ADVANCED DYNAMIC SEATS: AN ALTERNATIVE TO PLATFORM MOTION?

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Summary

The experimental program described in this paper is investigating advanced dynamic seats (g-seats) as an alternative to platform motion systems. The studies have quantified the effects of dynamic seat cuing on the performance of a roll-axis turbulence regulation task, and on transfer of training to a whole-body motion simulator. The studies have clearly demonstrated that the dynamic seat can elicit tracking performance and manual control behavior equivalent to that observed with whole-body motion. To date, significant transfer of training from the dynamic seat to whole-body motion has only been observed with pilot subjects. Techniques to achieve the same training benefit with naive trainees are being pursued.

Introduction

Over the past four years the Armstrong Aerospace Medical Research Laboratory and the Aeronautical Systems Division have investigated the potential of advanced dynamic seats as aircraft motion cuing devices. In particular we have addressed two questions: (1) Can a dynamic seat elicit performance in a motion-sensitive task equivalent to that observed in a whole-body motion device? (2) Does training on a dynamic seat transfer to a whole-body motion simulator? The studies have not addressed the question of when motion cuing is required in a flight training program. In addition, we have assumed that a ground-based, whole-body motion simulator is an appropriate criterion device. As a result, we do not expect that the exact dynamic seat drive algorithms employed in these studies will be appropriate for aircraft simulation. However, we do believe that the same principles and procedures can be applied in the aircraft simulation context.

Our investigations of the dynamic seat have dealt with the issue of simulation fidelity on several levels. The initial studies focused on the physical fidelity of the simulation of whole-body motion. The second phase might be labled an information fidelity approach, i.e. attempting to provide the simulator pilot with the same aircraft motion state information that the whole-body simulator provides. Our current studies are addressing the issues of perceptual fidelity and instructional strategy. The perceptual fidelity studies will determine if increasing the experiential similarity of the dynamic seat and whole-body motion simulator has any significant effect on performance or transfer of training. The instructional strategy studies will take a very different tack. Given a relatively low fidelity simulation, effective training may still be accomplished by identifying specific skills or capabilities that are required for performance in the criterion device, and developing a procedure that trains or permits the learning of these skills.

There are several reasons for the interest in dynamic seats as an alternative to platform motion systems. First, the tactual (somatosensory and kinesthetic) stimulation that the seats provide is also present in flight, where it may be an important source of motion information[1]. It is also well known[2] that the tactual sensory system is highly sensitive and responsive. Therefore, it should be capable of conveying information concerning rapid changes in the motion and force environment. The dynamic seat also places fewer constraints on simulator design. Finally, the life-cycle cost of the dynamic seat system is expected to be approximately 40% of that of a platform motion system[3].

Background

The dynamic seat display concept was originally developed under the trade name "DYNASEAT" in 1962[4]. However little was done with the idea until the mid-1970's when "g-seats" were installed in NASA and Air Force research simulators[5,6]. As reviewed by Puig, Harris, and Ricard[7], studies of the cuing effectiveness of dynamic seats have shown mixed results. Those studies reporting positive results typically simulated flight control scenarios where normal g-force cues were believed to be a primary source of information for the pilot[8,9]. On the other hand, attempts to use dynamic seats for rotational motion cuing have been generally unsuccessful[10,11]. This pattern of results should not be particularly surprising, since the seats used in these experiments were designed primarily to provide sustained normal g-force cues and had relatively low bandwidth[5,6,12].

Dynamic seats specifically designed to display "onset" as well as sustained motion information are now commercially available. The research reviewed in the present paper utilized the Advanced Low Cost G-cuing System (ALCOGS), a prototype device designed for research purposes[13]. Like the commercially available devices, the primary advantage of the ALCOGS over previous g-seats is its frequency response (gain bandwidth in excess of 1Ø Hz).

General Method

Subjects

A total of 51 male and female subjects participated in this series of studies. With the exception of 8 pilots who served in one of the experiments, all reported no flight control experience. The nonpilot subjects also were naive with respect to the type of tracking task used in these studies. They were between 18 and 3Ø years of age, in generally good health, and were fully capable of performing the assigned task with their right hand. The flight experience of the pilots was widely varied, as will be discussed later.

Apparatus

Two motion display devices were used: (1) the dynamic seat subsystem of the ALCOGS, and (2) the Roll Axis Tracking Simulator (RATS), a whole-body motion device. The dynamic seat includes hydraulically-actuated seat pan, backrest and seat belt elements mounted in an aircraft seat frame (Figure 1). In these studies, the seat pan was the only active cuing element. The rigid seat pan was thinly padded and contoured to emphasize contact in the thigh area and in the region of the ischial tuberosities of the buttocks. Details of the dynamic seat hardware are given by Kleinwaks[14].

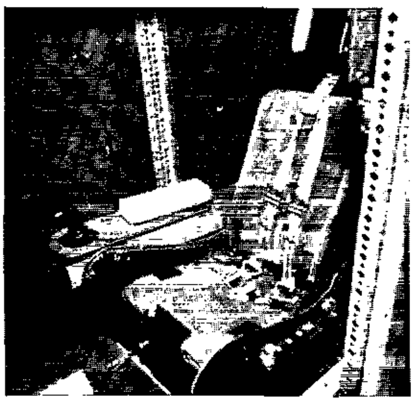


Figure 1. The Dynamic Seat

The RATS served as the criterion motion device (Figure 2). It is capable of 36Ø deg motion in the roll axis but was constrained to ± 9Ø deg travel in these experiments. The axis of rotation was through the subject's buttocks. The seat pan in the RATS was contoured identically to that in the dynamic seat, but was fixed with respect to the simulator frame. As shown in the figures, both simulators were enclosed to eliminate viewing of external visual references. Nine inch (diagonal) monitors were mounted at eye level and approximately 26 inches in front of the subject in the RATS and dynamic seat. These monitors were used for displaying the tracking task and for providing performance feedback in most experimental conditions. In the experiments which involved the manual control task, subjects made their tracking inputs using an isometric force-sensitive control stick that was mounted in an arm rest on the right side of each simulator.

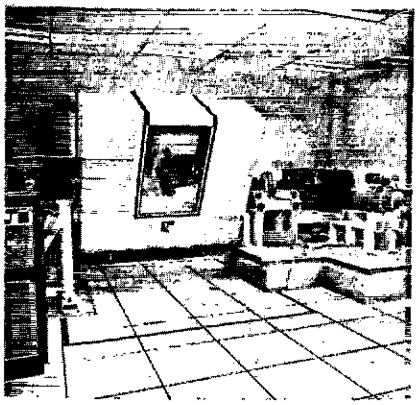


Figure 2. The Roll Axis Tracking Simulator

The RATS and dynamic seat were incorporated in a hybrid simulation consisting of an EAI 58Ø analog computer, a DEC PDP 11/6Ø digital computer, a GT-4Ø vector graphics system, and analog/digital conversion devices. The vehicle dynamics, simulated on the EAI 58Ø, were representative of the roll response of a fighter aircraft. The overall controlled plant dynamics, expressed in terms of the Laplace operator "s", were:

$$\frac{P(s)}{U(s)} = \frac{16}{s} \times \frac{1}{Ø.2s+1} \times \frac{e^{-.Ø75s}}{Ø.Ø5s+1} \qquad (1)$$

where P(s) is the aircraft roll angle in deg, and U(s) the control force in pounds applied to the control stick. The numerator dynamics include the stick gain of 16 deg/s commanded velocity per pound of control force, and the total effective transport delay (75 ms) resulting from the low-pass filters in the simulator, the dynamics of the ALCOGS seat pan, and quantization effects due to sampling[15]. The denominator dynamics include an integrator which converts roll velocity to roll angle, the simulated aircraft roll dynamics (200 ms time constant), and the RATS cab dynamics (50 ms time constant). Identical dynamics were involved whether the subject was performing in the RATS, the dynamic seat, or with the visual display alone. In addition, detailed measurements confirmed that the visual and motion displays were synchronized to within 5 ms. The simulation was operated at 100 Hz under all experimental conditions. Recorded signals were sampled at a 25 Hz rate, which was sufficient for the Digital Fourier Transform analyses routinely conducted on the experimental data.

Tracking Task

A roll-axis compensatory tracking task was also implemented in the simulation. The task objective was to maintain wings-level flight in the presence of strong roll turbulence. This task has been extensively used and refined in our laboratory, and is highly sensitive to the presence of motion information[16]. That is, performance of this task is significantly improved when whole-body motion is provided. The gust disturbance was composed of 13 sinusoids ranging in frequency from 0.2 to 32 rad/s. The amplitudes of the sinusoids were weighted to represent white noise passed through a low-pass filter with a double pole at 2 rad/s. The phases of the frequency components were randomized for each 3 min tracking trial, making the signal unpredictable.

Tracking error was provided visually using the displays shown in Figure 3. (In the experiments which compared the two displays, the type of moving element was not found to be a significant variable.) The dotted line subtended a visual angle of approximately 9 deg. The display gain was set so that 1 deg of displayed roll error corresponded to 1 deg of vehicle roll angle.

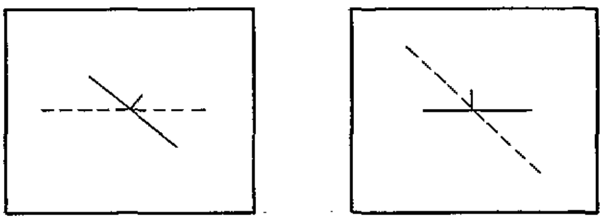


Figure 3. The Visual Displays

Physical Fidelity Studies

Development Of A Pressure-matching Algorithm

Given the lack of any generally accepted methodology for displaying roll-axis motion information using a dynamic seat[10,13], the initial phase of this research addressed the development of a viable drive algorithm for evaluation. We postulated that a reasonable first approach was to drive the dynamic seat so that the contact pressures produced on the subject's buttocks were similar to those which would be experienced in the RATS. Such an approach had in fact been suggested by Borah[17], who had independently developed an array of force-sensing strain guages for measuring these contact pressures in simulated or actual flight. Borah's "Seat Sensor Array" includes a pad consisting of six load cells embedded in thin neoprene rubber. For our measurements, we used only two load cells located in the region of the ischial tuberosities of the the buttocks. With this system, we first measured the pressures produced by pure sinusoidal roll motion in the RATS. Pressure data were collected for a range of frequency and amplitude combinations which covered the motion spectrum of the tracking task. (However, the three subjects who participated in this study passively "rode" in the simulator.) A multiple regression performed on these data suggested that buttocks pressures were a function of the instantaneous roll angle and roll acceleration of the RATS:

$$\text{Pressure} = (-.064 \times \text{RATS Roll}) + (.0042 \times \text{RATS Accel.}) \qquad (2)$$

where pressure is in psi, RATS roll is in deg, and RATS acceleration is in deg/s/s. The negative sign accounts for the phase inversion of roll angle relative to roll acceleration, since their pressure producing effects are in phase with one another[15]. Data were collected on the same subjects exposed to similar sinusoidal roll motion in the dynamic seat. In this device, buttocks pressures were a simple function of the instantaneous seat pan angle:

$$\text{Pressure} = .081 \times \text{Dynamic Seat Roll} \qquad (3)$$

where pressure is again in psi and roll is in deg. A drive algorithm designed to provide a scaled buttocks pressure match was then derived by setting Equations 2 and 3 equal to one another and solving for the dynamic seat roll angle in terms of RATS roll angle and acceleration:

$$\text{Seat Roll} = K\,[(-.79 \times \text{RATS Roll}) + (.052 \times \text{RATS Accel.})] \qquad (4)$$

where all units are as previously specified. The K term was introduced to allow for scaling. In practice, a maximum value of 0.4 was used to prevent the dynamic seat from striking its limits of travel. In addition, the analog model of the RATS implemented in Equation 1 was used to provide the roll angle and acceleration inputs for the drive equation.

Performance Effects Of The Pressure-matching Algorithm

Procedure. The utility of this algorithm was evaluated by comparing performance of the roll-axis tracking task under static (visual display alone) and dynamic seat motion conditions (visual display plus dynamic seat using Eq. 4). A group of six nonpilot subjects was alternated between the two conditions, and completed nine sessions with each type of cuing. A session consisted of four 3 min tracking trials. For three of the subjects the K term in Equation 4 was set to Ø.4, and for the other three it was set to Ø.25. After each trial the root-mean-squared (RMS) tracking error was displayed to the subject.

Results and Discussion. Mean RMS errors for the two motion cuing conditions are shown in Figure 4(a). These data represent averages across the final four trials (session) for the six subjects. The difference between the two conditions was small but statistically significant, $t(5) = 6.08$, $p<.01$. In a separate analysis[15], the effect of gain was found to be nonsignificant. Despite the statistical significance found for the pressure-matching algorithm, the effect was not considered to be of operational importance. Past data[16] for the same tracking task showed that tracking errors in the presence of whole-body motion approached a value of 3 deg RMS, almost twice the improvement seen with the dynamic seat.

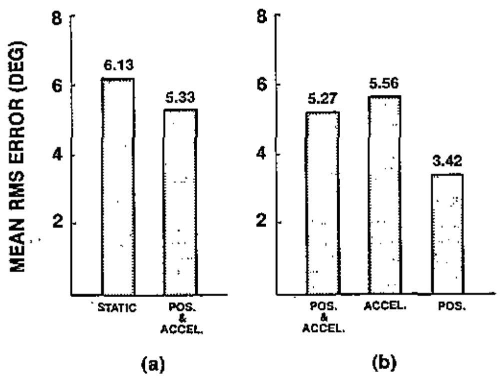


Figure 4. Mean RMS Tracking Errors From The Evaluation And Decomposition Of The Pressure-matching Algorithm.

Decomposition Of The Pressure-matching Algorithm

Procedure. To determine whether the acceleration or position component of the algorithm might be masking useful information provided by the other, the pressure-matching algorithm was split into its two components. A pure position algorithm was derived from Equation 4 by setting the acceleration coefficient to zero. A pure acceleration algorithm was likewise obtained by setting the position coefficient to zero. Two of the above subjects were retained on the original algorithm as experimental controls. The remaining four subjects received a counterbalanced sequence of four sessions with each of the new algorithms.

Results and Discussion. The results of this study are summarized in Figure 4(b), which shows the mean RMS errors for the last session under each condition. While the data for the pure position and acceleration algorithms do no represent asymptotic performance, they do strongly suggest that the position component was providing much more useful information than the acceleration component. In addition, the results indicate that the acceleration component, when combined with the position component, partially masked the useful information. Based upon these data we decided to dismiss any further testing of the pure acceleration algorithm.

Training Effectiveness Of The Pressure-matching Algorithm

Procedure. While the first two studies explored the effects of the pressure-matching algorithm and its components on performance, they did not evaluate its training utility. Accordingly, four of the above subjects were used in a third study which tested transfer of training to the RATS whole-body motion environment. Two of the subjects were given eight additional sessions of training with the pressure-matching algorithm. The remaining two were given eight sessions of training with the pure position algorithm. (A coefficient of Ø.32 was used, i.e. Ø.4 x Ø.79 ≈ Ø.32.) At this point all subjects were transitioned to the RATS, where 1:1 motion was provided. Transfer of training was evaluated for five sessions.

Results and Discussion. The mean RMS errors for the final dynamic seat training session and the first and last RATS transfer sessions are shown in Figure 5. Only the pressure-matching group exhibited transfer in a positive sense, i.e. an initial RATS score no worse than the final training score. However, their initial RATS score was inferior to that of the position group. Further, only the position group achieved scores during dynamic seat training which approximated the scores they *obtained during their final RATS session.*

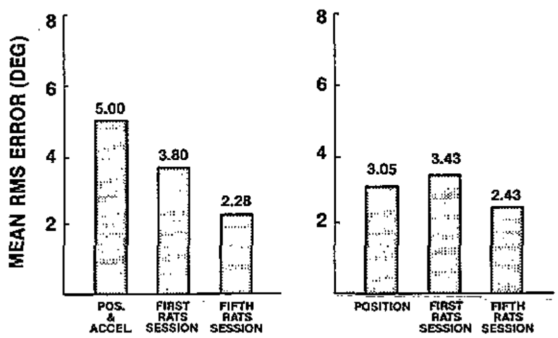


Figure 5. Mean RMS Errors From The Evaluation Of The Training Effectiveness Of The Pressure-matching Algorithm.

The results of these three studies clearly suggest that the pressure-matching algorithm has limited utility, either for improving performance in a motion-sensitive task or for training. Thus, it does not appear that attempting to provide a limited physical match between the RATS and dynamic seat buttocks pressures is an effective strategy. However, the promising results with the position algorithm did argue that the dynamic seat is capable of providing useful motion information. With this algorithm, performance approaching that with whole-body motion was achieved. Therefore, the next series of studies evaluated the ability of the dynamic seat to provide even better motion information, and the resulting effects on transfer of training.

Informational Fidelity Studies

Development Of The Velocity Algorithm

Because of the promising results with the position algorithm, this phase of the research included an evaluation of a velocity algorithm, i.e. one in which dynamic seat roll angle was made proportional to simulated aircraft roll velocity. This decision was partially based upon the premise that the tactual cuing might to some degree substitute for the velocity information provided by the semicircular canals[1] during whole-body motion. Since we now regarded this and the position algorithm as sources of information rather than simulations of sensory events in the RATS, the appropriate gain and phase relationship between dynamic seat roll position and simulated vehicle roll position or velocity was no longer[15] clear. In a series of mini-experiments designed to address these issues, we found that the gain of the velocity algorithm could be reduced 50% with no significant effect on performance of the tracking task. (Experiments conducted during the physical fidelity phase had also suggested that performance with the position algorithm was insensitive to gain.) We found that performance was better (approximately 35% decrease in tracking error) when the seat pan was driven 180 deg out of phase with the vehicle. However, for both the position and velocity algorithms, performance was most similar to that in the RATS when the in-phase relationship was used. Based on the results of these studies and a desire to match the dynamic range of seat pan motion with the two algorithms, the following drive laws were utilized in the first informational fidelity study:

The position algorithm:

$$\text{Seat Roll} = (1/3) \times \text{Simulated Aircraft Roll} \qquad (5)$$

The velocity algorithm:

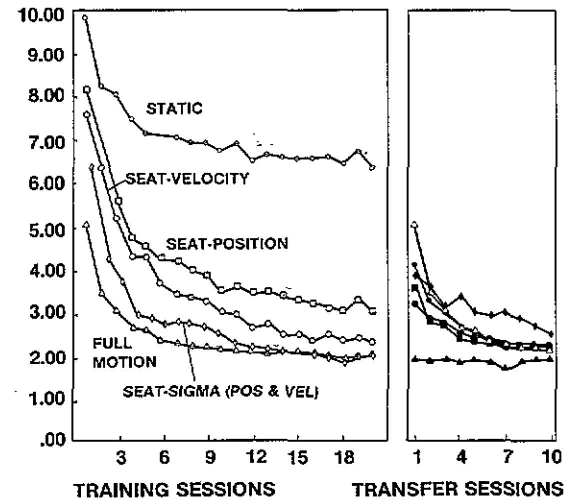
$$\text{Seat Roll} = (1/8) \times \text{Simulated Aircraft Roll Velocity} \qquad (6)$$

Evaluation Of The Position And Velocity Algorithms

Procedure. This study was designed: (1) to evaluate the effectiveness of the position and velocity algorithms in providing useful motion information, and (2) to determine whether the skills developed while training with these seat cues would transfer to the whole-body motion environment. Twenty four naive subjects participated. Subjects were divided into training groups of three male and three female subjects each, under the following four levels of motion information: (1) STATIC (visual display alone), (2) POSITION (visual display plus dynamic seat using Eq. 5), (3) VELOCITY (visual display plus dynamic seat using Eq. 6), (4) MOTION (visual display plus RATS whole-body motion). Following the training phase, all subjects were transitioned to RATS 1:1 motion. The tracking task was identical to the one used above.

Data were collected under the four training conditions for 20 sessions (80 trials). Following transition to the RATS, data were collected for an additional 10 sessions (40 trials). We compared both performance (RMS tracking error) and control behavior (characterized in terms of four frequency domain variables: effective human-vehicle bandwidth, phase margin, open-loop gain, and the slope of the open-loop gain curve) across the four experimental conditions.

Results and Discussion. Figure 6 shows the average tracking performance for each group over the 20 training and 10 post-transition sessions. The beneficial effects of either dynamic seat or whole-body motion cuing are evident during the later training sessions.



(a) (b)

Figure 6. Training and Transfer Curves From The Evaluation Of The Position And Velocity Algorithms. (The initial learning curve for the FULL MOTION group is also plotted (open diamonds) on the transfer data for comparison. The curve labled SEAT-SIGMA will be discussed later.)

The quasi-linear human operator describing functions identified for each group late in training are presented in Figure 7. These data are averaged across the six subjects in each group and over sessions 17 through 20. Modifications in the human's lead equalization and gain resulting from the various types of motion information are clearly evident in this figure. With better quality motion information, subjects operated with more high-frequency lead equalization and were consequently able to increase their gain without sacrificing stability. Subjects with better motion information were also able/willing to track with lower stability (phase) margin, further facilitating a higher low-frequency gain. This higher low-frequency gain (and consequently higher human-vehicle bandwidth) accounted for the improved tracking performance seen with subjects provided dynamic seat or whole-body motion cues.

Late in training (sessions 17-20), the STATIC group differed[15] from the MOTION group on each of the performance and behavior metrics listed above. However, no statistically significant differences between the MOTION and VELOCITY groups were detected[15]. This suggests that the VELOCITY group was achieving performance scores indistinguishable from those of the MOTION group, and was doing it with the same control techniques.

Despite this manifest equivalence between the VELOCITY and MOTION groups late in training, the VELOCITY group did little better than the STATIC group upon transition to the RATS (Figure 6). The results for the POSITION group were similar. Session 21 tracking error for each of these groups was significantly[15] greater than that of the MOTION group. None of the pairwise comparisons between tracking scores for these three groups were significant[15]. In addition, comparison of the post-transition learning curves for the STATIC, POSITION, and VELOCITY groups to the initial learning curve of the MOTION group, showed no significant differences[15]. That is, they did not learn to track in the RATS at a faster rate than a group with no prior training.

Statistical tests were also conducted on the post-transition data to determine when differences among the groups disappeared. These tests indicated that where significant differences were observed for the first post-transition session, the differences were no longer significant by the fourth post-transition session[15].

The results of this study clearly demonstrate that the dynamic seat can effectively display motion information. It appears that a tactual display of this type could be useful in research simulators, or even for communicating information to vehicle operators. The disappointing training transfer results, however, indicated a need for further research.

Development Of A Subjective-matching (SIGMA) Algorithm

The next experiment began with the hypothesis that positive transfer between the dynamic seat and the RATS could be improved by increasing the subjective equivalence of the motion information provided by the two devices. To test this hypothesis a method was needed for comparing the subjective experiences in the two simulators. The method chosen was a cross modality matching task based on the work of Stevens[18]. In this task subjects were presented with a visual display which showed a schematic plane oscillating sinusoidally about the roll axis. Subjects were asked to adjust the RATS or dynamic seat motion so that it was oscillating at the same angular amplitude as the visual reference. The visual reference and the motion cuing device were driven by a single sine wave. The angular amplitude of the visual reference was fixed. The angular amplitude of the motion device was set to zero to begin a trial and the subject adjusted the amplitude until it subjectively matched the visual reference. Subject's adjustments had no effect on the phase relationship between visual and simulator motion, which were synchronized to within 5 ms. Matching data were collected for two different reference amplitudes (2^{o}, 5^{o}) at each of six different frequencies (0.08 Hz, 0.16 Hz, 0.25 Hz, 0.48 Hz, 0.80Hz, 1.11 Hz).

This procedure was designated SIGMA for Subjective Interactive Gain Measurement Analysis. The logic of SIGMA is illustrated in the equations below. Equations 7 and 8 represent the cross modality matching procedures in which sensed visual motion (Ψ_{VISUAL}) was compared to sensed motion in the two simulators (Ψ_{RATS} and Ψ_{SEAT}) as a function of frequency (ω). G_1 and G_2 represent the gain adjustments to the angular amplitude of the reference signal (ϕ). These gain adjustments were the dependent measures. Since the visual reference signals in the two cross modality matching tasks represented by Equations 7 and 8 were identical, the sensed motion in the two simulators could be compared as in Equation 9. Equation 10 compares the two simulators in terms of the gains (G_1 and G_2) and the physical references (ϕ_{RATS} and ϕ_{SEAT}). Finally, Equation 11 demonstrates how the gain ratios ($G_2(\omega)/G_1(\omega)$) can be treated as an amplitude describing function for equating the two simulators. This describing function can then be used to select the linear differential equation to be used as the drive algorithm for the dynamic seat. The hypothesis was that this drive algorithm would result in subjective equivalence between the motion information provided by the two simulators.

$$\Psi_{VISUAL}(\omega) = \Psi_{RATS}(\omega) = G_1(\omega)\,\phi_{RATS}(\omega) \quad (7)$$

$$\Psi_{VISUAL}(\omega) = \Psi_{SEAT}(\omega) = G_2(\omega)\,\phi_{SEAT}(\omega) \quad (8)$$

$$\Psi_{RATS}(\omega) = \Psi_{SEAT}(\omega) \quad (9)$$

$$G_1(\omega)\,\phi_{RATS}(\omega) = G_2(\omega)\,\phi_{SEAT}(\omega) \quad (10)$$

$$\phi_{RATS}(\omega) = G_2(\omega)/G_1(\omega)\,\phi_{SEAT}(\omega) \quad (11)$$

Matching data for both simulators were collected from six subjects. The resulting gain ratios are shown in Figure 8. The amplitude pattern shown there was fit

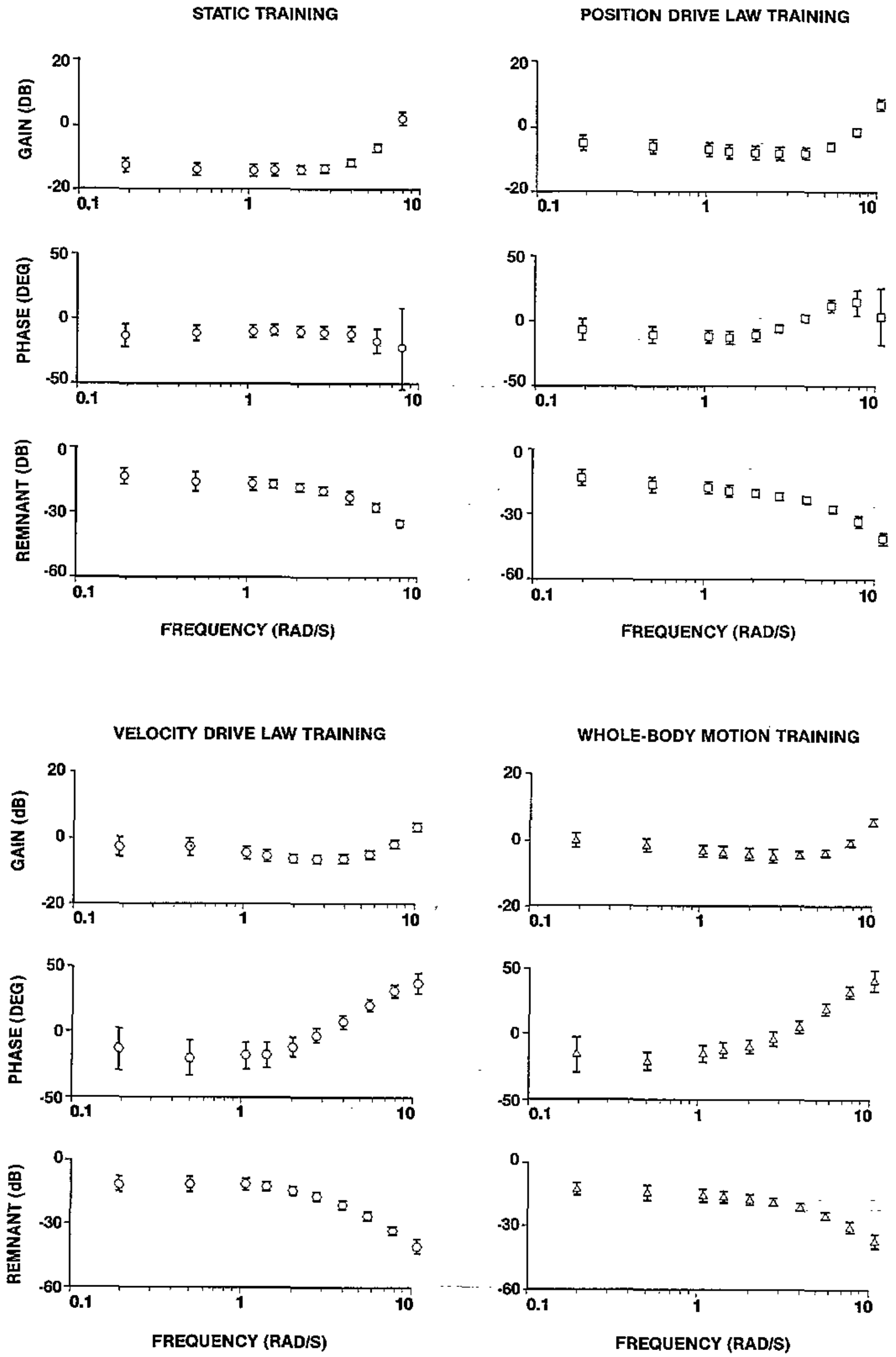


Figure 7. Human Operator Describing Functions From The Evaluation Of The Position And Velocity Algorithms. (Mean values, plus and minus one standard deviation are shown. Calculation of the remnant is described by Martin[15].)

graphically with a first order lead with a time constant of 1/6.0 and a gain of 0.67. This is shown as the solid line in the figure. The drive equation based upon this fit was:

$$\text{Seat Roll} = (.67 \times \text{Roll Position}) + (.11 \times \text{Roll Velocity}) \quad (12)$$

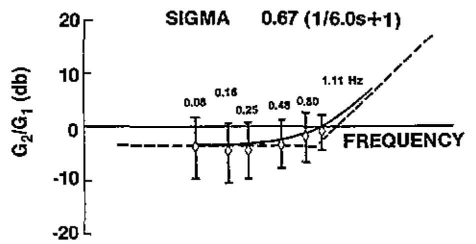


Figure 8. Gain Ratios Between The RATS (G_1) And Dynamic Seat (G_2)

Evaluation Of The Subjective-matching (SIGMA) Algorithm

Procedure. Four of the subjects who participated in the matching task continued into the evaluation phase of this experiment. The subjects performed the roll-axis tracking task used previously. The subjects received 20 sessions of dynamic seat training using the lead algorithm derived from SIGMA. Then the subjects were transferred to the RATS for an additional 10 sessions.

Results and Discussion. Late training performance for these subjects, both in terms of average tracking error (Figure 6) and in terms of frequency response characteristics (Figure 9), was remarkably similar to performance obtained from previous subjects trained in the RATS. These results indicate that not only did the SIGMA algorithm allow subjects to perform at a level comparable to that achieved with whole-body motion, but it also induced subjects to use an equivalent equalization strategy. Unfortunately, performance in the RATS following training with the SIGMA algorithm was slightly worse than the performance of subjects trained with the position or velocity algorithms (Figure 6). The results of the two information fidelity studies provide an interesting paradox. On the one hand, the dynamic seat, driven with either the velocity or the SIGMA algorithm appears to have provided subjects with similar information to that provided by the RATS. *Evidence for this comes from the similarity* of error scores and frequency characteristics observed in the three training conditions. On the other hand, transfer was equivalent to that obtained in a no motion training condition. These results strongly suggest that information equivalence between two devices is not sufficient to insure transfer from one to the other.

Transfer Of Training From The RATS To The Dynamic Seat

There are two possible explanations for the lack of training transfer from the dynamic seat to the RATS. One is that the perceptual-motor skills required to control the dynamic seat are different from the skills required to control the RATS. Another is that, while the skills required in the two devices are similar, there is something unique to the whole-body motion environment that is not useful in flight control, but is highly salient and must be overcome through training. For instance,

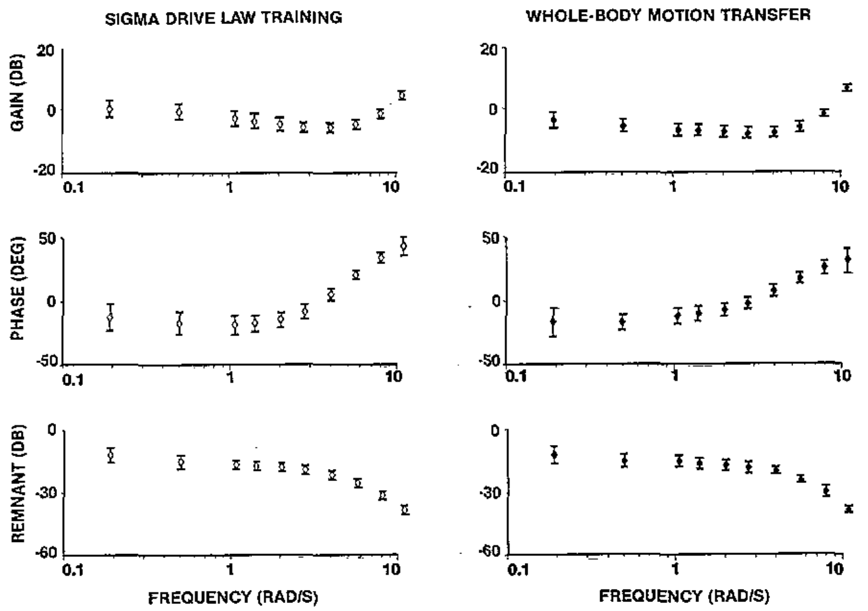


Figure 9. Human Operator Describing Functions From The Evaluation Of The Subjective-matching Algorithm. (Comments from Figure 7 apply here also.)

there may be some apprehension about the forces that one will experience in the RATS environment. There may also be other distracting phenomena during whole-body motion such as confusion about one's subjective orientation.

The error scores and frequency-domain characteristics obtained in the two previous experiments suggest that subjects use similar control strategies in the dynamic seat and the RATS. Therefore it is prudent to consider the second hypothesis for lack of transfer. One test of this hypothesis is to evaluate transfer of training from the RATS to the dynamic seat (reverse transfer).

<u>Procedure</u>. Four naive subjects performed the roll-axis tracking task used in the previous studies. For the first 2Ø sessions, subjects were trained in the RATS. After this subjects were transferred to the dynamic seat for another 1Ø sessions. The dynamic seat was driven with the algorithm derived in the SIGMA studies.

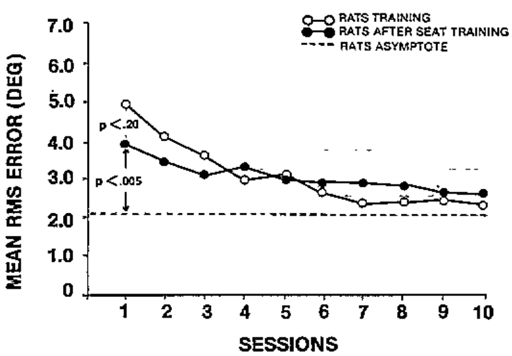
<u>Results and Discussion</u>. Data from this experiment were combined with data from the SIGMA experiment to evaluate forward and reverse transfer. The degree of reverse transfer was assessed by comparing performance in the dynamic seat after training in the RATS, to performance in the dynamic seat with no prior training. The degree of forward transfer was assessed by comparing performance in the RATS after training in the dynamic seat, to performance in the RATS with no prior training. Figure 1Ø presents the average tracking errors observed in the two conditions. Performance on the first session in the dynamic seat following RATS training was significantly better, $t(6) = 2.14$, $p<.Ø5$, than initial dynamic seat performance with no training (Figure 1Øb). The second statistical test indicates that, although significant transfer occurred, the subjects had not reached asymptotic performance in the first session. As we have seen in the previous studies, transfer of training from the dynamic seat to the RATS was not statistically significant (Figure 1Øa).

The results suggest that similar perceptual-motor skills are used to control the dynamic seat and the RATS. They also provide support for the hypotheses that there is something about the whole-body motion experience that makes it difficult to apply the appropriate skills acquired in the dynamic seat.

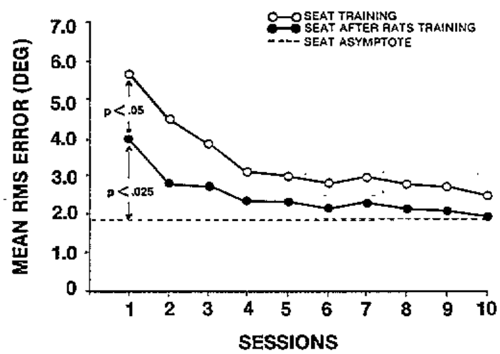
<u>The Effect Of Pilot Experience On Transfer Of Training</u>

The previous studies all used subjects who had no prior experience with whole-body motion environments like the RATS. The results suggest that these naive subjects initially have difficulty using skills learned in the dynamic seat that are appropriate for the RATS. Previous experience with whole-body motion may expedite transfer of training from the dynamic seat. For instance, pilots presumably would be less apprehensive about the forces experienced during whole-body motion. They would also be experienced in the use of visual and nonvisual sources of information about orientation of the body.

<u>Procedure</u>. Eight pilots with various amounts of experience in different types of aircraft (from single engine general aviation aircraft to military transports) were used. The number of flight hours ranged from 1ØØ to 445Ø. These pilots performed the same roll-axis tracking task used previously. For the first 1Ø sessions four pilots were trained in the RATS. These pilots were then transferred to the dynamic seat for another 1Ø sessions. The other four pilots received dynamic seat training followed by RATS transfer testing. The two groups were balanced as nearly as possible with respect to pilot experience. The dynamic seat was driven with the SIGMA algorithm.

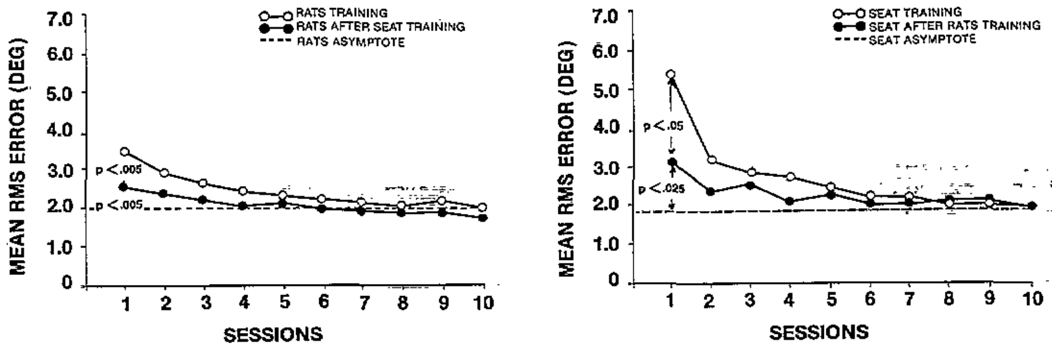


(a) NONPILOT FORWARD TRANSFER



(b) NONPILOT REVERSE TRANSFER

Figure 1Ø. Learning Curves From The Reverse Transfer Study. (Data from the initial 1Ø training sessions and all transfer sessions are shown. The dotted line is the mean of training session 2Ø in the RATS or dynamic seat. The p values represent the probability of the pairwise <u>t</u> test results, which compared performance in the initial session under each condition.)



(a) PILOT FORWARD TRANSFER

(b) PILOT REVERSE TRANSFER

Figure 11. Learning Curves From The Pilot Experience Study. (The dotted line is the mean of training session 10 in the RATS or dynamic seat. The p values are as described in Figure 10.)

Results and Discussion. Transfer of training was assessed as in the previous study. Figure 11 shows the average tracking errors for the two groups of subjects. The degree of transfer from the RATS to the dynamic seat was similar to that obtained for nonpilots. More importantly, transfer from the dynamic seat to the RATS was superior to that obtained for nonpilots. To permit comparisons across experiments, the forward transfer data were also analyzed using the technique employed in the study of the position and velocity algorithms[15]. This more conservative analysis of variance procedure also showed, $F(1,6) = 37.25$, $p<.01$, that the pilots' initial performance in the RATS following dynamic seat training was better than with no prior training.

Conclusions

The results of this program are encouraging, if not yet definitive, regarding the use of dynamic seats as an alternative to platform motion. The studies have consistently shown a substantial, and statistically reliable, improvement in turbulence regulation performance when dynamic seat cues are provided. In addition, the performance and control behavior can be made indistinguishable from that observed with whole-body motion. These results clearly support the use of dynamic seats in research and engineering simulators, where performance and workload equivalence is desirable. The results of the last two studies suggest that, with appropriate experience, significant training benefit may also be achieved. With pilot subjects, transfer of training occurred from the dynamic seat to whole-body motion and vice-versa. With the nonpilots, training benefit was only seen from whole-body motion to the dynamic seat. This suggests that modification of our training techniques (e.g., alternated versus blocked training) may permit naive trainees to more quickly acclimate to unique whole-body motion effects and realize a training benefit. In addition, these results suggest that increasing the experiential similarity of the two devices may improve transfer. By including peripheral visual displays, for example, we may be able to induce the feelings of self-motion that occur in whole-body motion and again improve transfer. Both of these approaches are being pursued in our current studies.

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