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Douglas K. Shirachi
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Douglas K. Shirachi
Richard S. Shirley

Computer Sciences Corporation
1101 San Antonio Road
Mountain View, CA 94043

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NASA
National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035

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ABSTRACT

An experiment was performed to investigate the effects of bandwidth differences between visual and motion cueing systems on pilot performance for a coordinated roll task. In addition, for visual and motion cue configurations which were judged to be acceptable, the effects of reduced motion cue scaling on pilot performance were studied to determine the scale reduction threshold for which pilot performance was significantly different from full scale pilot performance.

The major conclusions were that (1) the presence or absence of high frequency (ω>3.5 rad/sec) error information in the visual and/or motion display systems significantly affects pilot performance, and (2) the attenuation of motion scaling while maintaining other display dynamic characteristics constant affects pilot performance.

INTRODUCTION

One of the purposes for real-time flight simulation is to investigate pilot performance while engaged in real-world maneuvers or procedures but operating in a controlled experimental environment. The use of flight simulators allows one to eliminate flight costs, decrease pilot risk, maximize repeatability of flight conditions and conveniently allow the use of elegant mathematical analysis techniques and procedures.

One goal of the simulation experimenter is to understand and quantify pilot performance for tasks which are mathematical representations of real-world situations and to extrapolate these results into the real aircraft environment. However, the limitations of various simulators directly affect the degree of simulation realism, and, hence, the degree to which the pilot performance data can be extrapolated from the simulator to the real aircraft.

In order to determine if these simulator limitations exist and how they affect pilot performance, an investigation of the dynamic characteristics of visual and motion display systems on pilot performance was undertaken at NASA-Ames Research Center. The first of these investigations was documented by Shirachi and Shirley[1] in their study on the effects of visual and motion display mismatches for a roll control task. This present study is a continuation of the procedures and techniques introduced by this earlier study but applied to a coordinated roll maneuver which has two degrees of freedom rather than only one.

This study investigates the effects of bandwidth differences between visual and motion cueing systems on pilot performance for a coordinated roll task. In addition, for visual/motion cue configurations which were judged to be acceptable during the previous experiment[1], effects of reduced motion cue scaling on pilot performance were studied to determine the scale reduction threshold for which pilot performance was significantly different from full scale pilot performance.

The effects of simulator motion on pilot performance had been reviewed in an earlier paper by Young[2] in which he concluded that a moving-base simulation provided an experience which was closer to that of actual flight than a fixed-base simulation. He noted that motion cues were more helpful to the pilot as the vehicle dynamics were degraded and that the angular rotations were a more important cue to simulate than the translational cues. Bergeron[3] observed no differences between motion and no motion conditions for single-axis rotational tasks; however, two-axis rotational tasks did produce greater tracking errors for the no-motion condition compared to the motion condition. Stapleford, Peters and Alex[4] recorded data which showed that the pilot describing function phase lag decreases when motion is introduced with a resulting increased mid-frequency gain and crossover frequency. Simulator motion also decreases the input-correlated error and the error remnant. Motion effects on the visual system are to increase visual gain and decrease visual lead at low frequencies. Ringland and Stapleford[5] concluded that motion primarily contributes towards the pilot's sense of realism. They also showed that attitude variables showed improvement with motion, but position variables showed very little effect. Junker and Replogle[6] showed that when motion was introduced to a simulation, the task learning rate and root-mean-squared (rms) error decreased substantially as the difficulty of the controlled vehicle dynamics increased. Schmidt and Conrad[7] showed that motion decreased the variation of the lateral and vertical deviation error scores when compared to a fixed-base condition. The scatter of the fixed-base error scores also increased as the simulated aircraft dynamics became less acceptable. One of their significant observations was that without motion cues, pilots were unable to damp out the dutch roll mode.

The presence or absence of selected axes of motion have been investigated by researchers such as Ringland, Stapleford and Magdaleno[8] who showed that for a hover task, the pilots preferred and performed better with only angular motion without coordinated linear motion. Linear motion cues were unimportant. Another study by Ringland and Stapleford[5] for a STOL approach task showed that pilots can use only linear motion cues without angular motion if the controlled dynamics are simple and the motion is related to the control activity. Szalai[9] has shown, using an airborne simulator, that pilots are insensitive to large amounts of lateral acceleration which conflict with the information displayed by the cockpit instruments. Levison and Junker[10] have investigated the effects of the presence or absence of the tilt cue in a roll control task. Their data showed that motion/no-motion performance differences were greater when the tilt cue was present than when the tilt cue was absent.

Looking at simulator cueing systems in more detail, Ringland, et. al.[8] have shown that pilots are sensitive to differences in motion lag time constants of the order of 0.2 seconds. In another study[5], he concluded that motion fidelity in the region of 1 rad/sec should be high since pilots use linear motion cues in this frequency region. He also showed that instrument scaling effects were more important than the effects of motion cues. Stapleford, et. al.[4] showed that the visual system was sensitive to low frequency cues, whereas high frequency cues were important to the motion sensors. Shirachi and Shirley[1] showed that cue conflict such as bandwidth reduction in either the motion or visual displays was not important to pilot performance; however, the presence of any wideband cue is a significant factor which improves performance. They also showed that for the task used in the experiment, pilot phase was the most sensitive measure to changes in display system bandwidth. Bergeron[3] showed that motion scaling for multi-axis tasks did not affect pilot performance unless scale factors were less than $\frac{1}{4}$. For smaller scale factors, the pilot error increased substantially; whereas, it remained nearly constant for scale factors between $\frac{1}{4}$ and full scale motion.

EXPERIMENTAL DESCRIPTION

The Experiment:

A digital computer simulation of a jet transport aircraft with motion in the roll and y axes (lateral plane) was used as a test vehicle for this investigation. The aircraft was disturbed by moderate turbulence which rolled the aircraft, which in turn, resulted in flight path deviations in the lateral direction. The pilot's task was to maintain flight formation behind the aircraft in front of him using a stick controller to compensate for flight path deviations resulting from the turbulence.

The purposes of the experiment were to determine the following: (1) the effect of a performance mismatch between the visual and motion display systems on pilot performance while engaged in a formation flying task and (2) the effect of a reduction in maximum motion amplitude on pilot performance for that same task (Figure 1).

The experimental matrix for this experiment is described as follows (Figure 2)

Display Case A - normal visual and motion displays (normal), consequently, a conflict of cues.

Display Case B - visual display degraded to match the motion display (low bandwidth), no cue conflict.

Display Case C - motion display compensated to match the visual display (high bandwidth), no cue conflict.

Display Case D - visual display degraded to match normal motion display and motion display compensated to match normal visual display (reverse normal), a conflict of cues.

The "normal" configuration of the visual and motion display systems denotes the dynamic performance characteristics of the equipment as delivered by the manufacturers to NASA-Ames Research Center. The visual system normally has a much wider response bandwidth than the motion system, and furthermore, the motion system servo response characteristics are also modified by the washout filters (see Display Systems). Thus, there is a bandwidth mismatch and a resultant conflict of cues. The "low bandwidth" configuration has the visual system response degraded to match that of the motion system; whereas, the "high bandwidth" configuration compensates the motion system so that its response bandwidth is increased to match that of the visual system. For sake of completeness, the "reverse normal" configuration with degraded visual response and compensated motion response was included within the experimental matrix.

The motion scale experiment was performed only for Display Cases A and C. Motion scales of 1, 3/4, 1/2 and 1/4 were used in the experiments, resulting in the experimental matrix shown on Tables I and II.

Aircraft Model:

The aircraft model used in this simulation was a Boeing 367-80 jet transport[11]. The aircraft airspeed was maintained at a constant 395 knots with wind turbulence introduced into the aircraft roll dynamics.

The turbulence model consisted of an eight-frequency, sum-of-sines input sequence shown on Table III whose spectrum was shaped to match a Dryden turbulence model[12]. The turbulence disturbance was scaled as a displacement spectrum rather than as a velocity distribution. The rms values for angular displacement, rate and acceleration of the disturbance are also given on Table III.

The simulation was implemented in digital form as a real-time foreground program with a cycle time of 0.05 seconds.

Display Systems:

The visual display consisted of a monochromatic television picture of the rear profile of the leading aircraft presented by a video monitor mounted within the simulator cockpit (Figure 3). The visual scene had only roll and y-axis motions, and the simulator cockpit was completely enclosed so that no visual orientation cues other than those provided by the visual display would be available to the pilot.

No cockpit instruments were used in this simulation. The video monitor was located approximately 69 cm (27 inches) from the pilot with the visual scene subtending an angle of $\pm$ 21 degrees in the horizontal direction and $\pm$ 16 degrees in the vertical direction. The wingspan of the aircraft in the visual scene subtended a horizontal angle of $\pm$ 11 degrees with respect to the pilot's viewing position. The position commands to the visual system were processed through a unity gain or a first-order low-pass filter degradation network, depending upon the display condition, before being passed on to the visual display servo system.

The motion display system used was the Six Degree-of-Freedom (S.01) simulator located at NASA-Ames Research Center. The simulator had a single-seat cockpit which could be operated in either closed or open cockpit mode and operated with three orthogonal rotational and three orthogonal translational motion axes. In the case of this experiment, the simulator motions were confined to the roll and y axes with closed cab. In order to minimize requirements for any large amplitude motions, a second-order, high-pass washout filter was inserted into the signal flow pathway between the aircraft dynamic equations and the motion simulator. This washout filter operated upon the second time-derivative of the roll error to produce both a roll motion command and an acceleration component in the aircraft y-axis. The washout filter was of the form

$$\frac{K_S{}^2}{S^2 + 2\zeta\omega_n S + \omega_n{}^2}$$

where $\zeta = 0.7$, $\omega_n = 0.7$ and $0 \leq K \leq 1.0$. The washout parameters ζ and ω_n, were chosen to achieve maximum simulator travel for full scale motion without violating the simulator performance limits. The gain factor, K, was varied between 0 and 1, depending upon the motion scale factor chosen for a particular experimental condition. The motion commands then pass through a unity or first-order lead compensation network before reaching the motion simulator. The effect of the motion cues was to represent coordinated motion cueing as would be felt by the pilot during a coordinated turn maneuver.

Pilot Control:

Aircraft control to correct for lateral course deviations created by the turbulence was limited to aileron control. The control stick device was a MacFadden control loader with minimal force gradient, break-out force and dead zone settings. These settings were chosen so that the control stick dynamic characteristics would have minimal effect on the pilot's control responses.

Subjects:

The five experimental subjects were experienced airline pilots who had logged between 2500 and 11,500 hours of flight time in jet aircraft. Many of the pilots also had extensive experience in other types of aircraft such as light aircraft and helicopters.

Experimental Procedures:

The training procedure consisted of a pilot briefing in which the subject was given a set of written instructions and a sample set of pilot rating charts. At this time any questions regarding the experiment were answered by the researcher. The pilot was then allowed to complete a few trial runs in the no-motion condition with the turbulence disturbance and then a few runs with simulator motion but no turbulence disturbance. Subsequently, simulator motion and turbulence disturbance were enabled, and the pilot was trained for a particular experimental sequence by allowing the subject to complete as many runs as needed in order to asymptotically stabilize his error scores for the given run condition. When error score stability was achieved, a new condition in the experimental sequence was introduced and the stabilization process was initiated once again. The training process was terminated when all of the conditions of the sequence had been individually completed.

The experimental procedure for each day's runs consisted of checking a known digital transfer function using the describing function algorithm, separate visual display and motion simulator describing function checks and a trial experimental run by a researcher.

An experimental run consisted of three contiguous segments which were input ramp, warmup and data recording. The input ramp segment consisted of a constant growth rate (ramp) of the input amplitude for the sum-of-sines until maximum desired scale was reached, followed by a 15 second pilot warmup period. The third period consisted of 108 seconds of continuous data storage into computer memory, yielding a total run length of 128 seconds.

Analysis Techniques:

Pilot describing functions were measured between the error signal and the pilot control output. Therefore, the describing functions also included the transfer functions for the visual and motion simulators. In order to extract the effects of changes in the visual and motion simulator dynamics, an analysis of variance was performed comparing all display conditions and then paired display conditions.

In addition to pilot describing functions, pilot performance scores and pilot remnant were recorded and analyzed. The average and standard deviation of the describing function and the parameters just described were also computed for each pilot and experimental condition.

A three-dimensional analysis of variance was performed on the pilot describing functions, remnant and pilot performance scores. For the display effects experiment, the dimensions of the experimental matrix were display case, pilot and trial with display case having a fixed effect and pilot and trial having random effects. For the motion scaling experiments, the motion scale dimension was substituted for the display case dimension in the analysis of variance with motion scale also having a fixed effect. Each measurement of pilot amplitude ratio, phase and remnant at separate frequencies, plus each pilot performance score was considered an independent measure of pilot performance. Because the same experimental subjects were used for all of the display cases as well as the motion scale cases, the three-dimensional analysis used in this experiment was a special case of a two-dimensional analysis with data replication.

A detailed investigation of the effects of the experimental display conditions upon pilot performance was conducted by performing a variance analysis for combinations of paired displays, i.e., Display Case A versus Display Case B, etc. In this manner, significant effects of visual or motion system changes on pilot performance could be extracted from the pilot describing function measurements.

For the motion scale experiment, a variance analysis for scale pairs, with one of the elements of the pair being the full scale condition, was performed. Since the full scale condition was considered as the baseline condition for comparison of the effects of scale factor changes, pilot performance for other scale factors were compared to that for full scale motion. This analysis was used to determine if a scale factor threshold existed below which performance was significantly degraded from that for full scale motion. This scale factor threshold would be determined by the appearance of a significant degradation of pilot performance for a particular value of the scale factor as the motion scale was decreased. For larger motion scale factors than this threshold value, pilot performance would not be significantly different than that for full scale motion.

The pilot rating data were not analyzed.

RESULTS

The effects of various display configurations are summarized by the Tables IV, V and VI.

Table IV shows the effects of changes in the visual and motion system characteristics on pilot performance. A decrease of visual bandwidth produces greater integral-squared error scores and lower amplitude ratios in addition to greater phase lags at low frequencies ($\omega<2.6$ rad/sec) where the visual system plays its important role in providing attitude cues[1,4]. An increase of motion bandwidth lowers the integral-squared error score, especially in combination with a low bandwidth visual configuration, and lowers high frequency phase lags ($\omega>2.6$ rad/sec).

The intent of this present experiment was to apply knowledge acquired from a previous single degree-of-freedom experiment (Experiment I) to a more complex, two degree-of-freedom, coordinated motion with motion washout experiment (Experiment II). Comparisons between the two experiments would allow the author to determine the effects of the tilt cue in an aircraft simulation context. These differences are summarized on Table V. The primary difference between the two experiments is that the pilot amplitude ratio showed significant differences between display configurations with the added y-motion, whereas this significance did not appear in the roll-only study. The significance of the phase lag results was not diminished by the additional amplitude ratio results of Experiment II, but the two measures in combination should indicate that more complex control strategies are to be expected when the number of degrees of freedom of a simulation are increased.

The effects of motion scaling are presented as they relate to the motion system bandwidth. The two display combinations, both with wideband visual system response but one with narrowband and the other with wideband motion response were chosen to measure pilot performance. Given one combination of visual and motion response bandwidths, the motion scale was changed and pilot performance measured for each of the motion scales chosen for the experiment. The procedure was then repeated for the other display condition. Data from the present experiment are compared to those of Bergeron[3] on Figure 7, showing that as the motion scale is decreased, the normalized error (normalized to the error at full scale motion) increases. However, these recent results do not show as dramatic an effect as those of Bergeron.

An analysis of variance of the pilot amplitude ratios and phases plus an inspection of the data show that pilot performance begins to degrade at a scale factor which is affected by the motion display bandwidth. Results for the analysis of variance and averages for various parameters are summarized on Table VI. Pilot performance is degraded at a scale factor of 0.25 for the low bandwidth motion case (Display Case A); whereas, pilot performance is affected by a scale factor as high as 0.75 for wideband motion (Display Case C). Thus, wideband motion display combinations appear to be more sensitive to motion scaling than low bandwidth motion displays.

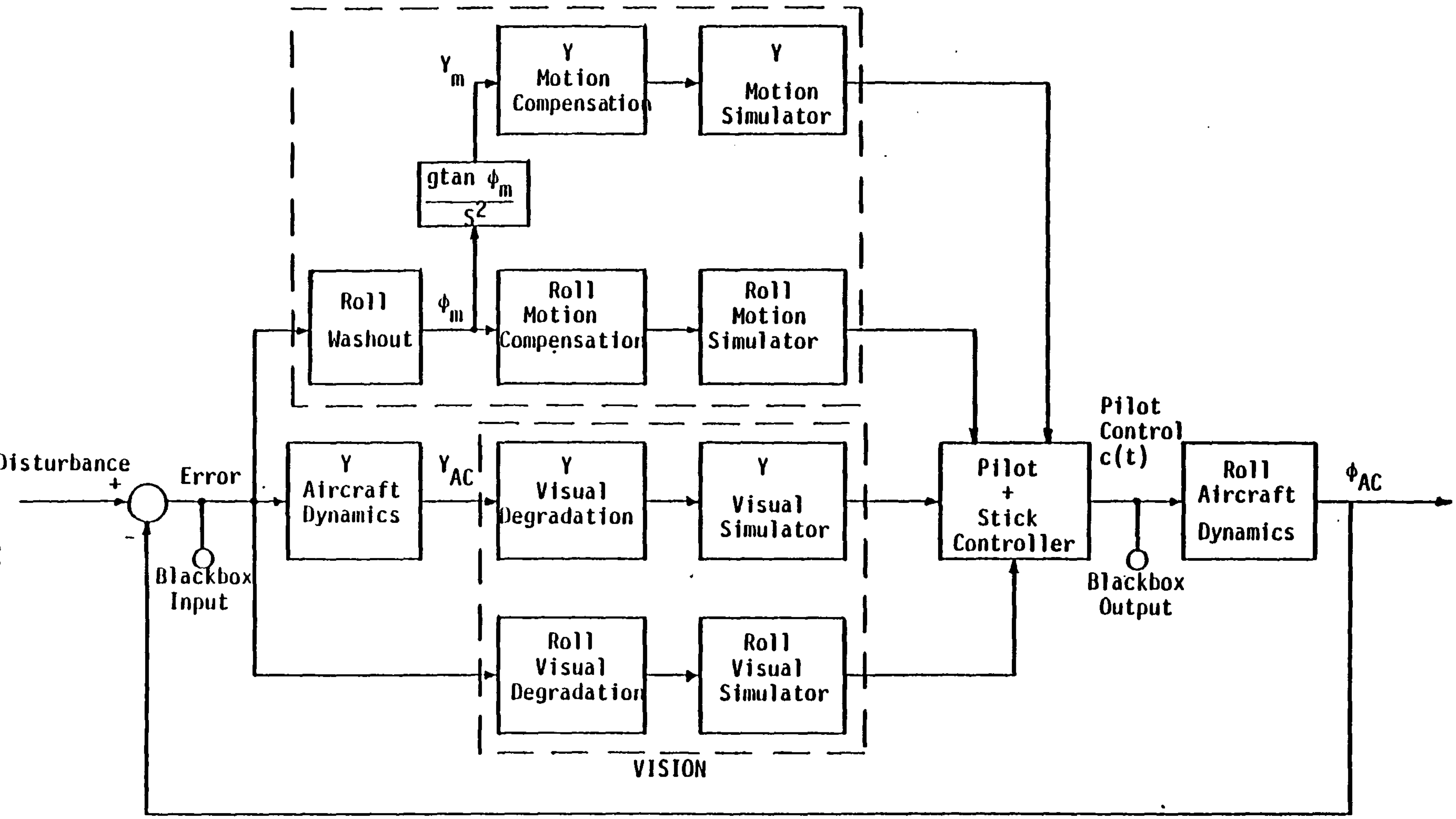


Figure 1: Experiment Block Diagram

Vision \ Motion	Normal	Compensated
Normal	**Vision** Roll: 1 Y: 1 **Motion** Roll: $\frac{1}{.21S+1}$ Y: $\frac{1-.083S+.002S^2}{1-.083S+.018S^2}$ (Case A)	**Vision** Roll: 1 Y: 1 **Motion** Roll: 1 Y: 1 (Case C)
Degraded	**Vision** Roll: $\frac{1}{.21S+1}$ Y: $\frac{1.022-.088S+.019S^2}{1+.285S-.001S^2}$ **Motion** Roll: $\frac{1}{.21S+1}$ Y: $\frac{1-.083S+.002S^2}{1-.083S+.018S^2}$ (Case B)	**Vision** Roll: $\frac{1}{.21S+1}$ Y: $\frac{1.022-.088S+.019S^2}{1+.485S-.001S^2}$ **Motion** Roll: 1 Y: 1 (Case D)

Figure 2: Simulator Cue Conditioning
(transfer functions)

Table I: Display Configuration Summary

Condition	Display Case	Scale Factor
a	A	1.0
b	A	0.75
c	A	0.50
d	A	0.25
e	B	1.0
f	C	1.0
g	C	0.75
h	C	0.50
i	C	0.25
j	D	1.0
k	A or C	no motion

Table II: Experimental Matrix

SCALE \ DISPLAY	Normal (Case A)	Low Bandwidth (Case B)	High Bandwidth (Case C)	Reverse Normal (Case D)
1.0	a	e	f	j
0.75	b		g	
0.50	c		h	
0.25	d		i	
no motion	(k)		(k)	

Table III: Sum-of-Sines Disturbance

Frequency (rad/sec)	Amplitude
0.35	.9
0.70	- .9
1.05	-1.0
1.75	.9
2.62	.7
3.49	- .5
6.28	- .2
10.50	.1

Displacement rms = 6.4 deg
Velocity rms = 11.7 deg/sec
Acceleration rms = 42.3 deg/sec^2

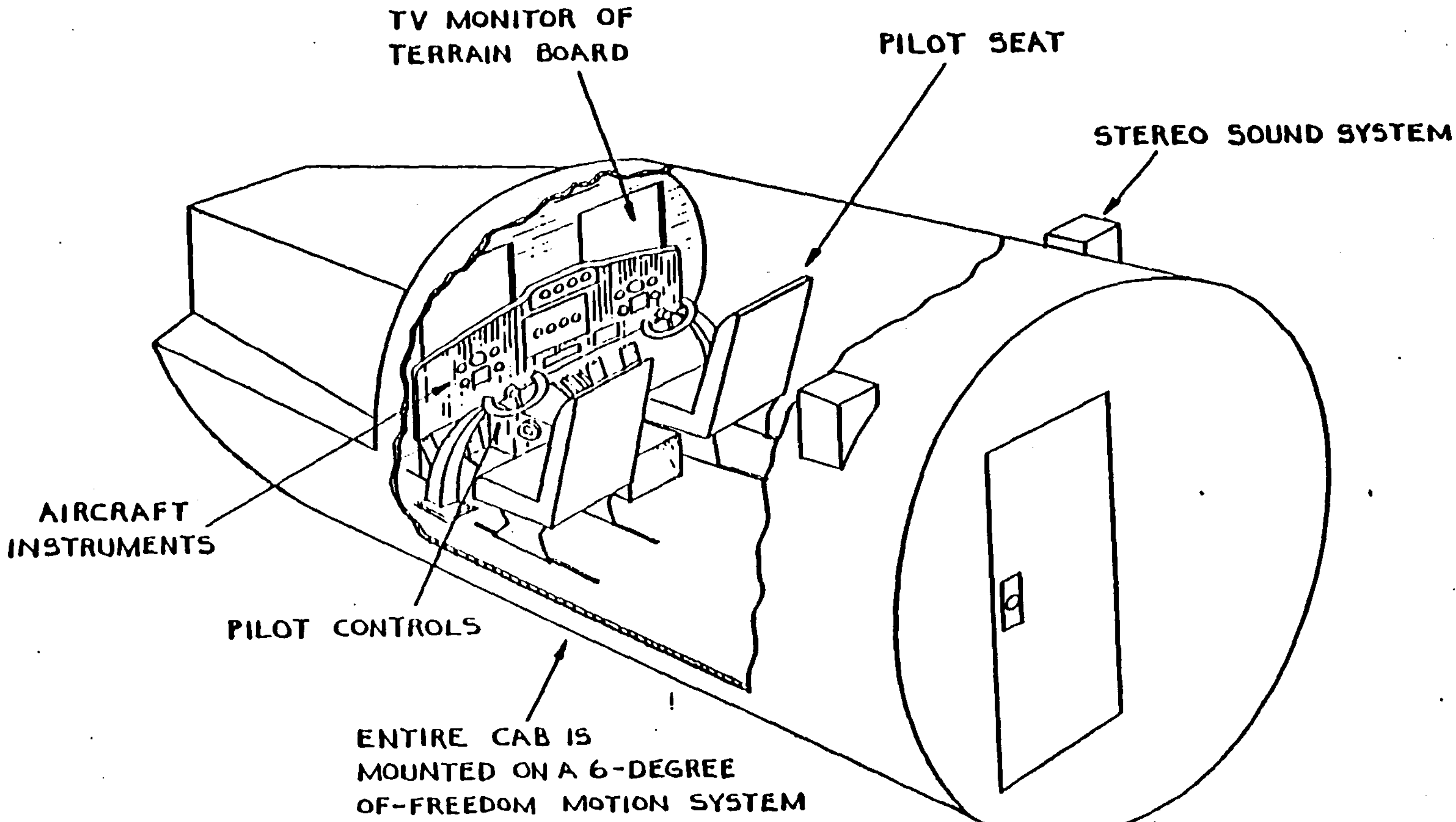


Figure 3: DIAGRAM OF SIMULATION CAB
(CUTAWAY VIEW)

Table IV: Summary of Display Effects

Visual Change:	Normal vision shows greater amplitude ratios. Less phase lag at low frequencies with normal vision. Degrading vision serves to produce a greater reliance on motion cues as shown by decreased phase lag at high frequencies. Lower error scores with normal vision (low bandwidth motion)
Motion Change:	Conflicting data for amplitude ratios. Lower phase lag at higher frequencies with increased motion bandwidth. Lower error scores with increased motion bandwidth, low bandwidth vision.

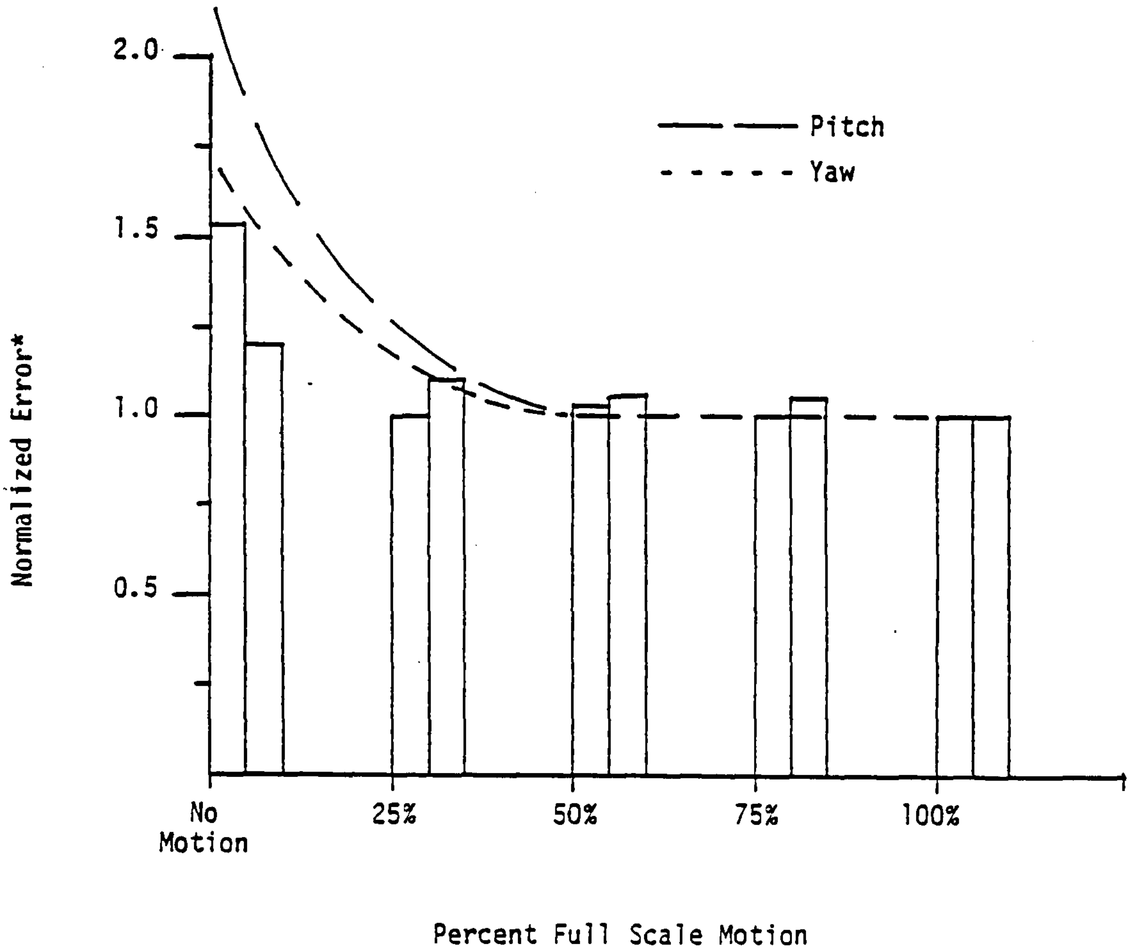
Table V: Comparison Between Experiments I and II

Displays Compared	Experiment I (Roll Only)	Experiment II (Roll-Y Coordination)
A & B	lower error scores with display A less phase lag (freq 4,5,6) at display A	lower error scores with display A less phase lag at low freq (3,5) but greater phase lag at high freq (7,8) at display A *greater amplitude ratios at display A (freq 3,7,8)
C & D	less phase lag (freq 4,5,6) at display C	no conclusive phase data *greater amplitude ratio at display C (freq 3,7,8)
A & C	less phase lag (freq 7,8) at display C	less phase lag (freq 6,7) at display C greater phase lag at freq 3 *greater amplitude ratio at display A (freq 3,5,6,7)
B & D	no significant effects	*lower error scores with display D *less phase lag (freq 5,7) at display D greater phase lag at freq 8 *amplitude ratio greater (freq 2) at display D

*Significant result which was not present in roll-only motion experiment

Table VI: Average Pilot Performance

Parameter	Display A (low bandwidth motion)	Display C (high bandwidth motion)
Pilot Amplitude Ratio	Significant change scale factor = 0.25	Significant change at scale factor = 0.75
Pilot Phase	Significant change at scale factor = 0.25	Significant change at scale factor = 0.75
Error Remnant	No effect	No effect
Controller Remnant	No effect	No effect
Average Integral Squared Error (ISE)	No effect	Increases with decreasing scale factor
Average Integral Squared Control (ISC)	Decreases with decreasing scale factor	Slight effect
Crossover Frequency	No effect	Decreases beginning at scale factor = 0.5



*error score normalized to error score for full motion

Figure 7: Motion Scaling Error

CONCLUSIONS

Displays:

1. The presence or absence of high frequency error information in the visual and/or motion display systems significantly affects pilot performance. In cases where the visual and motion display characteristics across the frequency spectrum between 0.4 and 10.5 rad/sec were not matched, the spectral disparity was not a major factor affecting pilot performance.

   Evidence for this conclusion is illustrated by the fact that Case B which has matched visual and motion cues, but low bandwidths, shows worse pilot performance than either Cases A or D which have this mismatch. This result implies that the pilot uses any high frequency cues which are available from the mismatched configurations to enable him to perform the task. Case C where the visual and motion cues are matched and have high bandwidth shows better performance than the mismatched cases. Therefore, it is best to have a matched set of high-bandwidth displays for the visual and motion systems; however, one can compromise one of the displays to low bandwidth operation, sacrificing optimum performance, without incurring a large performance penalty. This conclusion agrees with the first conclusion of the previous experiment[1].

2. As the task becomes more realistic by adding an additional degrees of freedom to the simulation, an increased number of performance measures become significant. In this case, a coordinated motion condition replaces a roll-only condition, thereby reducing the magnitude of

the tilt cue. The pilot adopts a strategy which permits him to exercise more control options, as reflected by a larger number of significant measurement variables as compared to a previously reported single degree-of-freedom case. He deemphasizes his phasing responses, distributing his actions between response magnitude (amplitude ratio) and control motion timing (phase). In addition, pilot error scores became significant, perhaps because of the sensitivity of the control task to small control corrections or because of the increased task realism.

This is in contrast to the roll motion only study reported previously where pilot phase was the only significant result. The authors predicted in the roll-only experiment that by increasing the simulation complexity, pilot amplitude ratios and error scores would show significant differences, and this is, indeed, the case.

Motion Amplitude:

1. The attenuation of motion scaling while maintaining other display dynamic characteristics constant affects pilot performance. Reduction of motion amplitude scale from 1.0 (relative to visual amplitude scale) to 0.75 shows a corresponding reduction of pilot amplitude ratios and phases. Further reductions of motion scale also causes decreased pilot amplitude ratios and increased phase lags.

   This conclusion modifies that of Bergeron[3] who noted that pilot performance was unchanged until the motion scale was reduced below a value of $\frac{1}{4}$ relative to the visual scale.

2. The high bandwidth motion system shows a greater effect of motion scaling on pilot performance than the low bandwidth system. That is, a larger number of pilot describing function frequency parameters are affected by changes in motion scaling for high bandwidth displays. In addition, the wider bandwidth motion system produced greater phase lags in the pilot describing functions, and the crossover frequency showed a noticeable reduction in value as the motion scale was decreased. This reduction in crossover frequency was not prominent for the low bandwidth motion system. The crossover frequency reduction occurred at a scale factor near 0.5 which is the value suggested by Conrad and Schmidt[14] for reduced force and rate scaling.

3. The effects of motion scaling on pilot performance is greater for the wide bandwidth motion system than for the low bandwidth system. One can interpret this result as signifying that the low motion bandwidth configuration is already sufficiently deprived of motion cues that further degradation of these cues shows no additional effects, whereas, the wide bandwidth motion system normally displays a wide spectrum of cues so that any degradation such as bandwidth limiting or amplitude scaling has an effect on pilot performance.

Tilt Cues:

It has been reported by other researchers[10,13] that the tilt cue plays a significant role in providing motion information to the pilot while he is performing a simulated aircraft flying task. Strong evidence for the use of this cue is provided by the fact that the experimental results of three independent research teams[1,10,15] arrived at basically the same results for a roll tracking task.

The tilt cue provides strong, reliable feedback information to the pilot regarding the effectiveness of his control motions. The motion feedback differs from the visual information in that the pilot's vestibular apparatus is well-suited for extracting velocity and acceleration information from body motion, whereas the visual system is an excellent position observer but not well suited for extracting time derivative information.

However, it would appear that the motion cues provided by a roll only, compensatory experiment are unrealistic because normal aircraft motion is "coordinated". That is, a rotational motion is coupled with a lateral acceleration so that in a steady-state configuration, the specific force vector maintains a vertical orientation (z-axis) with respect to the aircraft body axis. Rotational motion without the coupled lateral acceleration, as in a roll only tracking task, rotates the specific force vector about the roll axis and provides undesirable and unrealistic motion cues.

Since a rotational motion only experiment is "unnatural", such a simulation could convince a pilot into thinking that he is faced with an emergency situation which is endangering his aircraft and perhaps passengers. This situation demands immediate correction, thus one observes the significant changes in pilot phase, which are related to control motion timing, as the task demands change. The greater the amount of tilt cue present, the greater the severity of the simulated motion as interpreted by the pilot and the greater his attention to task regulation.

With coordinated motion, the pilot can distribute his performance between control motion amplitude and timing as he would normally during a routine compensatory flight. Therefore, one could expect additional sets of parameters besides pilot phase to be significant when the experimental task is changed from a single degree-of-freedom roll only task to a two degree-of-freedom coordinated roll motion task. In the case of this experiment, pilot amplitude ratios were the additional parameters which were significant.

Levison and Junker[10] show that significant differences between motion and no-motion occur when the tilt cue is present; whereas, when the tilt cue is absent as in their supine experiments, there are no significant differences between motion and no-motion. The present experiment which has the tilt cue only during the transient period between coordinated states can be considered as an intermediate condition between the tilt cue and no tilt cue conditions of Levison and Junker[10]. The coordinated task shows significance in pilot describing functions between motion and no-motion conditions even though the tilt cue was absent for a significant portion of the time due to steady-state coordination of the motion; however, the cue was present during transient periods and seemed to provide sufficient directional cueing to allow the pilot to perform the task better with motion cues.

With motion scaling, significant differences between motion and no-motion existed with motion scales as small as 50% of full scale. This result shows that the motion scale cannot be reduced below 50% of the visual scale without the pilot performance behaving similarly to an absence of motion. This figure is in agreement with Conrad and Schmidt[14] who recommend an angular rate scaling of 0.5 as reasonable and 0.4 as a lower bound.

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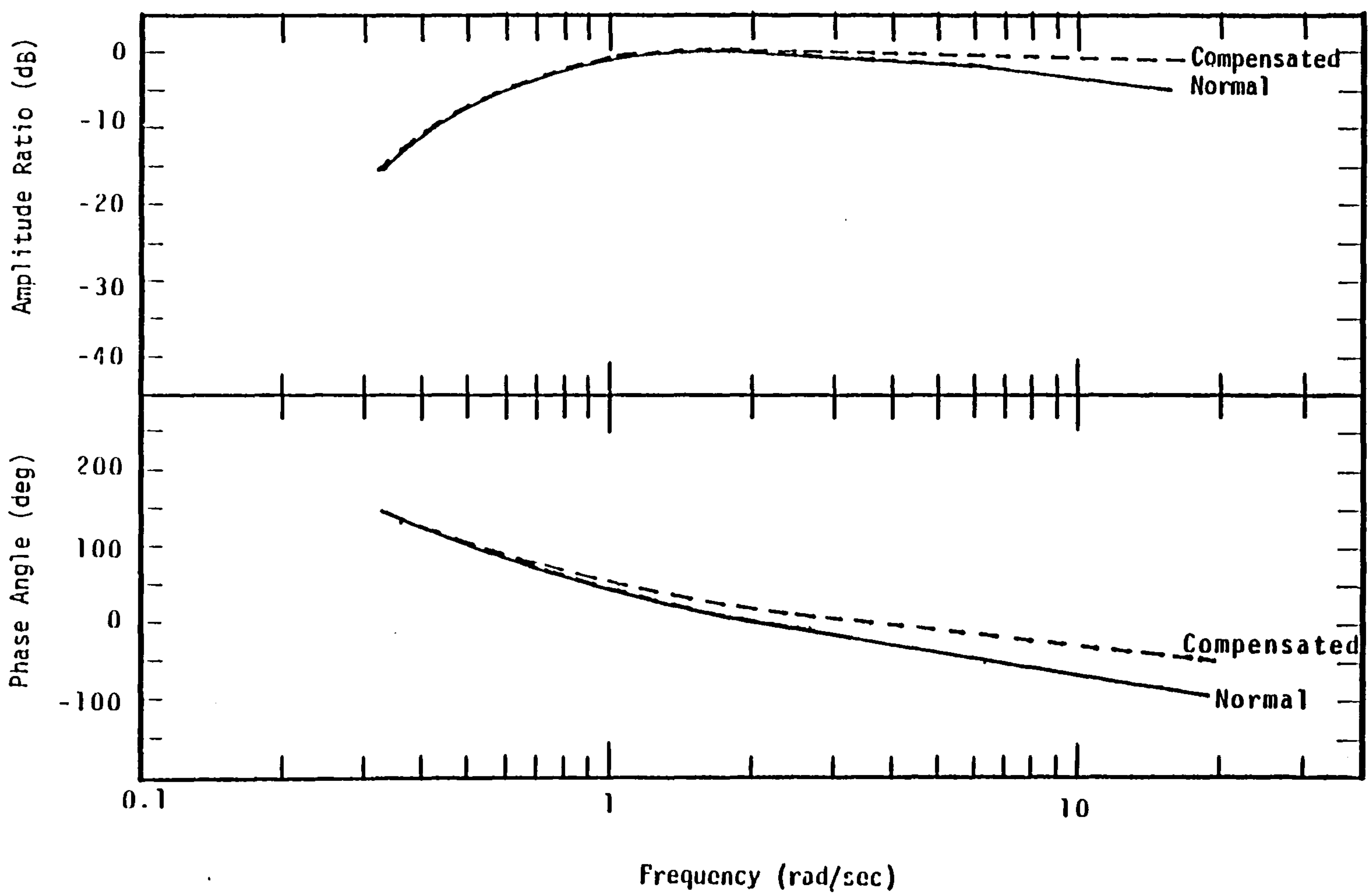
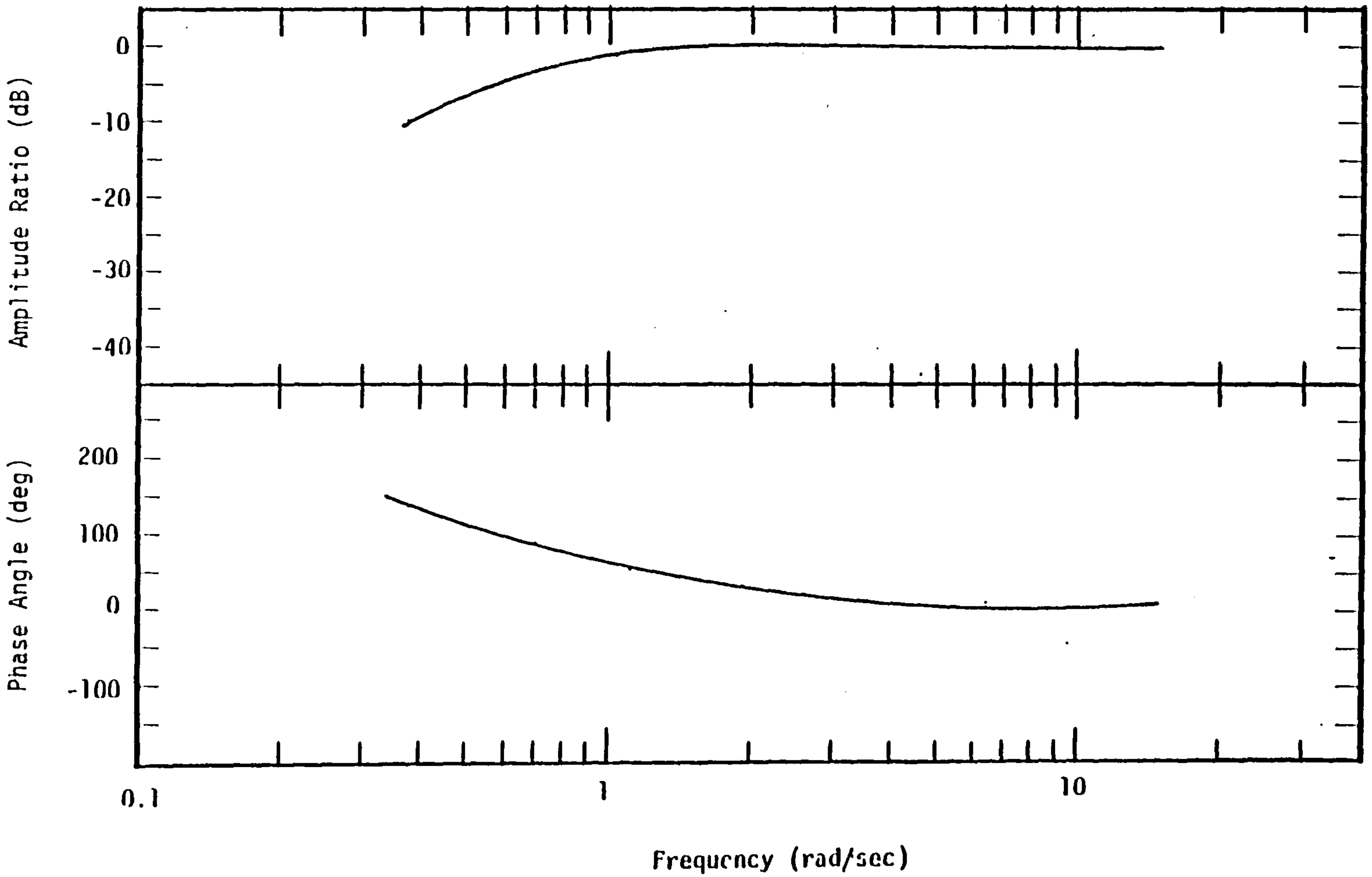
Appendix I

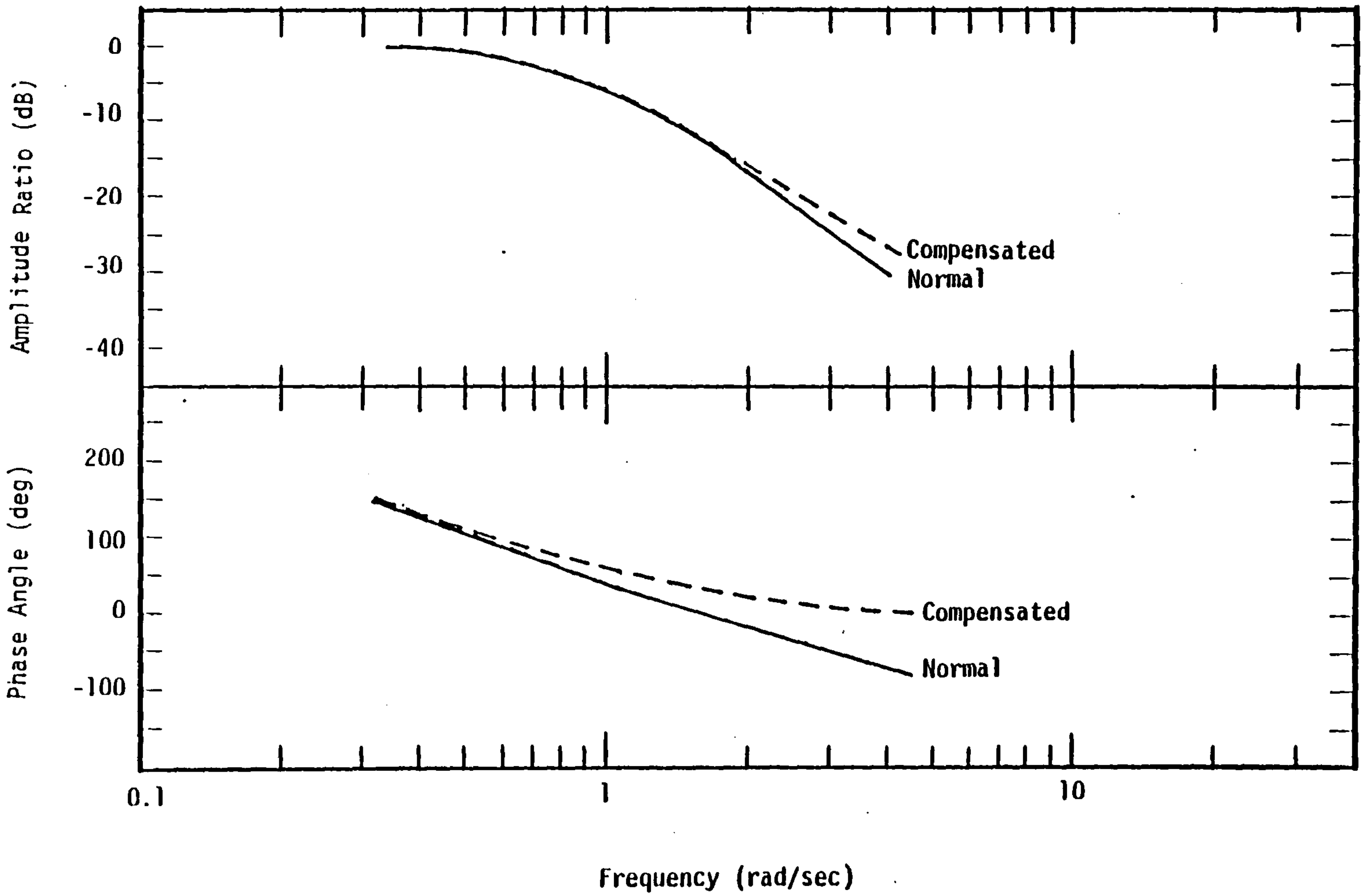
Simulator Transfer Functions



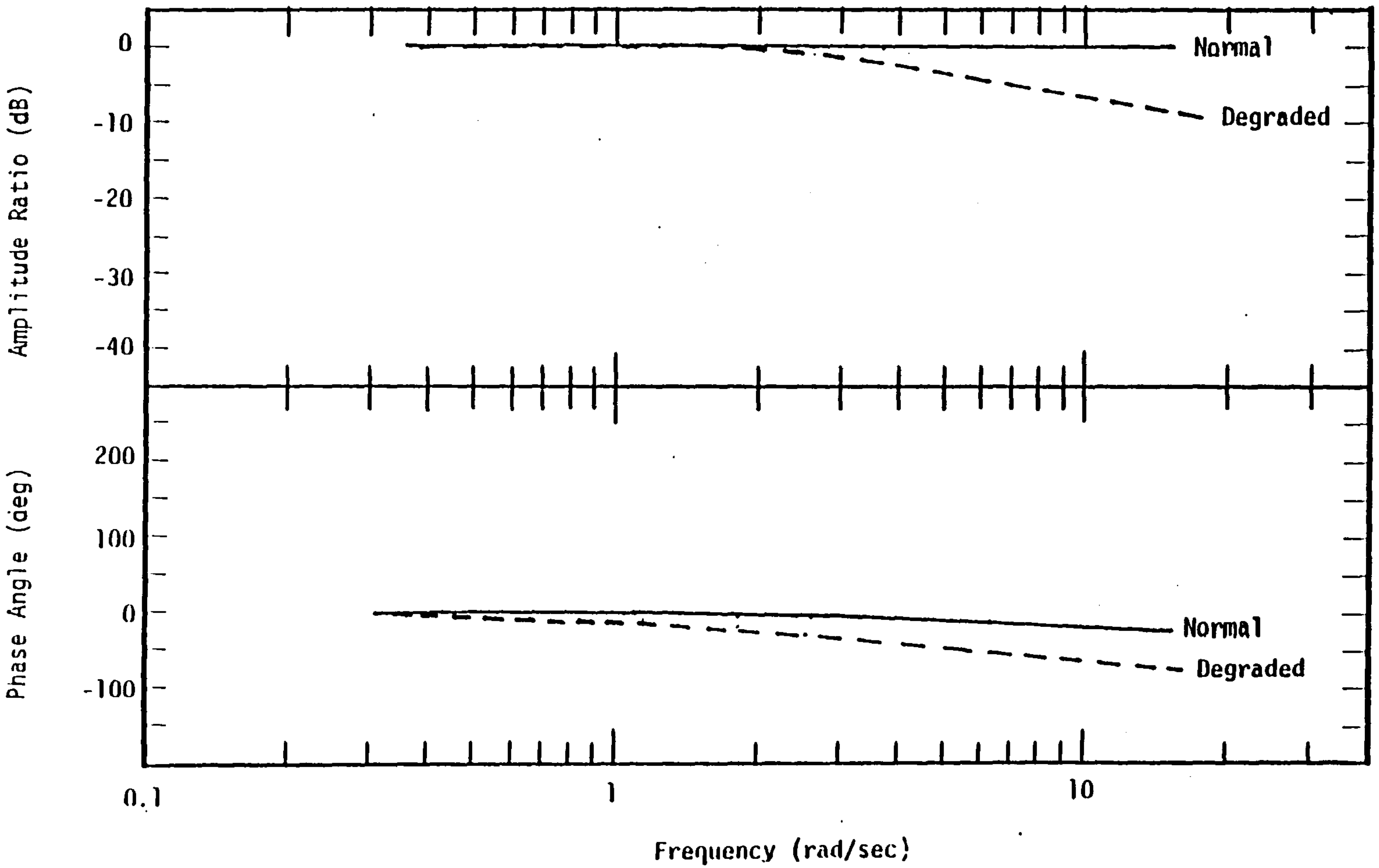
Motion Roll Transfer Function



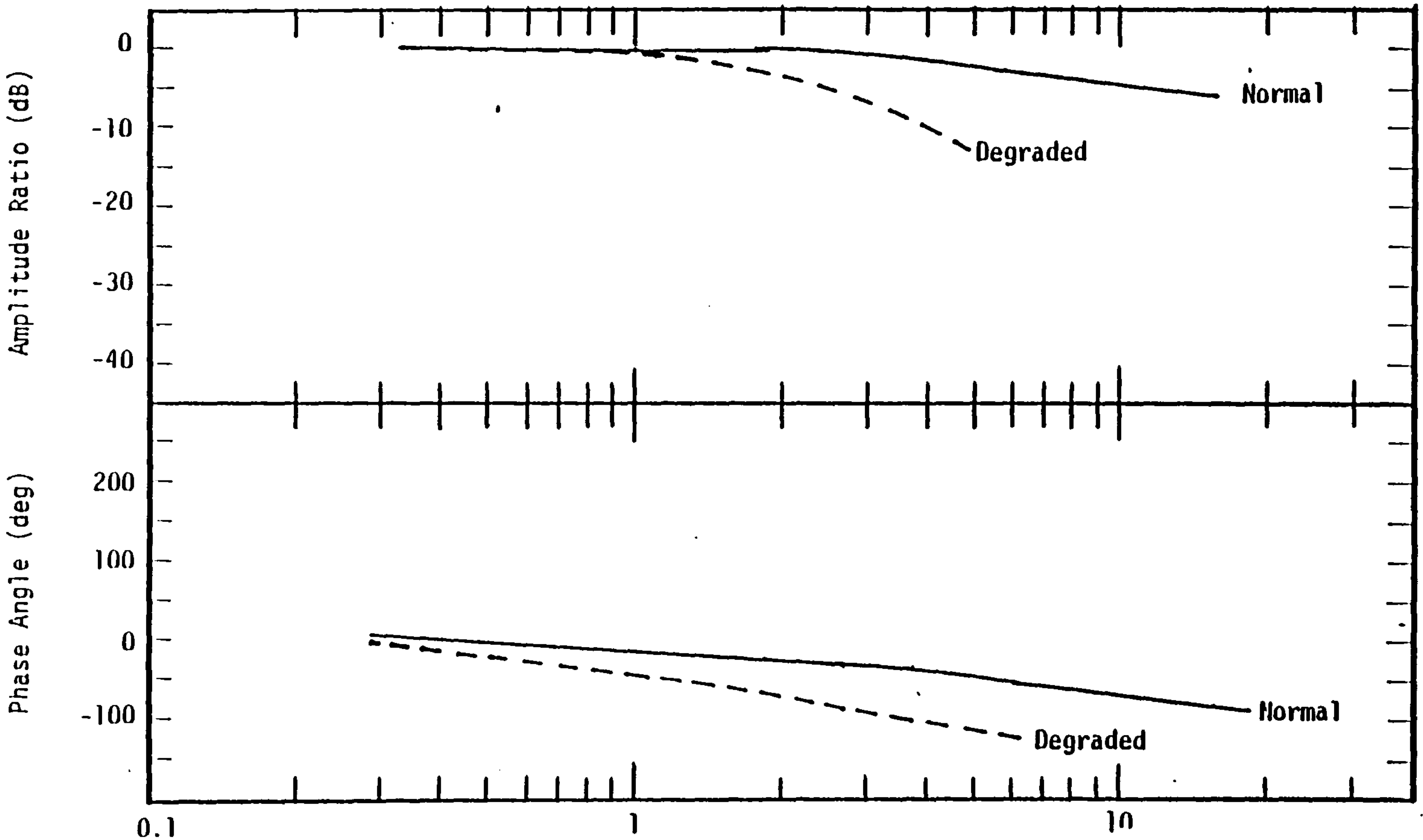
Washout Transfer Function



Motion Y Transfer Function



Visual Roll Transfer Function



Frequency (rad/sec)

Visual Y Transfer Function

Appendix II

Data

Table I: Display Effects

Amplitude Ratio (dB)

Freq. (rad/sec)	Display Case			
	A	B	C	D
.35	-10.8	-10.1	-10.1	-8.7
.70	-12.2	-12.8	-11.4	-10.5
1.05	-12.7	-12.8	-12.5	-13.0
1.75	-11.4	-12.2	-11.8	-12.0
2.62	-10.5	-10.8	-11.0	-10.8
3.49	-9.3	-9.7	-9.9	-9.8
6.28	-6.9	-7.1	-6.6	-7.3
10.47	-3.9	-5.7	-5.0	-5.9

Table II: Display Effects

Phase (deg)

Freq. (rad/sec)	Display Case			
	A	B	C	D
.35	-16.6	-63.4	-55.0	-46.8
.70	-28.5	-24.4	-23.8	-21.1
1.05	-48.3	-52.9	-61.9	-51.3
1.75	-45.9	-50.9	-47.2	-50.8
2.62	-45.7	-52.7	-44.4	-44.9
3.49	-49.8	-50.4	-41.9	-48.3
6.28	-48.3	-42.0	-22.3	-35.3
10.47	-98.8	-104.2	-101.0	-103.8

Table III: Display Effects

Remnant (dB)

Freq. (rad/sec)	Display Case			
	A	B	C	D
.17	-20.7	-21.4	-25.1	-23.1
.52	-14.5	-11.9	-16.4	-14.1
.87	-6.1	-5.7	-6.9	-5.9
1.57	-5.0	-3.9	-4.3	-4.6
2.09	-0.8	-3.2	-1.5	-4.8
3.14	-0.8	-5.6	-4.2	-6.9
5.24	-8.7	-9.6	-8.2	-9.7
7.85	-10.5	-15.8	-12.6	-12.8
15.7	-18.1	-23.8	-24.8	-21.0

Table IV: Display Effects

Average Pilot Performance Scores

Parameter	Display Case			
	A	B	C	D
Average Integral Squared Error (ISE) (degrees^2)	191.7	228.9	174.6	194.0
Average Integral Absolute Error (IAE) (degrees)	40.1	44.7	38.8	40.8
Average Integral Squared Control (ISC) (rad^2)	2.1	1.4	1.5	1.2
Average Integral Absolute Control (IAC) (rad)	3.8	3.2	3.1	3.0
Activity Ratio (ISC/ISE) (dB)	-19.6	-22.1	-20.7	-22.1
Crossover Frequency (rad/sec)	0.87	0.83	0.91	0.93

Table V: Motion Scaling: Display A

Amplitude Ratio (dB)

Frequency (rad/sec)	Scale Factor				
	1	.75	.5	.25	No Motion
.35	-10.4	-11.0	-11.5	-12.3	-12.9
.70	-12.6	-12.7	-12.2	-12.2	-13.2
1.05	-12.4	-13.0	-12.6	-13.2	-13.3
1.75	-11.5	-12.0	-12.2	-12.8	-13.4
2.62	-10.7	-11.0	-11.3	-11.7	-12.9
3.49	-9.6	-10.0	-10.7	-11.4	-11.4
6.28	-6.6	-6.7	-7.2	-7.3	-8.2
10.47	-4.7	-6.3	-6.7	-8.7	-11.6

Table VI: Motion Scaling: Display A

Phase (deg)

Frequency (rad/sec)	Scale Factor				
	1	.75	.5	.25	No Motion
.35	-31.3	-19.7	-24.8	-48.6	-65.5
.70	-33.3	-33.3	-42.4	-29.9	-45.1
1.05	-14.9	-17.3	-26.5	-23.3	-31.2
1.75	-12.5	-17.2	-18.0	-21.6	-26.0
2.62	-11.9	-19.8	-13.4	-24.4	-18.6
3.49	-15.6	-27.0	-19.2	-30.8	-17.6
6.28	-72.8	-83.1	-71.0	-90.4	-86.7
10.47	-125.8	-157.6	-145.2	-80.3	-85.7

Table VII: Motion Scaling: Display A

Remnant (dB)

Frequency	Scale Factor				
	1	.75	.5	.25	No Motion
.17	-22.8	-22.2	-22.4	-23.8	-22.9
.52	-15.1	-14.0	-16.0	-15.2	-14.7
.87	-6.3	-7.4	-9.1	-11.5	-10.6
1.57	-31.6	-1.2	-0.9	-4.8	-1.4
2.09	-0.6	-1.0	-0.9	-2.0	-0.9
3.14	-0.9	-3.8	-6.0	-7.2	-4.6
5.24	-9.2	-7.7	-8.1	-10.5	-8.5
7.85	-11.8	-12.7	-12.3	-12.5	-11.4
15.7	-23.6	-21.1	-24.2	-24.7	-23.0

Table VIII: <u>Motion Scaling: Display A</u>

Average Pilot Performance Scores

Parameter	Scale Factor				
	1	.75	.5	.25	No Motion
Average Integral Squared Error (ISE) (deg^2)	197.7	201.1	210.8	187.2	231.2
Average Integral Absolute Error (IAE) (deg)	40.4	41.0	42.2	40.1	44.3
Average Integral Squared Control (ISC) (rad^2)	2.1	1.8	1.4	1.1	1.4
Average Integral Absolute Control (IAC) (rad)	3.6	3.2	2.9	2.4	2.6
Activity Ratio (ISC/ISE) (dB)	-19.7	-20.5	-21.8	-22.3	-22.2
Crossover Frequency (rad/sec)	0.85	0.84	0.87	0.87	0.80

Table IX: Motion Scaling: Display C

Amplitude Ratio (dB)

Frequency (rad/sec)	Scale Factor				
	1	.75	.5	.25	No Motion
.35	-9.8	-11.0	-11.9	-12.2	-12.9
.70	-11.5	-11.3	-12.5	-12.6	-13.2
1.05	-12.8	-12.4	-12.7	-13.3	-13.3
1.75	-12.1	-12.1	-12.6	-13.1	-13.4
2.62	-11.3	-11.1	-11.7	-12.6	-12.9
3.49	-10.3	-10.6	-11.0	-11.8	-11.4
6.28	-6.9	-7.3	-7.7	-8.5	-8.2
10.47	-6.5	-6.8	-8.1	-9.8	-11.6

Table X: Motion Scaling: Display C

Phase (deg)

Frequency (rad/sec	Scale Factor				
	1	.75	.5	.25	No Motion
.35	-49.2	-69.2	-15.0	-41.6	-65.5
.70	-29.7	-34.7	-20.4	-6.8	-45.1
1.05	-66.6	-62.3	-62.9	-76.0	-31.2
1.75	-47.2	-56.9	-60.7	-64.0	-26.0
2.62	-41.3	-56.4	-57.6	-65.3	-18.6
3.49	-46.3	-50.4	-62.8	-68.6	-17.6
6.28	-22.2	-51.5	-40.0	-41.5	-86.7
10.47	-100.3	-102.8	-126.3	-99.4	-85.7

Table XI: Motion Scaling: Display C

Remnant (dB)

Frequency (rad/sec)	Scale Factor				
	1	.75	.5	.25	No Motion
.17	-22.8	-22.2	-22.4	-23.8	-22.9
.52	-15.1	-14.0	-16.0	-15.2	-14.7
.87	-6.3	-7.4	-9.1	-11.5	-10.6
1.57	-31.6	-1.2	-0.9	-4.8	-1.4
2.09	-0.6	-1.0	-0.9	-2.0	-0.9
3.14	-0.9	-3.8	-6.0	-7.2	-4.6
5.24	-9.2	-7.7	-8.1	-10.5	-8.5
7.85	-11.8	-12.7	-12.3	-12.5	-11.4
15.7	-23.6	-21.1	-24.2	-24.7	-23.0

Table XII: Motion Scaling: Display C

Average Pilot Performance Scores

Parameter	Scale Factor				
	1	.75	.5	.25	No Motion
Average Integral Squared Error (ISE) (deg^2)	151.8	165.9	165.3	189.6	231.2
Average Integral Absolute Error (IAE) (deg)	36.4	37.7	37.8	40.1	44.3
Average Integral Squared Control (ISC) (rad^2)	1.1	1.3	1.0	0.8	1.4
Average Integral Absolute Control (IAC) (rad)	2.6	2.7	2.4	2.1	2.6
Activity Ratio (ISC/ISE) (dB)	-21.4	-21.1	-22.2	-23.7	-22.2
Crossover Frequency (rad/sec)	0.90	0.91	0.85	0.84	0.80

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Technical Monitor: William B. Cleveland, Mail Stop 243-9, NASA Ames Research Center, Moffett Field, CA 94035 (415) 965-5352; FTS 448-5352

16. Abstract An experiment was performed to investigate the effects of bandwidth differences between visual and motion cueing systems on pilot performance for a coordinated roll task. In addition, for visual and motion cue configurations which were judged to be acceptable, the effects of reduced motion cue scaling on pilot performance were studied to determine the scale reduction threshold for which pilot performance was significantly different from full scale pilot performance.

The major conclusions were that (1) the presence or absence of high frequency ($\omega >$ 3.5 rad/sec) error information in the visual and/or motion display systems significantly affects pilot performance, and (2) the attenuation of motion scaling while maintaining other display dynamic characteristics constant affects pilot performance.

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