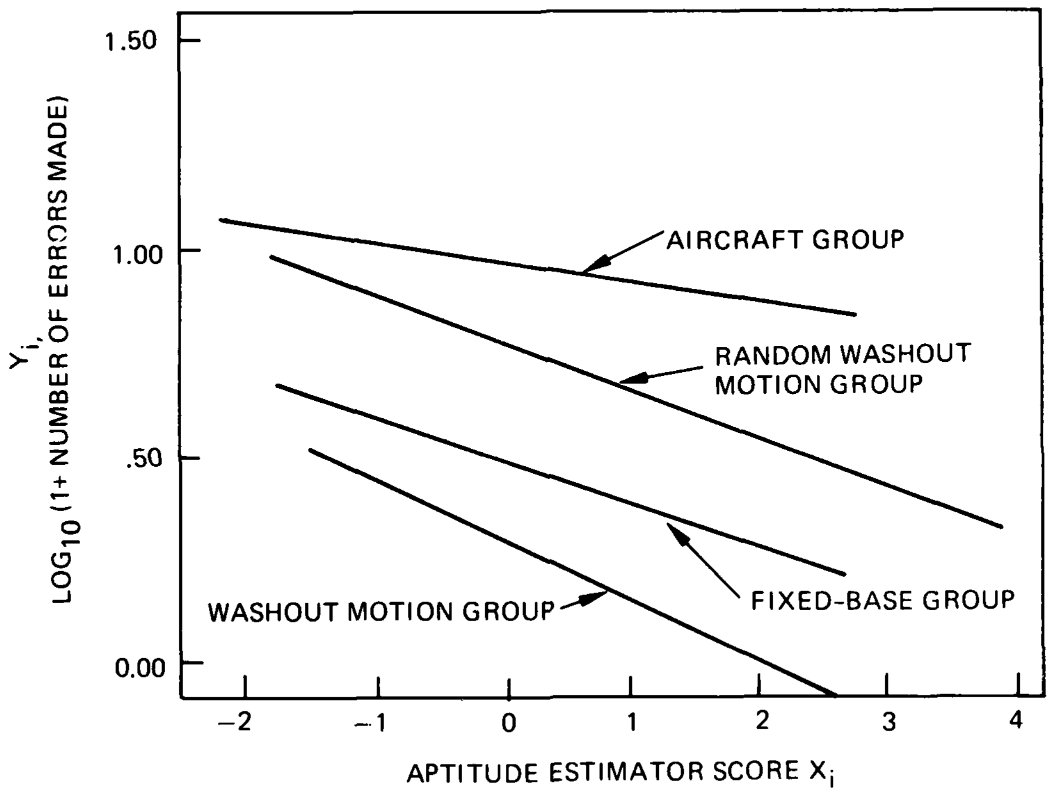


Figure 13. Regression lines showing best-fitting linear relationships between transformed error totals and aptitude predictor scores for each group obtained during power setting in flight.

DISCUSSION

Once again, training in a ground-based flight simulator has been shown to yield positive transfer to performance in flight, but more importantly, the amount of such transfer does not seem to depend to a reliable degree upon the presence of motion cues, at least during initial training. In the simulator, a consistent and reliable trend across many categories of error measures favored the performance of the students in the higher fidelity motion condition over that of the student group trained without motion. Performance in the air, however, failed to provide a basis for reliable differentiation between normal-washout motion and fixed-base groups. Although it cannot be said that the transfer levels were equivalent, there was certainly no basis in the data obtained here for advocating cockpit motion in primary flight trainers. While performance in the training simulator depends upon the type of cockpit motion, performance and transfer effectiveness do not bear a simple, direct relationship.

Conclusions on the Research Issues

The present experiment was conducted to gather evidence bearing upon the two issues presented earlier. The first dealt with the question of whether cockpit motion facilitates transfer from simulator practice of basic flight tasks. Students trained under the normal-washout motion condition did indeed show reliable transfer of learning to the aircraft transfer task. But then, so did those trained with no simulator motion, and to a sufficient degree that the performances of these groups could not be statistically distinguished. The assertion that an enriched motion cue environment in the simulator increases the transfer effectiveness of the device is, at best, of questionable validity, considered within the bounds of the present study.

The second issue addressed was the determination of the nature of motion cues used by the student. If such cues merely alert the student to attend to aircraft instruments during changing conditions, students with random-washout motion and normal-washout motion could be expected to perform equally well on average. On the other hand, if these cues are important determinants of the direction of response to changing conditions, the unreliable directionality of the random-washout motion would be expected to degrade performances in the simulator, with possible consequent adverse affects upon transfer. The results bearing upon this issue do not support a positive conclusion. Performances in the simulator were generally though not reliably better with normal-washout motion than with the directionally random motion. A consistent tendency was clear, however, from the fact that the normal-washout motion group made fewer errors during practice in the simulator on 78% of the measures.

Overall Savings and Transfer Effectiveness

Flight time measures used in the statistical comparisons of group performances included only the time spent practicing the eleven criterion maneuvers. Additional flight time, in amounts approximately equal for each transfer group and slightly greater for the control group, was required for presenting taped instructions, for review and criterion trials, and for flight activities by the safety pilot unrelated to student training, such as takeoff, flying to and from the practice area, approach delays, and landings.

While the scientific aim of providing a uniform and sensitive quantitative basis for evaluating experimental treatments was promoted by basing comparisons on practice time only, the practical application of the findings requires an additional analysis more representative of actual instructional economics. For meaningful cost effectiveness comparisons, total flight time, excluding only that time required for demonstration of criterion performance, is presented for each group in Table 10, which also includes flight time saved, time spent in the simulator, and the resulting transfer effectiveness ratios (Roscoe, 1971).

Cost Effectiveness

The transfer effectiveness ratio is a measure of the efficiency of training in the simulator relative to the airplane. Here, for example, each hour of simulator time under the normal-washout motion condition replaced, or "saved", 0.314 hours of practice in flight prior to criterion performances. The inverse of the transfer effectiveness ratio sets a threshold of airplane to simulator operating costs above which simulator use is cost effective. The inverse values of the transfer effectiveness ratios given in Table 10 are 3.18, 3.35, and 4.00 for the normal-washout, fixed-base, and random-washout modes of simulator operation, respectively. Typical 1976 costs of owning and operating primary training airplanes at a modest profit are on the order of $28.00/hour, including instruction. Corresponding costs for

TABLE 10

Summary of Overall Flight Time Savings in Minutes and Transfer Effectiveness as a Function of Simulator Cockpit Motion Conditions

Experimental Group	Flight Time	Time Saved	GAT-2 Time	Transfer Ratio
Airplane Only	387			
Normal Washout	248	139	442	0.314
Fixed-Base	255	132	442	0.299
Random Washout	280	107	429	0.250

two ground-based flight trainers representative of moving-base and fixed-base operation, respectively, are summarized in Table 11.

Although the type of moving-base trainer cited in Table 11 was not represented in this experiment, the normal-washout motion of the modified GAT-2 included pitching and banking cues most nearly corresponding to those in question. Multiplying the inverse transfer effectiveness ratios obtained for normal-washout motion and fixed-base operation by the respective costs given in Table 11 yields minimum airplane operating costs of $48.65 and $35.44 for economical use of moving-base and fixed-base trainers in the 6.5-hour flight curriculum taught in this experiment. If there were no other considerations, use of either type of trainer should be rejected as uneconomical. However, such a conclusion is unwarranted and would be misleading.

Factors Affecting Transfer

Factors other than simulator cockpit motion influenced transfer effectiveness in predictable directions but by unknown amounts in this experiment. The maneuvers taught, the amount of training given in the simulator, the highly standardized instructional procedures, and limited performance feedback were all decided upon in the interest of precision of experimental control and sensitivity of discrimination among experimental conditions; each served also to limit transfer in all groups, presumably to a uniform extent.

Certain maneuvers that can be taught effectively in simulators were not included to reduce the likelihood of disrupting the experiment by damaging the specially equipped airplane. Individualization of instruction in response to student difficulties and other techniques of training

TABLE 11

Typical Direct Costs of Owning and Operating Representative Moving-Base and Fixed-Base General Aviation Flight Trainers

Costs	TYPE OF SIMULATOR	
	Sustained Pitch, Bank, and Yaw Motion	Fixed-Base
Yearly Amortization @ 1%/mo	$2625	$1560
Year Maintenance	$2850	$ 375
Yearly Total	$5475	$1935
Hourly Cost @ 750 hr/yr	$ 7.30	$ 2.60
Hourly Instruction	$ 8.00	$ 8.00
Hourly Total	$ 15.30	$ 10.60

for maximum transfer were not employed by the instructors in the interest of uniform experimental treatment. The fixed amount of simulator training, independent of student aptitude or demonstrated performance, was essential to the meaningful comparison of motion conditions in terms of transfer effectiveness but does not represent the optimum simulator use strategy.

Optimization of Simulator Use

Optimization of simulator use involves consideration of the diminishing nature of the incremental transfer effectiveness function (Roscoe, 1971) and the fact that this function varies both among students and with changes in simulator characteristics, curriculum content, instructional practices, and interpolation of practice in the simulator and airplane, to name but a few of many factors. The amount of simulator training given was determined during extensive pretesting to assure students at the lower aptitude levels sufficient transfer to reach criterion performance in the airplane in a reasonable time, regardless of the simulator motion condition. This inevitably gave the more apt students, particularly those in the normal-washout motion group, simulator training well beyond their individual cost-effective crossunder points (Roscoe, 1975). This effect is clearly evident from the varying slopes of the regression lines for different groups shown in Figures 8-11.

Simulator Selection and Use

Despite the experimental constraints that served to limit total transfer for some and transfer effectiveness for others, a further cost analysis of the unduly pessimistic results provides, through example, a rational basis for simulator selection and use. Figure 14 depicts hypothetical relationships among incremental and cumulative transfer effectiveness and associated profit or loss as functions of the amount of training time in representative fixed-base and moving-base general aviation flight trainers. The scales of transfer, time and cost have been set to be consistent with the amount of training and findings of this study, but the relationships shown are of a generalizable nature, subject to scale adjustments to accommodate longer periods of training and higher levels of transfer effectiveness associated with better conditions for learning.

For a particular simulator, a cost effectiveness crossunder point is reached when its incremental transfer effectiveness ratio equals the ratio of its hourly cost to that of the counterpart airplane. With cost ratios of 0.546 and 0.379 between the two simulators and the airplane represented in Figure 6, corresponding incremental transfer effectiveness ratios are reached at slightly less than 1 hr and 2 hr, respectively, for this brief, 6.5 hr flight curriculum. Thus, in each cockpit motion condition, use of the simulator beyond these respective points would waste the time of the student, the instructor, and the simulator, all of which may be expressed in terms of money.

There is compelling evidence from the results obtained that the amount of simulator training given students in this experiment was uneconomical under the particular circumstances that prevailed. For a training simulator to be cost effective, its cost must be low, its

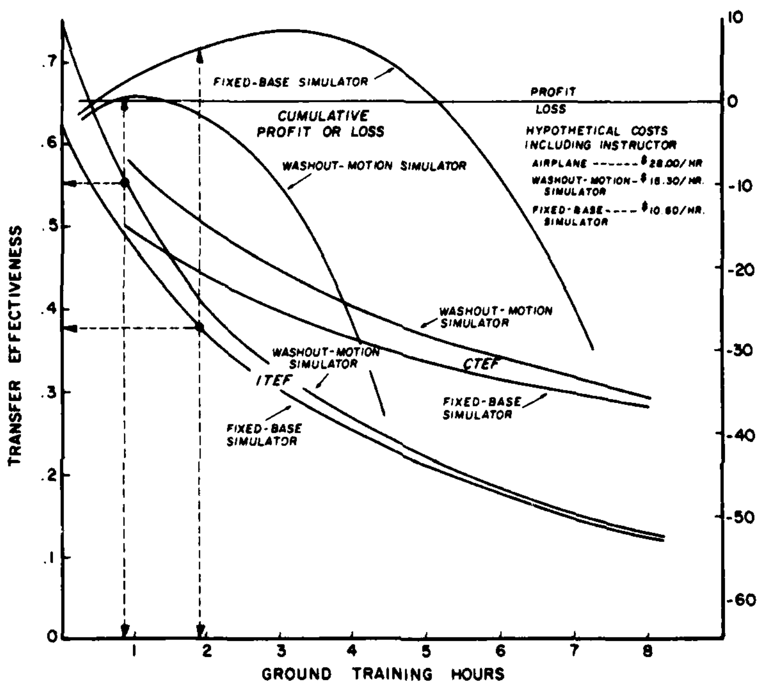


Figure 14. Hypothetical incremental and cumulative transfer effectiveness, in a 6.5-hr initial flight training curriculum, as functions (ITEF and CTEF) of the amount of training time in representative fixed-base and moving-base general aviation flight trainers and the associated profit or loss.

transfer effectiveness high, and its use limited to the point at which its incremental transfer ratio crosses under its cost ratio relative to the airplane.

Experimental Methodology and Measures

The results of the present study illustrate that the selection of experimental measures for simulator transfer studies should be made carefully. Of a large number of performance evaluation measures considered, and of a smaller number actually used in the present experiment, only a few provided a consistent basis for discriminating among experimental treatment groups. In general, measures associated with the more difficult perceptual-motor skills of flying were found to be superior in this respect. Not surprisingly, performances of less challenging control tasks have little discriminating value, and measures of procedural compliance could not be expected to discriminate well because procedural fidelity of the simulator was constant for all motion conditions.

The stability of those measures which did serve to differentiate among treatment conditions demonstrates that the use of transfer groups as small as nine subjects each is effective when subjects are matched among groups by the use of an independent performance aptitude estimator and by applying the analysis of covariance adjustment procedure. Neither aptitude prediction nor analysis of covariance have been used previously to cope with the large individual differences among subjects typically encountered in flight training and transfer research. In view of the direct relationship between the cost of such research and the number of subjects involved, the future use of this method is encouraged, and continuing work to develop better learning aptitude measures is warranted.

Perceptual and Performance Equivalence

There have been suggestions made in recent literature that the measurement of transfer of training might not be the best approach to the evaluation of training device effectiveness. Mudd (1968) attacks transfer studies on the grounds that they provide situation specific conclusions only and not generalizable principles for increasing simulator effectiveness by fidelity manipulation. As an alternative, he draws upon the work of Sadoff and Harper (1962) in handling qualities assessment to suggest the direct subjective assessment of fidelity at the component level. This assessment is to be made by introspective reference to a memorial model of the operational cue environment. It is asserted that high fidelity elicits a behavioral environment corresponding most closely to the operational situation; hence, transfer effectiveness is maximized.

Mudd's (1968) arguments can be criticized on three grounds. Introspective judgments are highly suspect as scientific data because of their great variability and because their inherently private nature renders their objective communication equivocal. Furthermore, the behavioral environment of a simulator pilot assessing the fidelity of a training device may be affected by the assessment process itself. Thus a distorted appraisal of the simulator qualities that affect the flight task may be provided. Thirdly, the data gathered here do not support the contention that heightened physical fidelity leads directly to increased transfer effectiveness.

Caro (1970) proposes another approach based upon a combination of analytical and pilot rating methods. Limiting consideration to visual and functional characteristics of training devices, he suggests that heightened transfer results from corresponding stimulus-response associations in the trainer and operational task situations. An analysis is made to identify and compare stimulus elements in the two environments, followed by pilot evaluation of the similarities of the corresponding stimuli and the responses they elicit. To the extent that these agree, positive transfer is predicted.

Caro's method lacks quantitative precision, and may be inappropriate for use in connection with motion cue comparisons. The human motion perception apparatus is not adept at isolation of components of the total perceived acceleration environment. Thus critical evaluations would have to be made by consideration of each component in isolation. Such a strategy would ignore important interactive effects.

Matheny has combined these ideas in an unpublished technical report for the Air Force Office of Scientific Research dealing with the effectiveness of training devices and the perceptual or performance equivalence between the device and its operational equivalent. He initially speculates that transfer effectiveness is maximized if the perceived environment in the simulator corresponds as closely as possible to the perceived environment in flight. This theory assumes that all performance determining factors of the simulator are perceivable. Recognizing that this may not always be the case, Matheny suggests that the effectiveness of the training device may depend more directly upon the performance equivalence between the two environments. We have already noted, however, that the environmental cues which promote high performance in a task are not necessarily the same as those which promote learning (Holding, 1965). The present research fails to support either perceptual or performance equivalence as a strong correlate of transfer effectiveness.

Two regression lines from Figure 9 relating time-to-criterion in flight to pilot aptitude for the groups that flew the simulator with normal-washout motion and with random-washout motion are reproduced with an expanded ordinate scale in Figure 15. In view of the fact that no subject in the random-washout group at any time detected the half-time diametric conflict between roll accelerations and instrument indications of bank attitudes, there is no reason to question the subjective perceptual equivalence of the two simulator motion conditions for these beginning flight students, although the randomly reversed direction of cockpit motion was painfully evident to the experimenters and performance observers in the simulator. Although these two widely different simulator motion conditions may be "perceptually equivalent," they are equivalent in no other respect.

Group performances in the simulator, illustrated in Figure 9, showed a close performance equivalence between the random-washout motion group and the fixed-base group, both of which appeared to differ from the normal-washout motion group. Clearly the fixed-base condition is not perceptually equivalent to either type of cockpit motion, even for beginning flight students. These findings in conjunction with those of Koonce serve as a warning against predicting group performances in flight from group performances in training simulators, despite the fact that predictions of individual performances in flight relative to group means may be highly reliable (Koonce, 1974).

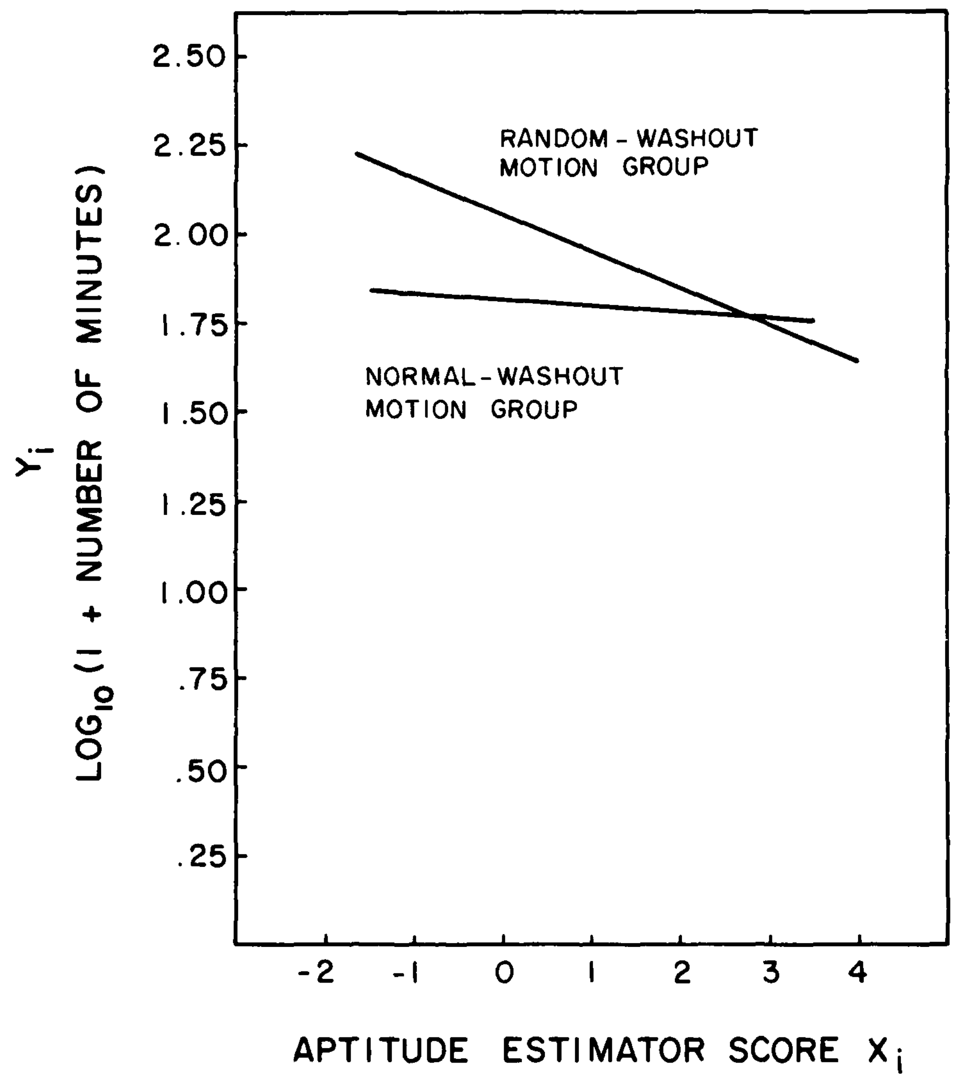


Figure 15. Regression lines showing best-fitting linear relationships between transformed times to reach performance criteria in flight and aptitude predictor scores for the normal-washout and random-washout simulator motion groups.

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Transfer of flight training from a Singer-Link GAT-2 training simulator, modified to approximate a counterpart Piper Cherokee Arrow airplane, was measured for independent groups of nine flight-naive subjects, each trained in one of three simulator cockpit motion conditions: normal washout motion in bank with sustained pitch angles, washout banking motion in which the direction of motion relative to that of the simulated airplane was randomly reversed 50% of the time as the cab passed through a wings-level attitude, and a fixed-base →

condition. Subjects received predetermined fixed amounts of practice in the simulator on each of 11 flight maneuvers drawn from the Private Pilot flight curriculum. Transfer performance measures, including flight time and trials to FAA performance criteria and total errors made in the process, showed reliable transfer for all groups with differential transfer effects and cost effectiveness implications depending upon the type of simulator motion. An aptitude estimator measure and the analysis of covariance technique provided increased discrimination among groups in the presence of considerable individual variation in performance within treatment conditions

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