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Russell V. Parrish
and George G. Steinmetz
Langley Research Center
Hampton, Virginia

NASA
National Aeronautics
and Space Administration

Scientific and Technical
Information Branch

SUMMARY

Vertical-motion cues supplied by a g-seat to augment platform motion cues in the other five degrees of freedom were evaluated in terms of their effect on objective performance measures obtained during simulated transport landings under visual conditions. In addition to evaluating the effects of the vertical cueing, runway width and magnification effects were investigated.

The g-seat was evaluated during fixed-base and moving-base operations. Although performance with the g-seat only improved slightly over that with fixed-base operation, combined g-seat and platform operation showed no improvement over platform-only operation. However, the magnitude of the improvement of motion-only operation (with no vertical cueing) over fixed-base operation indicated that the pilot-vehicle task was motion sensitive enough to detect any benefit of vertical cueing, had one been present, with g-seat operation. From these results, it may be inferred that the slight improvements obtained with motion cueing from either the g-seat or the platform are attributable to the feedback of state-change information.

When one runway width at one magnification factor was compared with another width at a different factor, the visual results indicated that runway width probably had no effect on pilot-vehicle performance. The few performance differences that were detected may be more readily attributed to the extant (existing throughout) increase in vertical velocity induced by the magnification factor used to change the runway width, rather than to the width itself.

INTRODUCTION

A generally accepted premise within the flight-simulation community is that high-fidelity motion cueing is available for transport simulation. The acceptance of this premise is based partly on objective data, demonstrating task performance dependences, and, to a large degree, on subjective opinion. (See refs. 1 to 4.) A corollary to this premise is that the simulator device that produces the motion cues need not be an exotic machine that is unobtainable to the majority of the community. This corollary is not held to be inviolate, however, for a few specific tasks that are purported to require extensive translational capability. (See ref. 5.) One such task is the simulation of aircraft flare and touchdown.

The deficiencies of flight simulators in visual flare and touchdown performance are generally attributed to inaccuracies in ground-effect modeling, inadequacies of visual displays in attitude reference, altitude estimation, and sink-rate estimation, and, in references 6 and 7, to the lack of vertical-motion cueing.

The simulator motion device currently in use at Langley Research Center is of the six-degree-of-freedom, synergistic type that has seen widespread application throughout the simulation community. The synergistic nature of the device, combined with the generally low-valued, short-period frequency of most transport aircraft, makes it a poor candidate to alleviate the vertical-motion cueing problem. In fact, in most applications at Langley, the vertical degree of freedom is used only to introduce turbulence cues into the motion environment. (See refs. 8 and 9.)

Another simulation device that does provide vertical cueing information to the pilot is the g-seat. The Langley-developed version of the g-seat is an inexpensive, high-bandwidth, four-celled pneumatic seat that has proved to be effective in fighter simulations. (See refs. 10 and 11.) The present paper presents the objective results from a study that used the g-seat to augment the platform motion cues for simulated transport landings.

In addition to evaluating the effects of the vertical-motion cues, the study had an additional factor, runway width and magnification. The effects of a change in runway width or magnification on touchdown performance were evaluated in an attempt to assess the importance of fidelity in runway width. The Langley terrain board has a runway width of 265 ft rather than the more typical real-world width of 200 ft. A method of obtaining the width of 200 ft by changing the magnification factor of the scene to 1.3 was conceived. In light of some suggested effects of magnification on sink-rate performance (ref. 12), some comparison was necessary. Therefore, for this comparison, the visual scene supplied to the pilot was that of a 12 000-ft runway with either a width of 265 ft at a magnification factor of 1.0, or a width of 200 ft at a magnification factor of 1.3.

Prior to presentation of the results on both factors, a brief description of the simulator characteristics and the experimental design and task is given.

SIMULATOR CHARACTERISTICS

Airplane Mathematical-Model Characteristics

The mathematical model of a Boeing 737-100 airplane included a nonlinear data package for all flight regions; a ground-effect model; a nonlinear engine model; and nonlinear models of servos, actuators, and spoiler mixers. The simulation of the basic airframe was validated prior to its use in numerous studies.

For this investigation, the simulated airplane was in the landing-approach configuration with the approximate flight characteristics presented in table I and was manually flown by the evaluation pilot without control-wheel steering or autoland.

Computer Implementation

The mathematical model of the airplane and the simulation hardware drives were implemented on the Langley Flight Simulation Computing Subsystem. This subsystem, consisting of a Control Data CYBER 175 computer and associated interface equipment, solved the programmed equations 32 times per second. The average time delay from input to output (1.5 times the sample period) was approximately 47 msec.

Simulator Cockpit

The cockpit of the Langley Visual/Motion Simulator (VMS) was configured as a transport cockpit. The primary instrumentation consisted of an attitude direction indicator (including steering commands without flare guidance), an altimeter, and vertical-speed, horizontal-situation, airspeed (both indicated and true), angle-of-attack, angle-of-sideslip, and turn-and-slip indicators.

Visual Display

The VMS is provided with an "out-the-window" visual display by a virtual-image system of the beam-splitter, reflective-mirror type. The system, located nominally 1.27 m from the pilot's eye, has a nominal field of view 48° wide and 36° high and uses a 525-line TV raster system. The display system provides a 46° by 26° instantaneous field of view. The system supplies a color picture of unity magnification with a resolution on the order of 9 minutes of arc.

The scene depicted in the virtual-image system was obtained from a television-camera transport system used in conjunction with a terrain model board. The model board, 24 ft by 60 ft, offers terrain and an airport complex at a 1500:1 scale, complete with taxi lights, visual approach slope indicators (VASI), runway end identifier lights (REILS), and so forth.

The television-camera transport system used in conjunction with the terrain model board is described in reference 13. The maximum horizontal speed capability of the system is 444 knots, with a vertical-speed capability of ±30 000 ft/min. The translational lags of the system are 15 msec or less, and the rotational lags are 22 msec or less. The average total visual delay, including computational throughput delay, was thus less than 70 msec.

The airport complex has two parallel runways (12 000 ft in length) that have a width of 265 ft. Normally, runways of that length have widths of 200 ft. To assess the effects of runway width on touchdown performance, the vertical and lateral drive scale factors of the camera transport system were multiplied by a factor of 1.3. This change induced a width of 200 ft, with a magnification factor of 1.3. Figure 1 displays the landing scene for both visual conditions.

Motion System

The motion performance limits of the VMS are shown in figure 2. These limits are for single-degree-of-freedom operation. Conservatism must be exercised in the use of the position limits, because they change as the orientation of the synergistic base varies. References 4 and 14 to 16 document the characteristics of the system, which possesses steady-state time lags of less than 15 msec. Thus, the average total motion delay, including computational throughput, is less than 70 msec (ignoring the lead introduced by washout) and is quite compatible with the visual delays. The washout system used to present the motion-cue commands to the motion base is nonstandard. It is the nonlinear, coordinated, adaptive washout method (refs. 17 and 18) which was developed at Langley to provide motion drive signals to the six-degree-of-freedom moving base. The nonlinear adaptive washout filters of this washout method are based on the optimization technique of continuous steepest descent.

Motion was restricted to five degrees of freedom because of the objectionable hydraulic noise induced by the vertical motion of the synergistic base, and because only a small amount of vertical cue was available. The small amount of vertical-acceleration cue available was due to a combination of position limits of the motion base and the short-period frequency of the 737-100 airplane in the landing-approach configuration. The cue available for heave (vertical acceleration) under these conditions was less than 0.05g (1g = 9.81 m/sec^2), which is the product of amplitude (1.5 ft) and the square of frequency (frequency was less than 1 rad/sec). Therefore, the heave axis was not used. However, touchdown cues were subjectively evaluated as realistic when presented through the pitch axis only. (See ref. 9.)

g-Seat

The g-seat used in this study was a second-generation seat designed and fabricated at the Langley Research Center. The seat contains inflatable pads or bladders supported by a hard surface. Initially, the pressure in these pads is biased to support a pilot so that just his two main areas of support, the ischial tuberosities, contact the hard pan. This bias adjusts the "firmness" of the seat. As acceleration increases (positive g values develop), air is removed, allowing the pilot's weight to compress the bladders and force more of his weight to be supported by the area about the tuberosities. However, some air is left to prevent a false cue of the seat falling away from the sides of the legs and buttocks. For negative g values, sufficient air is added to the bladders to support the body weight without allowing them to become too firm as a result of the pressure. This manner of operation, which reproduces the seat actions found during flight, also reproduces other related events, such as raising or lowering the body, which changes the pilot's eye position and joint angles.

Reference 10 provides data indicating a pressurization time of 45 msec and a bleed time of 60 msec for step inputs of 50 percent of maximum for these bladders. Analysis of the step and sinusoidal responses of the seat shows that it can be considered a 0.45 damped, 25 rad/sec, second-order system over the frequency range of 0 to 8 Hz. This provides an equivalent 35-msec steady-state time delay from seat command to seat pressure over the full range of operation of the seat, and when the simulator computational delay of 47 msec is added to this, it yields a g-seat delay slightly in excess of 80 msec.

Normally, for simulations of fixed-wing fighter aircraft, the full dynamic range of the seat is scaled from 0g to 6g with the 1g neutral position biased as a function of the pilot's weight. For the transport application, subjective evaluation resulted not only in scaling changes, but also in a change in the drive command. The goal of the augmentation effort was to provide vertical cueing that would allow the pilots to have better control of aircraft sink-rate information. It was hypothesized that since sink-rate information (in the inertial-axis system) is not readily extracted from normal acceleration (in the body-axis system) without computations (fig. 3), a direct presentation of inertial vertical acceleration by the g-seat would provide the maximum opportunity to detect the potential of g-seat application to the landing simulation problem. Figure 3 also shows the g-seat drive command, which was proportional to inertial vertical acceleration. The gain and the neutral position of the seat were determined subjectively for the landing task.

DESCRIPTION OF THE EXPERIMENT

The experiment is described in terms of its statistical design, the pilot-vehicle tasks, the participating pilots, and the objective performance measures.

Experimental Design

In order to evaluate the effects of the vertical cues supplied to the pilot by the g-seat as an augmentation of platform motion cues, four levels of motion were examined. Fixed-base operation, g-seat operation, moving-base operation, and combined g-seat and moving-base operation are the four levels. The two levels of runway width were used as a visual factor, and four pilots, flying four replicates each for each experimental condition, completed the full-factorial design.

Approach, Flare, and Touchdown Task

The simulated airplane was trimmed straight and level at an airspeed of 120 knots on the glide slope and localizer at a range of 10 500 ft from the runway threshold. The glide-path intercept point on the runway was 1000 ft beyond the threshold. The pilot's task was to effect a transition from straight and level flight to the 3° glide slope; then, while controlling speed, the pilot would complete the approach and then flare visually and touch down.

Participating Pilots

Four NASA research pilots participated in each of the landing studies. Three of the pilots have had extensive experience with visual landings in flight simulators, whereas the other one has had only limited experience. Each pilot flew several practice runs before completing four repetitions of the task for each motion condition under a given visual condition. The visual condition was then changed and the practice and data collection for each motion condition were repeated. Ordering of motion conditions within the visual condition was random, as was the ordering of the visual condition presentation for each pilot.

Objective Performance Measures

Analyses of variance were used as the chief analysis tools for the experimental results. The measures to be analyzed consisted of the three inertial velocities (longitudinal, lateral, and sink rate), the inertial vertical acceleration, the pitch attitude just prior to touchdown, and the runway touchdown point (both longitudinal and lateral coordinates).

EXPERIMENTAL RESULTS

Table II is a summary of the analyses of variance for the seven performance measures. The sections which follow are discussions of the statistically significant sources of variance.

Pilots

All measures provided differentiation among pilots, although the relative differences among individuals varied from measure to measure. To demonstrate this point, three pilots produced quite similar mean values of lateral velocity (which were different from that of the other pilot), but entirely different mean values of lateral touchdown point. In most pilot-vehicle tasks, pilot differences are large sources of experimental variance, which must be and are easily isolated from the analysis of other factors. Table III presents the means and standard deviations of each pilot for the seven measures.

Visual

The differences in visual presentation (one runway width at one magnification compared with another width at a different magnification) were detectable in the data of only two measures, pitch attitude and longitudinal velocity. Table IV presents the means and standard deviations for these measures. Mean performance with the 200-ft runway at a 1.3 magnification factor differed from the means achieved with the 265-ft runway at a 1.0 magnification factor by an increase of 0.7° in pitch attitude and a decrease of 5 ft/sec in longitudinal velocity at touchdown. One interpretation of these results is that the magnified visual vertical velocity presented to the pilot throughout the approach in the case of the 200-ft runway induces a higher pitch attitude, which in turn creates a lower forward velocity. The reduced sink rate at touchdown that is expected with a larger pitch attitude may be offset by the change in ground effect induced by the angle-of-attack change (about 0.6°). Hence, there was no detectable change in sink rate at touchdown.

Another interpretation is that the pitch change detected was an instantaneous measure at touchdown and may not have existed long enough to affect the sink-rate dynamics. In any event, there was no detectable change in sink rate at touchdown between the visual conditions.

Pilot By Visual Interaction

The significance of this second-order term indicates that the detectable visual effect was not constant across the pilot population. Indeed, the visual effects measured by changes in pitch and forward velocity were more pronounced in the performance of one pilot. Although the directions of change were the same, the changes for the other three pilots were smaller. Table V presents the means and standard deviations of this interaction term for these measures.

Motion

The motion factor was statistically significant for three of the measures, although these statistical significances probably have little practical value. (See figs. 4 and 5 and table VI.) The standard errors of a difference s_d between treatment means (table VI), based on the mean-square error s from the analyses of variance, were

$$s_d = \sqrt{\frac{2s^2}{32}}$$

with 93 degrees of freedom.

In terms of the principal measure of this study, sink rate, the best condition, moving-base operation, differed from the worst condition, fixed-base operation, by only 0.84 ft/sec. Vertical acceleration at touchdown was also slightly less for the moving-base condition. Landing position down the runway lengthened slightly with the addition of motion cues (165 ft).

For two of the three measures (longitudinal position and sink rate), g-seat cueing results fell between fixed-base performance and moving-base performance, and the combined operation produced only comparable results to the moving-base-only condition. From these results, it can be inferred that the slight improvements obtained with motion cueing from either the g-seat or the platform (moving base) are attributable to the feedback of state-change information which they provide. Certainly, the improved performance under moving-base-only conditions cannot be attributed to vertical-motion cues, because none are provided by the platform.

Replicates

The replication factor was significant for the touchdown point on the runway when averaged over all conditions. (See fig. 5 and table VII.) The distance of the touchdown point from the glide-path intercept point increased with increasing experience. More detailed checks of higher-order interactions between experimental conditions and replicates were not significant. This effect indicates increasing longitudinal position with replication for all conditions. An insufficient number of practice landings before data collection for each condition must be assumed to be the cause of this effect. However, no effects of replication were detected in the other measures.

CONCLUDING REMARKS

The results of this study concerning g-seat augmentation of platform motion for vertical cueing for transport applications are somewhat disappointing. Although performance with the g-seat only did improve slightly over that for fixed-base operation, combined g-seat and platform operation showed no improvement in performance over motion-only operation. However, the magnitude of the improvement of motion-only operation (with no vertical cueing) over fixed-base operation indicates that the pilot-vehicle task was motion sensitive enough to detect any benefit of vertical cueing, had one been present, with g-seat operation. From these results, it may be inferred that the slight improvements obtained with motion cueing from either the g-seat or the platform are attributable to the feedback of state-change information.

When one runway width magnification factor was compared with a different combination, the visual results indicated that runway width probably had no influence on pilot-vehicle performance. Performance differences that were detected may more readily be attributed to the extant (existing throughout) increase in vertical velocity induced by the magnification factor used to change the runway width, rather than to the width itself.

Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
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TABLE I.- LINEAR APPROXIMATIONS OF THE FLIGHT CHARACTERISTICS OF THE B-737-100 AIRPLANE

Weight, N	400 341
Center of gravity	$0.31\bar{c}$
Flap deflection, deg	40
Landing gear	Down
Damping ratio for -	
Short period	0.562
Long period	0.089
Dutch roll	0.039
Period, sec, for -	
Short period	6.30
Long period	44.3
Dutch roll	5.12
Spiral divergence	24.0
Roll subsidence	0.53

TABLE II.- SUMMARY OF ANALYSIS OF VARIANCE

Factor (a)	Degrees of freedom	Significance[b] of performance measures at touchdown						
		Pitch	Longitudinal		Lateral		Vertical	
			Velocity	Position	Velocity	Position	Velocity	Acceleration
P	3	**	**	**	**	**	**	**
V	1	**	**	—	—	—	—	—
P × V	3	**	**	—	—	—	—	—
M	3	—	—	*	—	—	*	*
P × M	9	—	—	—	—	—	—	—
V × M	3	—	—	—	—	—	—	—
P × V × M	9	—	—	—	—	—	—	—
Repetitions	3	—	—	**	—	—	—	—
Error	93							

[a]Factors are as follows: P - pilot; V - visual; M - motion.
[b]Significance shown as follows:
— not significant at levels considered.
* significant at 5-percent level.
** significant at 1-percent level.

TABLE III.- MEANS AND STANDARD DEVIATIONS FOR STATISTICALLY SIGNIFICANT MEASURES OF PILOT FACTOR WITH 32 TOUCHDOWNS PER PILOT

Longitudinal measures				
Pilot	Position, ft		Velocity, ft/sec	
	Mean	Standard deviation	Mean	Standard deviation
1	-857.553	636.924	-202.472	4.909
2	-252.223	299.745	-208.523	8.121
3	-547.621	255.730	-194.522	3.416
4	262.504	257.852	-204.350	2.437

Vertical measures				
Pilot	Velocity, ft/sec		Acceleration, ft/sec^2	
	Mean	Standard deviation	Mean	Standard deviation
1	-3.041	1.186	-4.821	2.007
2	-5.276	1.196	-8.632	4.234
3	-4.308	1.242	-5.806	2.415
4	-4.767	1.344	-6.926	2.670

Lateral measures				
Pilot	Position, ft		Velocity, ft/sec	
	Mean	Standard deviation	Mean	Standard deviation
1	-11.720	13.407	0.266	2.708
2	-1.590	5.784	-.174	1.557
3	15.026	11.036	-.085	1.677
4	12.729	8.902	-1.797	2.026

Pitch, deg		
Pilot	Mean	Standard deviation
1	3.157	0.951
2	2.088	1.471
3	4.286	1.083
4	2.746	.873

TABLE IV.- MEANS AND STANDARD DEVIATIONS FOR STATISTICALLY SIGNIFICANT MEASURES OF VISUAL FACTOR WITH 64 TOUCHDOWNS PER VISUAL CONDITION

Visual		Measure			
		Pitch, deg		Longitudinal velocity, ft/sec	
Width, ft	Magnification	Mean	Standard deviation	Mean	Standard deviation
265	1.0	2.730	1.508	-204.947	8.171
200	1.3	3.408	1.118	-199.986	5.118

TABLE V.- MEANS AND STANDARD DEVIATIONS FOR STATISTICALLY SIGNIFICANT MEASURES OF PILOT BY VISUAL INTERACTION WITH 16 TOUCHDOWNS PER CONDITION

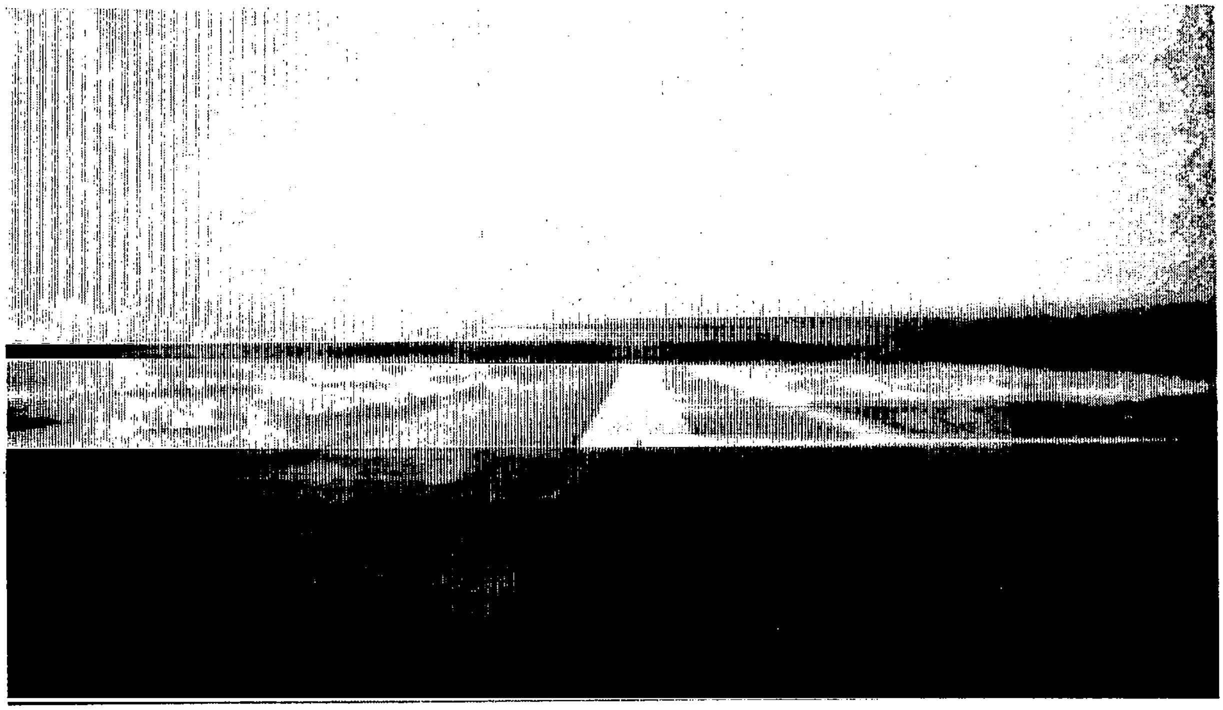
Pilot	Visual		Measure			
			Pitch		Longitudinal velocity, ft/sec	
	Width, ft	Magnification	Mean	Standard deviation	Mean	Standard deviation
1	265	1.0	2.792	0.966	-204.168	4.989
	200	1.3	3.521	.808	-200.776	4.334
2	265	1.0	1.014	.797	-215.399	3.672
	200	1.3	3.162	1.174	-201.646	4.684
3	265	1.0	4.094	1.436	-195.210	4.189
	200	1.3	4.477	.534	-193.834	2.358
4	265	1.0	3.019	.840	-205.010	2.494
	200	1.3	2.474	.842	-203.690	2.264

TABLE VI.- MEANS AND STANDARD DEVIATIONS FOR STATISTICALLY SIGNIFICANT MEASURES OF MOTION FACTOR WITH 32 TOUCHDOWNS PER CONDITION

Motion	Measure					
	Longitudinal position, ft		Vertical			
			Velocity, ft/sec		Acceleration, ft/sec^2	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Fixed base	-257.578	543.343	-4.807	1.634	-6.478	2.829
Motion base	-426.164	572.989	-3.968	1.319	-5.590	2.387
g-seat	-285.859	503.758	-4.425	1.452	-7.743	4.419
Combined	-425.292	654.643	-4.192	1.451	-6.375	2.741
Standard error		78.4		.295		.733

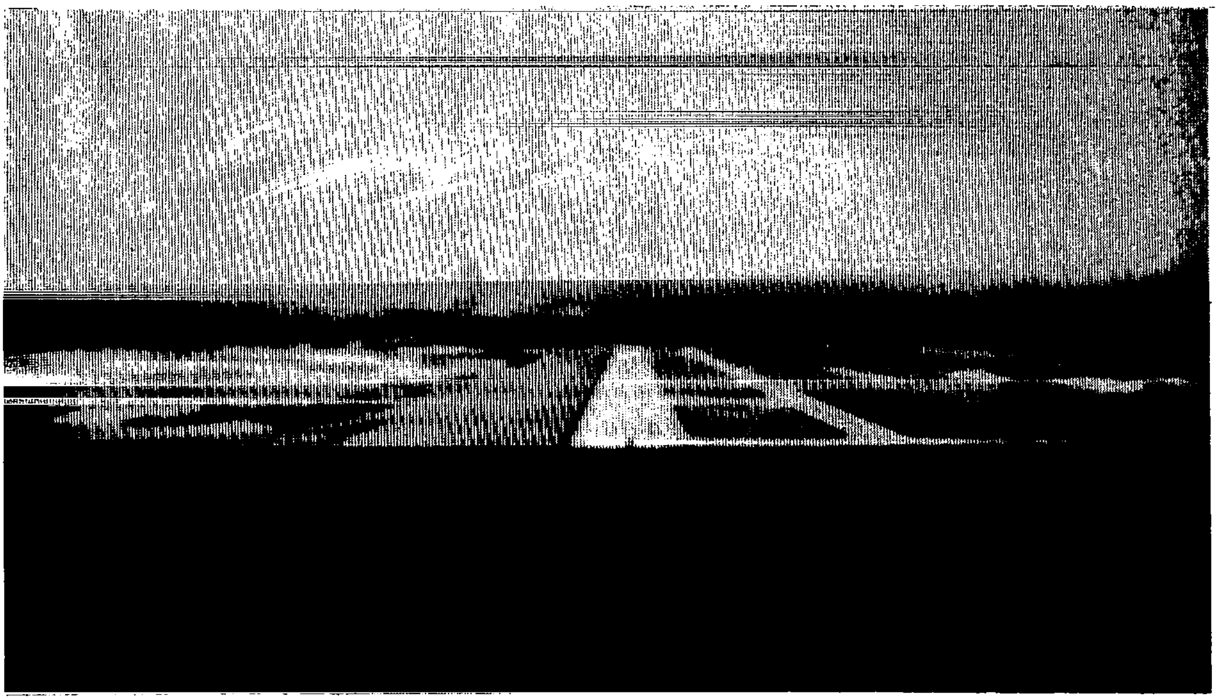
TABLE VII.- MEANS AND STANDARD DEVIATIONS FOR STATISTICALLY SIGNIFICANT MEASURES OF REPLICATE FACTOR WITH 32 TOUCHDOWNS PER REPLICATE

Replicate	Longitudinal position, ft	
	Mean	Standard deviation
1	-173.873	438.029
2	-355.049	491.912
3	-364.621	547.683
4	-501.351	735.564



L-80-2092

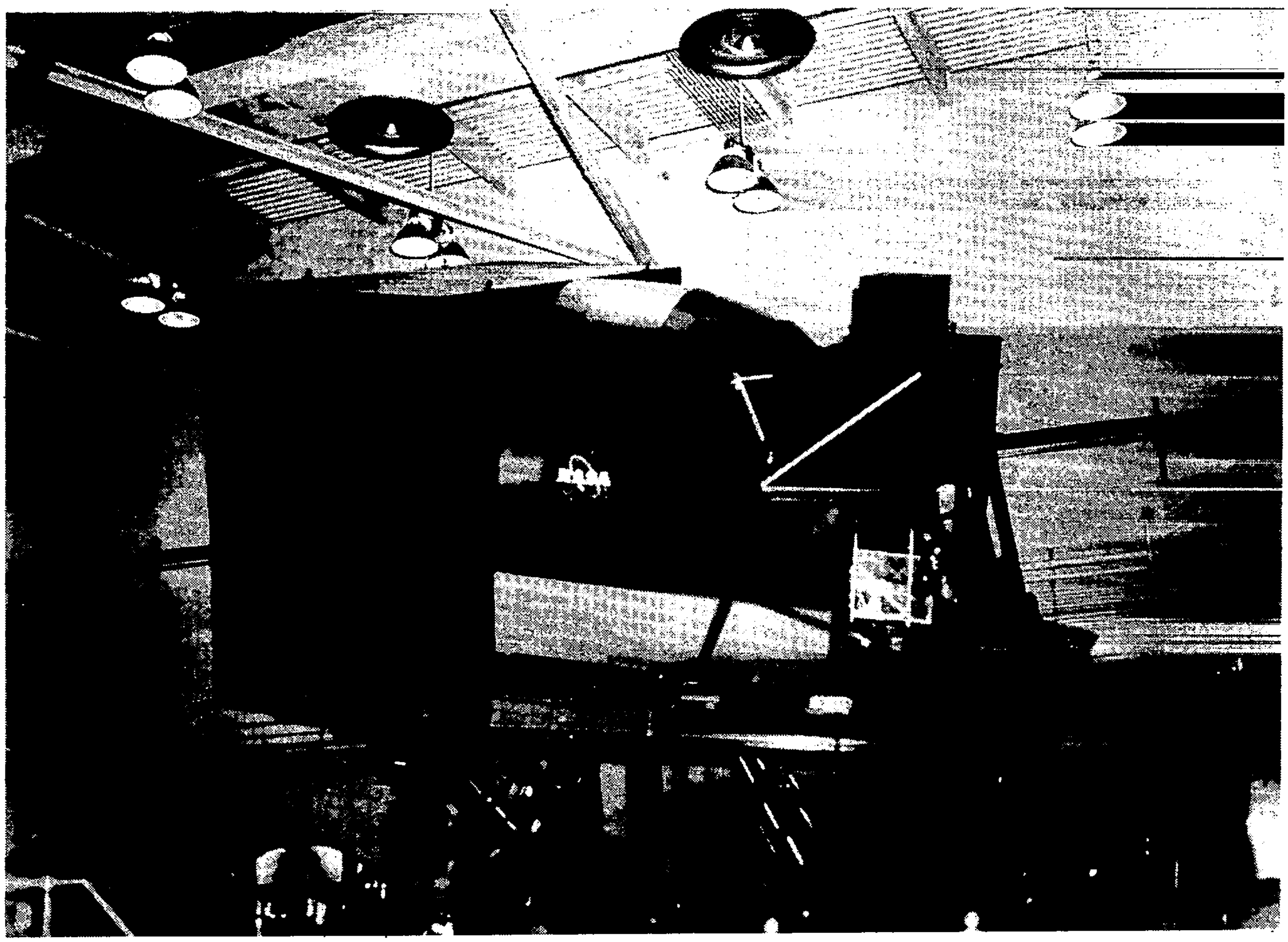
(a) View of 265-ft-wide runway with magnification factor of 1.0.



L-80-2096

(b) View of 200-ft-wide runway with magnification factor of 1.3.

Figure 1.- Views from glide path at altitude of 200 ft with the two visual conditions.



	Position	Velocity	Acceleration
Pitch	+30, -20°	±15 deg/sec	±50 deg/sec^2
Roll	±22°	±15 deg/sec	±50 deg/sec^2
Yaw	±32°	±15 deg/sec	±50 deg/sec^2
Vertical	+0.762, -0.991 m	±0.610 m/sec	±0.6g
Lateral	±1.219 m	±0.610 m/sec	±0.6g
Longitudinal	+1.245, -1.219 m	±0.610 m/sec	±0.6g

L-79-312

Figure 2.- Motion performance limits of the Langley Visual/Motion Simulator. 1g = 9.81 m/sec^2.

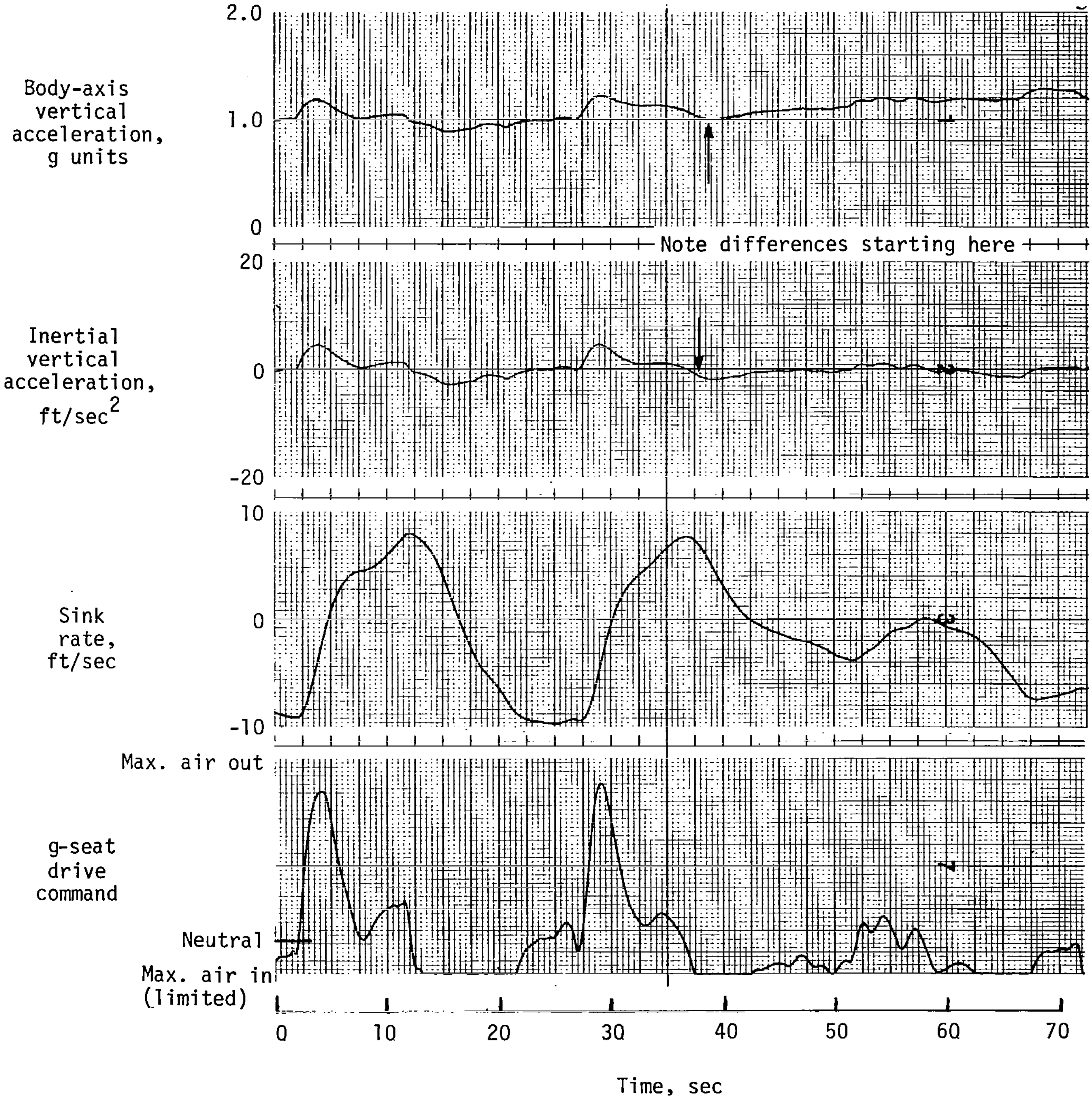
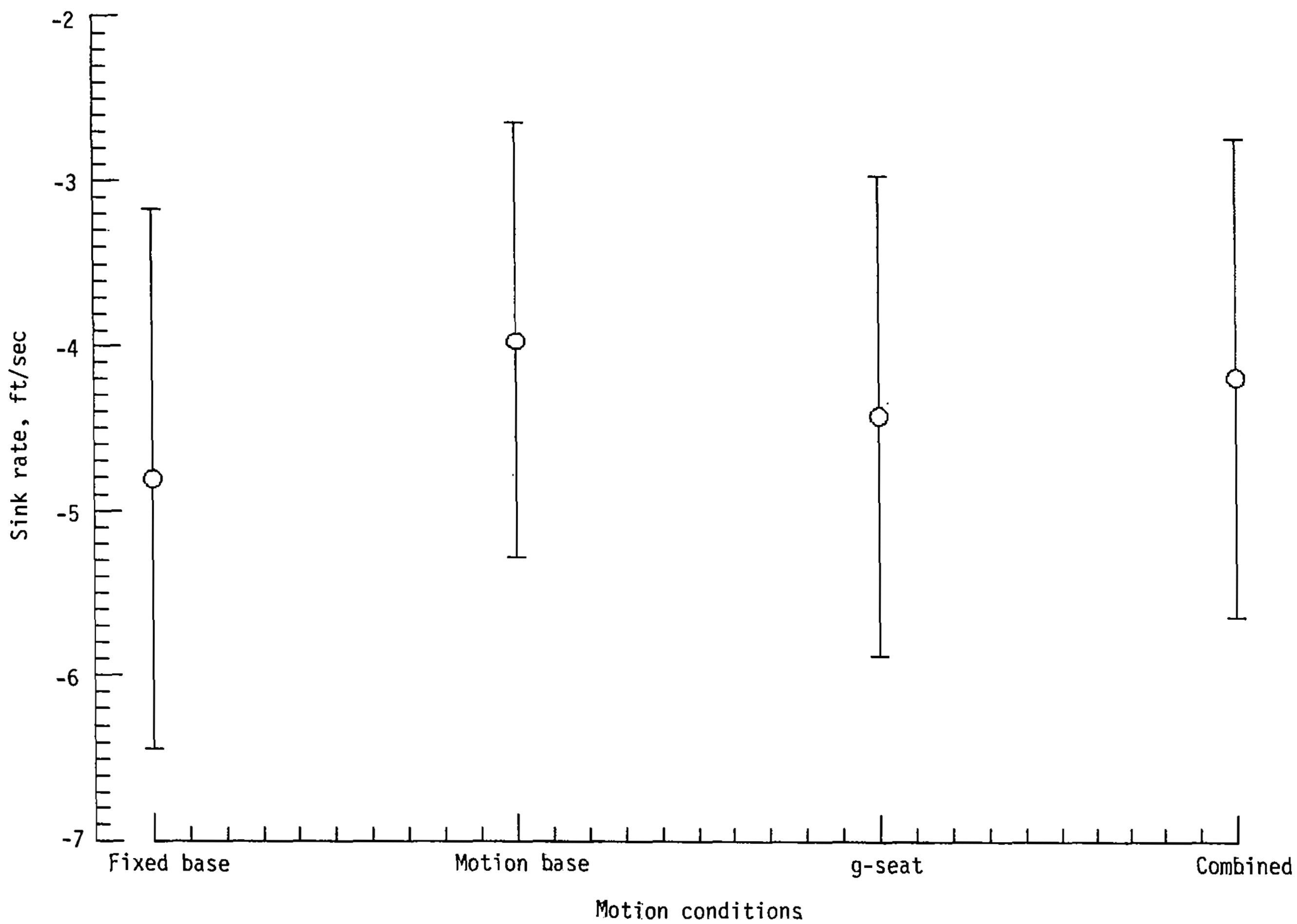
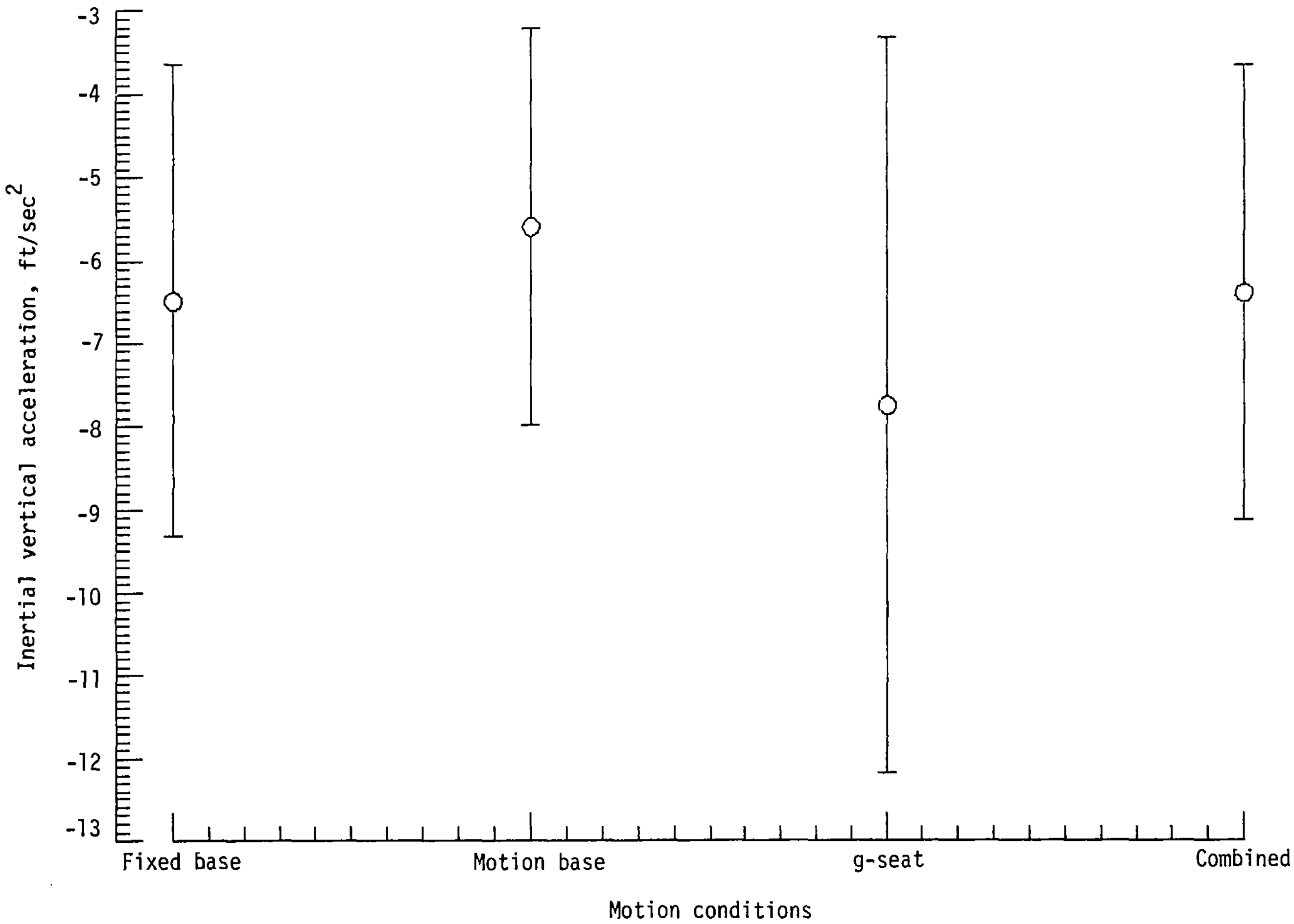


Figure 3.- Illustration of g-seat cueing for vertical maneuvers. (Although not a typical run, these maneuvers cover the range encountered during the landing task.)



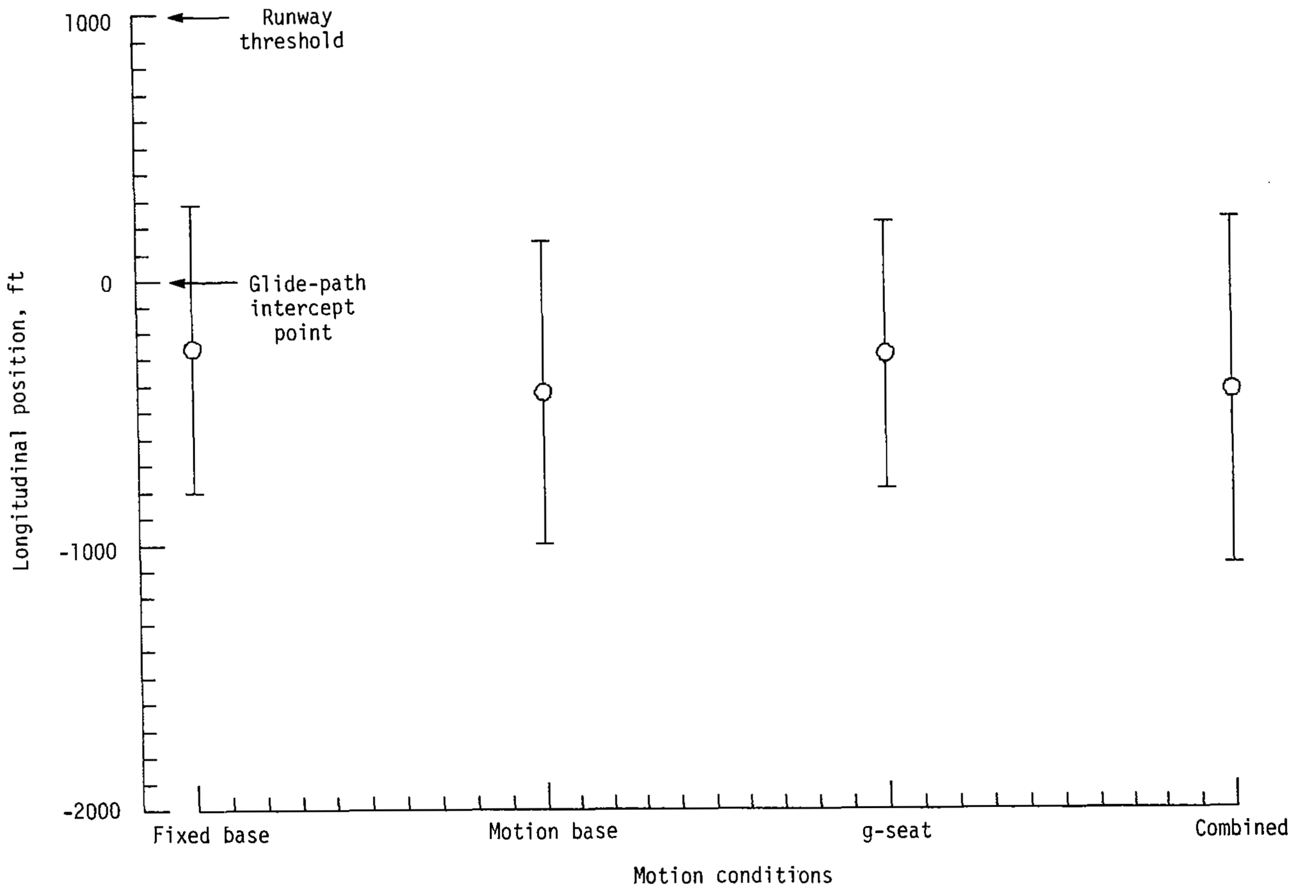
(a) Vertical velocity (sink rate).

Figure 4.- Significant measures for motion factor.



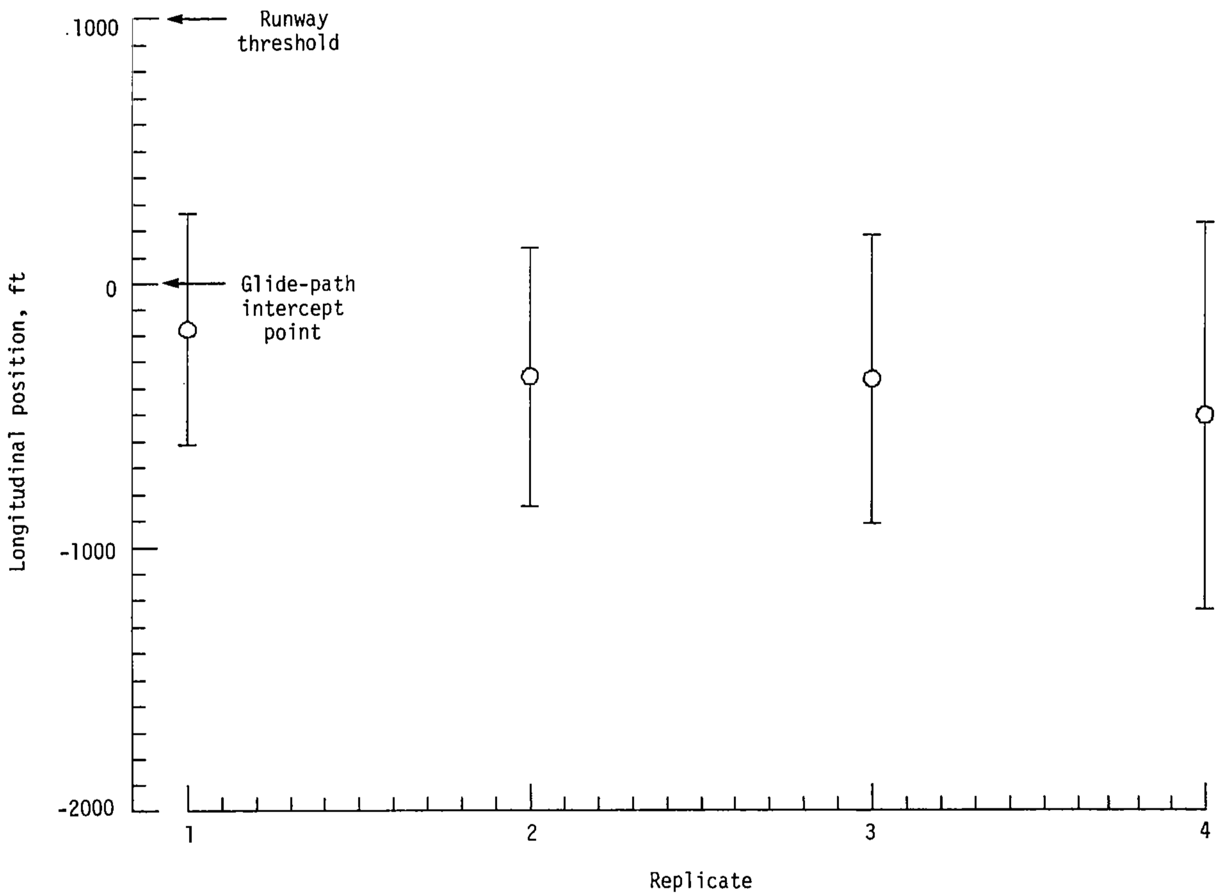
(b) Inertial vertical acceleration.

Figure 4.- Concluded.



(a) Longitudinal position at touchdown as a function of motion condition.

Figure 5.- Factor plots for longitudinal position measure.



(b) Longitudinal position at touchdown as a function of replicate number.

Figure 5.- Concluded.

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16. Abstract

Vertical-motion cues supplied by a g-seat to augment platform motion cues in the other five degrees of freedom were evaluated in terms of their effect on objective performance measures obtained during simulated transport landings under visual conditions. In addition to evaluating the effects of the vertical cueing, runway width and magnification effects were investigated. The g-seat was evaluated during fixed-base and moving-base operations. Although performance with the g-seat only improved slightly over that with fixed-base operation, combined g-seat and platform operation showed no improvement over platform-only operation. When one runway width at one magnification factor was compared with another width at a different factor, the visual results indicated that the runway width probably had no effect on pilot-vehicle performance. The few performance differences that were detected may be more readily attributed to the extant (existing throughout) increase in vertical velocity induced by the magnification factor used to change the runway width, rather than to the width itself.

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