N79-17512

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A MODEL FOR THE PILOT'S USE OF MOTION CUES IN ROLL-AXIS TRACKING TASKS

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ABSTRACT

An experimental and analytical study was undertaken jointly by the Aerospace Medical Research Laboratory and Bolt Beranek and Newman Inc. to test a model for the pilot's use of motion cues in roll-axis tracking tasks. Simulated target-following and disturbance-regulation tasks were explored with subjects using visual-only and combined visual and motion cues. The effects of motion cues on task performance and pilot response behavior were appreciably different for the two task configurations and were consistent with data reported in earlier studies for similar task configurations.

The "optimal-control" model for pilot/vehicle systems provided a task-independent framework for accounting for the pilot's use of motion cues. Specifically, the availability of motion cues was modeled by augmenting the set of perceptual variables to include position, rate, acceleration, and acceleration-rate of the motion simulator, and results were consistent with the hypothesis of attention-sharing between visual and motion variables. This straightforward informational model allowed accurate model predictions of the effects of motion cues on a variety of response measures for both the target-following and disturbance-regulation tasks.

Presented at the Thirteenth Annual Conference on Manual Control, MIT, Cambridge, Mass., June 15-17, 1977.

INTRODUCTION

This paper summarizes the work performed in the second year of a joint study by the Aerospace Medical Research Laboratory (AMRL) and Bolt Beranek and Newman Inc. (BBN) to explore the use of motion cues in roll-axis tracking tasks. Results of this study have been documented by Levison and Junker [1]; results of the preceding study are reported in [2] and [3].

This study has continued to be concerned with the use of motion-related sensory information for continuous flight control. Other potential effects of motion, such as providing alerting cues to the pilot or providing "realism" to aircraft simulations, are not considered. Analysis of the experimental results has been directed towards developing a generalized description of the manner in which the pilot uses motion cues, with the ultimate goal of providing a model that can predict the effects of motion cues on system performance in a variety of control situations.

Analysis of the experimental data obtained in the preceding study revealed that the effects of motion cues on roll-axis tracking could be modeled primarily by inclusion of sensory variables likely to be provided by motion sensors (position, rate, and acceleration of the controlled vehicle). In addition, pilot time delay was incremented by 0.05 seconds. Modeling of dynamics associated with motion sensors was not required.

The experimental results did not allow us to determine conclusively whether or not the pilot had to "share attention" between visual and motion modalities. Nevertheless, tracking performance was consistent with the notion that attention was shared optimally between visual and motion cues. Moreover, model analysis indicated that the optimal allocation of attention between modalities was different for the two control tasks explored in that study.

The results of the study reported in [2] and [3] appeared to conflict with the findings of others regarding the effects of motion cues on tracking performance. Both Shirley [4] and Stapleford et al. [5] concluded that the addition of motion cues allowed the pilot to generate greater lead at high frequencies, thereby permitting an increase in gain-crossover frequency. Furthermore, Shirley concluded that motion cues were relatively more beneficial for tracking tasks involving low-order plants than for those involving high-order dynamics. On the contrary, the results of the AMRL/BBN study showed that phase lead was increased at *low* frequencies, rather than *high* frequencies;

phase lag increased somewhat at high frequencies; gain-crossover frequency remained essentially unchanged; and motion cues had a greater effect with the higher-order of the two plants explored.

These apparent contradictions do not necessarily indicate that the AMRL experimental subjects used motion cues in a manner different from the subjects who participated in the studies of Shirley and of Stapleford et al. There were some important differences between the AMRL experiments and the earlier studies. Both Shirley and Stapleford et al. applied the input disturbance in such a manner that both the visual display and the motion simulator were driven by the input. (That is, the input was applied essentially in parallel with the pilot's control.) In the AMRL study, the external input was applied as a command signal; only the pilot's input drove the controlled plant. Thus, in the latter study, motion cues provided some inner-loop information that was not directly obtained from the visual cues.

In order to explore the apparent discrepancies between the initial AMRL/BBN study and earlier investigations, a small but carefully controlled experiment was conducted to compare the use of motion cues in disturbance and command situations. The results of this study form the main topic of this paper.

EXPERIMENTAL PROCEDURES

The reader is referred to a companion paper for detailed descriptions of the tracking task and experimental procedures [6]; only a brief summary is given here.

The pilot was required either to regulate against a simulated gust disturbance (the "disturbance condition") or to follow a commanded target (the "target condition"). Plant dynamics were basically $K/s(s+5)$ to approximate roll-axis characteristics of high-performance fighter aircraft. These dynamics were modified by the high-frequency rolloff properties of the moving-base simulator and by delays of approximately 0.1 seconds introduced by recording and simulation procedures. The external forcing function was a sum of thirteen sinusoids constructed to simulate white noise shaped by a second-order filter with two identical real poles. Pole locations were 1.0 rad/sec for the target input and 2.0 rad/sec for the disturbance input.

Each input condition was tracked with and without the moving-base simulator operative, making a total of four experimental conditions. In all cases, the subject was presented with a compensatory display of roll error. Subjects (six in all) were trained to asymptote on all conditions and were instructed to minimize a "cost" defined as $C = \sigma_e^2 + 0.1\,\sigma_{\ddot{p}}^2$, where σ_e^2 is the variance of the tracking error and $\sigma_{\ddot{p}}^2$ is the variance of the plant acceleration. The cost on acceleration was imposed partly to force the subjects (non pilots) to track in a smooth manner, and partly to assure that roll rates and accelerations would be well within the physical limits of the moving-base simulator most of the time.*

EXPERIMENTAL RESULTS

Analysis Procedures

Variance scores were computed for each experimental trial for the tracking error, error rate, plant position (i.e., roll angle), plant rate, plant acceleration, control force, and control force rate. (For disturbance-regulation tasks, error and error rate were identical to plant position and plant rate.) Also computed was total "cost" as defined above. Square roots were taken of the measures to yield rms performance scores.

Performance scores were first averaged across replications of a given test subject for each experimental condition; the mean and standard deviation of the subject means pertaining to each experimental condition was then computed. In order to test for significant differences between motion and static conditions, paired differences were formed from corresponding subject means; these differences were subjected to a two-tailed t-test.

Similar statistical analysis was performed for frequency-response measures. Additional details on analysis procedures are given in Levison and Junker [1].

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*Pre-experimental analysis was performed with the optimal-control pilot/vehicle model to select various experimental parameters (including the relative cost penalty on acceleration) to achieve certain experimental goals. This design procedure succeeded, very successful, and experimental results were close to those predicted a priori by the model. Use of the pilot model in the design of these experiments is described in Junker and Levison [6].

Principal Results

Variables for which rms performance scores were computed, their units, and their symbolic notation are shown in Table 1. Average rms performance scores are shown in Figure 1. For ease of comparison with other performance metrics, the square root of the "cost" is shown, and various rms scores have been scaled so that all scores may be shown on the same ordinate scale. Significant static-motion differences are indicated by the arrows, where the coding of the arrow indicates the significance level as defined in Table 2. Mean performance scores and standard deviations of subject means are given in [1].

Figure 1 shows that the availability of motion cues had little effect on rms performance measures for the target-tracking task. Plant position showed the greatest effect, decreasing by about 20% in the motion case. Smaller but statistically significant reductions were found for total cost and for control-related scores. The fact that statistical significance can be shown for these relatively small differences indicates that the influence of motion cues, however slight, was consistent across subjects.

Static-motion differences were considerably greater for the disturbance-tracking task. Although no significant change was observed in the control-related scores, total cost and error-related scores were reduced substantially; these differences were significant at the 0.01 level or lower.

The average frequency-response measures presented in Figure 2 show that motion-cue effects were qualitatively different for the two tasks. The three measures shown in the figure are, from top to bottom, amplitude ratio (i.e., pilot gain), pilot phase shift, and the ratio of remnant-related to input-correlated control power (which we shall refer to as the "remnant ratio").

The effects of motion cues on pilot response behavior for the target-tracking and disturbance-regulation tasks are summarized in Table 3. The major influence of motion cues in the target task was to induce a substantial phase lead at low frequencies. There was no change in gain-crossover frequency (about 1 rad/sec), and the remnant ratio increased somewhat. In the disturbance task, however, motion cues allowed the subjects to convert a high-frequency phase lag into a substantial phase lead, increase amplitude ratio at low and mid frequencies, and thereby increase gain-crossover frequency from about 1.5 rad/sec to around 3.5 rad/sec. There was a consistent decrease in remnant ratio, although static-motion differences were largely not statistically significant.

Table 1

Tracking Variables Analyzed

Variable	Symbol	Units
Total Performance Cost	c	---
Tracking Error	e	degrees
Tracking Error Rate	$\dot{e}$	degrees/second
Plant Position	p	degrees
Plant Rate	$\dot{p}$	degrees/second
Plant Acceleration	$\ddot{p}$	degrees/second^2
Control Force	u	pounds
Control Rate	$\dot{u}$	pounds/second

Table 2

Coding for Significance Level

Symbol	Alpha Level of Significance
↓	0.05
↡	0.01
⤋	0.001

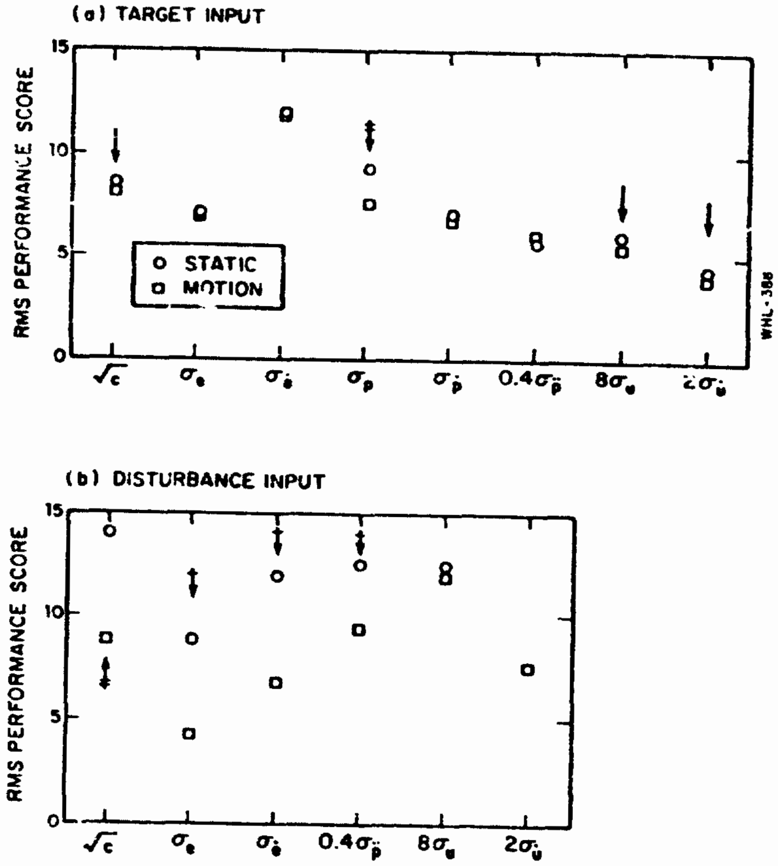

Figure 1. Effect of Motion Cues on RMS Performance Scores

Average of 6 subjects.

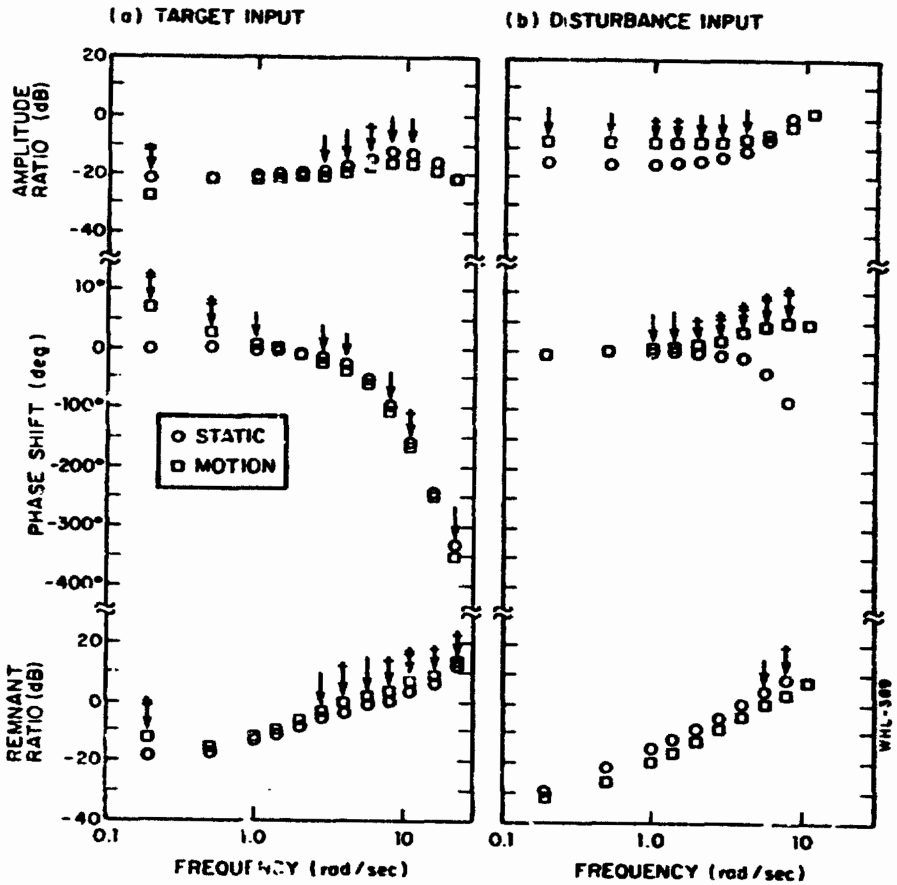

Figure 2. Effect of Motion Cues on Pilot Frequency Response

0 dB represents 1 pound control force per degree roll for the amplitude ratio and unity (dimensionless) for the remnant ratio.

Average of 6 subjects.

Table 3

Effects of Motion Cues on Frequency Response

Measurement	Effects of Motion Cues	
	Target Input	Disturbance Input
Low-frequency phase	Substantial increase in phase lead	No change
High-frequency phase	Small increase in phase lag	Convert phase lag to phase lead, a substantial change
Low-frequency amplitude-ratio	No change	Substantial increase
Gain-crossover frequency	No change	Increase by over factor of 2
Remnant ratio	Overall increase	Overall decrease

During the course of this analysis we addressed the question of whether or not the average pilot response characteristics shown in Figure 2 were typical of the response characteristics of individual subjects. That is, we wanted to ascertain that important response characteristics were not obscured by the averaging process. Accordingly, the procedure for eliminating atypical performance described in [1] was applied to subject means to successively eliminate all but one subject per experimental condition.

Figure 3 compares the responses of typical subjects to the average response of all six subjects for the static and motion conditions in the disturbance-regulation task. Typical and average responses very nearly coincided for the static condition. The correspondence between typical and average response was also high for the motion condition, with only small differences in overall amplitude of response. Thus, we are justified in averaging these response measures across subjects.

Discussion of Results

The results obtained in this experiment agree qualitatively with results obtained previously in similar tracking situations. The effects of motion cues in the target-tracking task are similar to those obtained in the preceding AMRL experimental study for "Task 1" (the less severe of the two tasks studied in that program). In both cases, motion cues allowed an increase in low-frequency phase shift that was unaccompanied by any substantial improvement in tracking performance.

Similarly, the effects of motion cues observed in the disturbance-regulation task agree with the effects reported by other researchers [4, 5] who found that moving-base simulation allowed the pilot to reduce high-frequency phase lag and to increase gain-crossover frequency and thereby, in many cases, lower his error score.

Motion/static performance differences were enhanced somewhat by the time delays introduced by the data-recording and computational algorithms. These delays influenced only the visual cues provided to the pilot; the motion cues were provided by the moving-base simulator. Thus, motion cues provided a double benefit to the pilot; information was obtained via motion sensors in advance of information obtained visually, and, as we infer from the model analysis described below, vehicle acceleration and possibly rate-of-change of acceleration were also sensed.

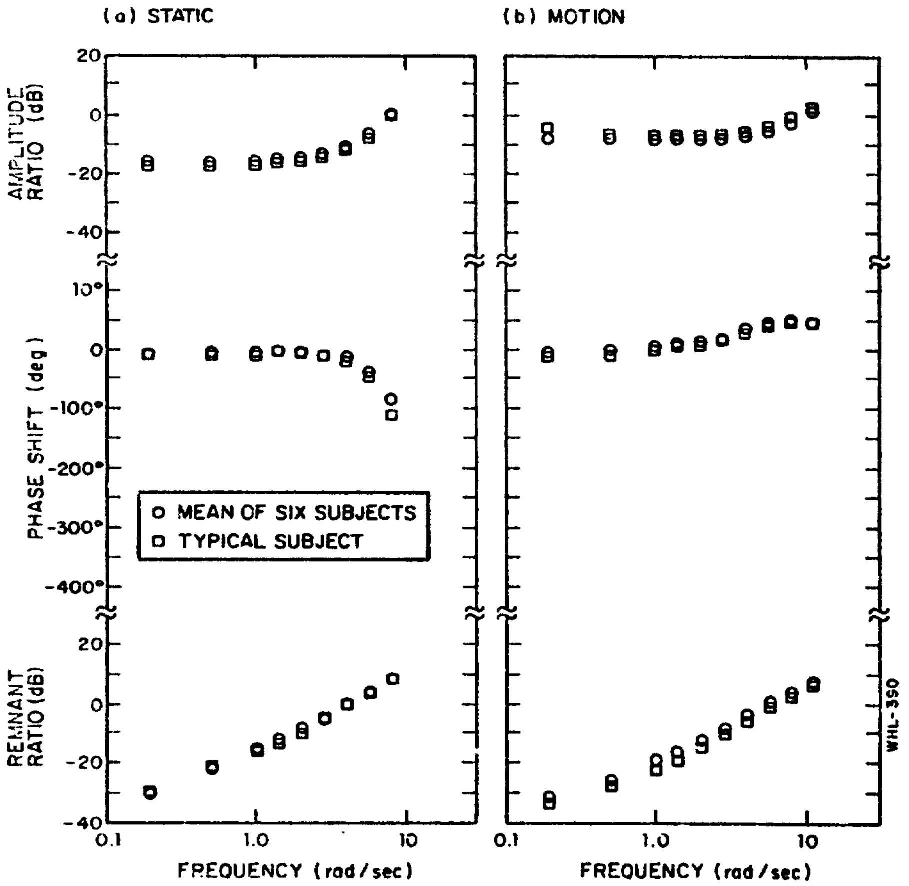

Figure 3. Comparison of Typical and Mean Responses for the Disturbance-Regulation Task

It is clear from the results of this experiment that the effects of motion cues on pilot response cannot be generalized in terms of classical response measures. We have shown that the effects of motion cues on rms performance scores, pilot describing function, and pilot remnant can all differ qualitatively from one control situation to the next.* Some form of generalization is needed, nevertheless, if we are to extrapolate the results of these and earlier experiments to other control tasks. That is, we need a model which accounts for the interaction between available motion cues and pilot response in terms that are essentially independent of the details of the control task. Such a model is discussed below.

MODEL ANALYSIS

Analysis Procedure

The revised optimal-control pilot/vehicle model developed in the preceding phase of this study was applied to the results of the experiment described above. This model is described by Levison, Baron, and Junker [2].

The treatment of motion cues was similar to that of the preceding study in that the presence or absence of motion cues was represented by an appropriate definition of the sensory variables assumed to be available to the pilot. A three-element "display vector" consisting of tracking error, error rate, and (in one instance) error acceleration was used to model static-mode tracking. To model pilot response in moving-base tasks, we simply expanded this display vector to include position, rate, acceleration, and acceleration-rate of the vehicle; no other model parameters were changed to account for motion/static differences. Model runs were also obtained which included the effects of dynamic response properties of vestibular motion sensors.

The scheme for identifying model parameters was similar to that described in [2, 3]. Parameter values were sought that would simultaneously provide a good match to performance scores, describing function, and remnant ratio. A multi-dimensional "matching error"

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*Relative effects of motion cues are affected not only by the type of external input, as demonstrated here; pre-experimental model analysis indicated that input bandwidth and performance criterion would also influence motion/static differences in response behavior.

was defined, with the dimensions being (1) rms performance, (2) amplitude ratio, (3) phase shift, (4) and remnant ratio. Matching error was defined in such a way that a score of unity was obtained whenever model predictions differed on the average from experimental measurements by one standard deviation.

As in the preceding study, the primary goal of model analysis was to determine a straightforward and reliable procedure for predicting the effects of motion cues in a variety of control tasks. Therefore, we attempted to account for performance on all four tasks with the fewest variations in parameter values. We did not allow all parameters to vary in order to obtain the best match in each condition; rather, variations were made in only those parameters that could reasonably be expected to relate to the kind and quality of information provided to the pilot.

Primary Results of Model Analysis

Attentional parameters were the only model parameters that were varied across experimental conditions; all other parameter values were held fixed. Numerical values for pilot-related parameters, shown in Table 4, were obtained as follows:

Control-Rate Cost Coefficient. Based on previous studies of single-variable laboratory tracking tasks, the control-rate cost coefficient was adjusted to provide a "motor time constant" of 0.1 second.

Acceleration Cost Coefficient. In accordance with instructions given to the subjects, we initially attempted to match experimental results with an acceleration cost coefficient of 0.1 seconds. A somewhat better match was obtained with a coefficient of 0.05, however, and this latter value was adopted for the remainder of the analysis.

Time Delay. A time delay of 0.22 seconds provided the best match across conditions.

Motor Noise/Signal Ratios. On the basis of previous analysis, the "driving" motor noise/signal ratio was made negligibly small; a "pseudo" noise/signal ratio of -30 dB gave a reasonably good match to low-frequency phase shift (see Levison, Baron, and Junker for a discussion of the motor noise aspect of the pilot model.)

Observation Noise/Signal Ratio. On the basis of previous studies, an observation noise/signal ratio of -20 dB was adopted.

Table 4

Values for Pilot-Related Model Parameters

a. Invariant Parameters

Control-rate cost coefficient	1.0
Motor time constant	0.1 seconds
Acceleration cost coefficient	0.05
Time delay	0.22 seconds
Driving motor noise/signal ratio	(negligible)
Pseudo motor noise/signal ratio	-30 dB
Observation noise ratio for "Full Attention"	-20 dB
Perceptual thresholds, error rate, visual	3.2 deg/sec
Perceptual thresholds, all other variables	(negligible)

b. Attentional Allocation

Perceptual Mode	Perceptual Variable	Tracking Task			
		Target Static	Target Input Motion	Disturbance Static	Disturbance Input Motion
Visual	error	1	0.95	1	0.1
	error rate	1	0.95	1	0.1
	error acceleration	---	---	0.05	0
Motion	plant	0	0.05	0	0.9
	plant rate	0	0.05	0	0.9
	plant acceleration	0	0.05	0	0.9
	plant acceleration rate	0	0.05	0	0.9

Perceptual Threshold. Because vehicle roll rates and accelerations were large compared to published detection thresholds for these variables, thresholds for motion-related variables were set to zero. A good match to the data was obtained with thresholds of 0 degrees and 3.2 deg/sec associated with visually-obtained error and error rate.

Attentional Variables. With the exception of visually-obtained error acceleration, attention was assumed to be shared between visual display variables as a group and motion variables as a group, and there was assumed to be no interference among perceptual quantities within a sensory mode. The absence of motion-related information in a tracking task was modeled as zero attention (i.e., extremely large observation noise) on motion variables and unity attention on visual variables. The attentional allocations between visual and motion cues shown in Table 4 provided the best match to the data.

Figure 4 shows that the model accurately reflected the influence of both the nature of the external input and the presence or absence of motion cues. Of the 28 performance scores predicted by the model, all but three were within 10 percent of corresponding experimental measures; and in only one of these cases did the model score fail to be within one standard deviation of the experimental mean.

As shown in Figure 5, model outputs agreed quite well with experimental frequency-response measures, and major trends in the data were predicted. Specifically, inclusion of motion-related sensory information caused the model to predict an increase in low-frequency phase shift for the target task. For the disturbance task, the model correctly predicted large increases in low-frequency gain and high-frequency phase lead. The model also predicted an overall decrease in remnant ratio for this task.

It is worthwhile to re-emphasize that the effects of motion cues have been accounted for solely by changes in model parameters related to the information availability and quality; other parameters have been kept fixed for the four experimental conditions.

Additional Model Results

Values for two of the parameters – cost-of-acceleration and time delay – were somewhat different from those initially expected. The acceleration cost coefficient that provided the best fit to the data was half that used in computing the total performance cost during the experiments. In order to estimate the subject's ability to detect differences between subjective and objective cost criteria,

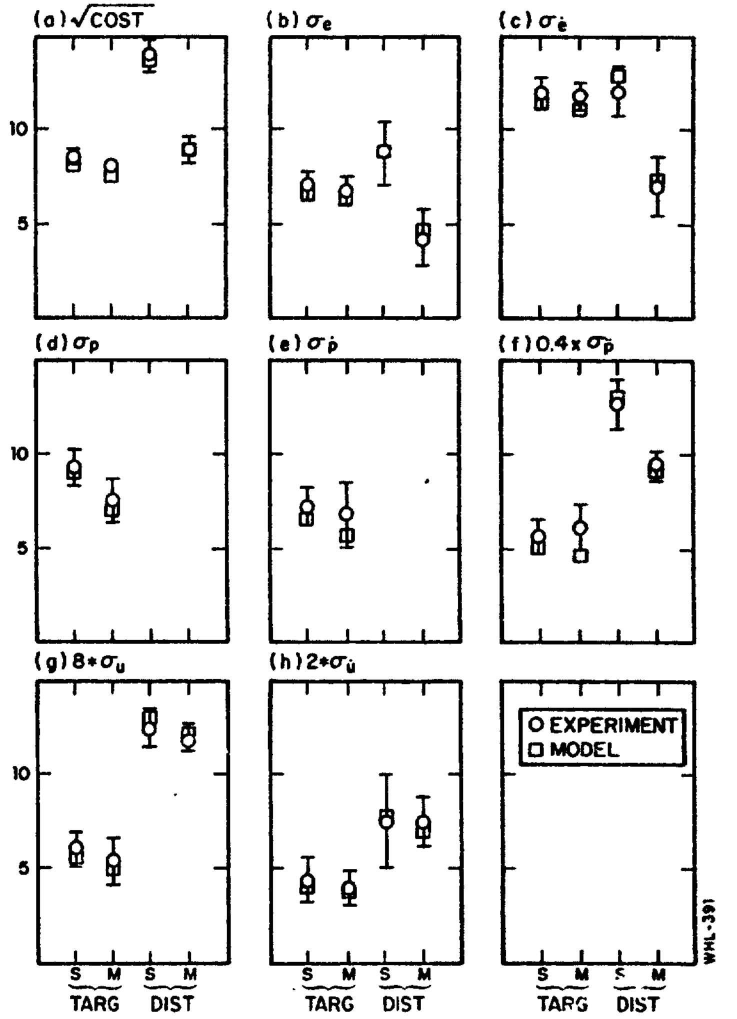

Figure 4. Comparison of Model and Experimental Performance Scores
S=static condition, M=motion condition.
Average of 6 subjects.

The inclusion of acceleration rate in the display vector had a considerable influence on the matching error for the disturbance-regulation task; the matching error on phase shift was reduced by over a factor of 4, and other component matching errors were substantially reduced as well. The improvement occurred largely at high frequencies. Inclusion of acceleration rate had no influence on the match to the data obtained in the target-following task, since high-frequency information was of less importance in performance of this task.

Although matching of the data for the disturbance-regulation task was enhanced by consideration of acceleration-rate information, predicted system performance was little effected by this factor. Model analysis indicated that both rms tracking error and rms roll acceleration would be reduced by about 10% with such information available for a high level of attention to the task, with this benefit disappearing at lower levels of attention.

The disturbance-regulation task was re-analyzed with the vestibular sensor dynamics suggested by Curry, Hoffman, and Young [8] added to the system equations of motion. The "display vector" assumed for model analysis was further augmented by the addition of the outputs of the semicircular and otolith sensors, as well as the rates of change of these outputs. In this analysis, the best match to the data was obtained with the assumption of no interference between visual and motion variables.

The match to the data was nearly identical to that shown above for the simple informational analysis. We therefore conclude that, while models of vestibular dynamics are consistent with the results obtained experimentally, model accuracy is not enhanced by the consideration of such models. For the type of tasks explored in this study, a simple informational analysis appears to be adequate.

One should be careful not to make the conclusion that sensor dynamics can be ignored in all instances. The experiments described in the paper employed steady-state tasks for which response power was concentrated largely within the passband of the vestibular motion sensors. For transient maneuvers where very low frequency characteristics are important, sensor dynamics may have to be considered. This is particularly true for situations in which the low-frequency washout characteristics of the sensors may induce illusions [9].

Reanalysis with Typical Pilot Parameters

By allowing nearly all pilot-related model parameters to vary from one study to the next, we have been able to obtain close agreement between model and experimental results for all tasks explored in this study program. Many of these parameter differences have been attributed to the relative insensitivity of overall system performance to such parameter values.

If the model is to be used as a *predictive* rather than as a *diagnostic* tool, it is important that one be able to predict the effects of task variables on system performance using a single set of typical pilot parameter values. Because there generally exists a range of pilot response behavior that gives near-optimal system performance in a typical control situation, one would not expect such a procedure to yield accurate predictions of all response metrics. Nevertheless, one would expect that important trends in system behavior would be revealed.

To test the predictive capability of the model, a comparison was obtained between measured and predicted rms tracking error for all eight tasks explored in this program, using a set of "typical" pilot parameter values. These values were chosen largely on the basis of previous laboratory studies and are not necessarily those that would provide the best overall fit to the data base. The following parameter values were used:

Cost Functional. Cost functionals were $J = \sigma_e^2 + G\,\sigma_{\dot{u}}^2$ for the tasks explored in the previous study phase [2, 3] and $J = \sigma_e^2 + 0.1\,\sigma_{\dot{p}}^2 + G\,\sigma_{\dot{u}}^2$ for the tasks described in this paper.* The coefficient G was chosen to provide a motor time constant of 0.1 seconds in all cases.

Time Delay. A pilot time delay of 0.2 seconds was assumed.

Perceptual Thresholds. Thresholds of 1.6 degrees for visual perception of tracking error and 6.4 degrees/second for visual perception of error rate were calculated as described in [1]. Because of the large vehicle motions, thresholds for motion-derived perceptions were assumed negligible.

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* No penalty was associated with acceleration in the preceding study.

Motor Noise/Signal Ratios. Driving motor/noise signal ratio was negligibly small; pseudo noise/signal ratio was set at -35 dB.

Observation Noise/signal Ratio. A value of -20 dB was used.

As shown in Figure 6, model predictions correlated well with experimental measures. ("Year 1" and "Year 2" refer to the studies described in [2,3] and in this paper, respectively.) All significant trends related to task configuration and availability of motion cues were predicted. Furthermore, individual scores were predicted, on the average, to within 15%.

CONCLUSIONS

The principal results of this study may be summarized as follows:

1. The effects of motion cues on task performance and pilot response behavior are strongly dependent on the structure of the tracking task. The major effect of motion cues in a target-following task is to allow the pilot to generate low-frequency phase lead; in a disturbance-regulation task, the main effects are more phase lead (alternatively, less phase lag) at high frequencies accompanied by an increase in gain-crossover frequency.

2. Because of the strong interaction between motion-cue effects and task structure, a pilot/vehicle model is required to extrapolate the results from one task to the next.

3. The "optimal-control" model for pilot/vehicle systems provides a task-independent framework for accounting for the pilot's use of motion cues. Specifically, the availability of motion cues is modeled by augmenting the set of assumed perceptual variables to include position, rate, acceleration, and acceleration rate of the moving vehicle.

4. Results are consistent with the hypothesis that the subject shares attention between visual variables as a group and motion variables as a group. This hypothesis has not been conclusively proven, however.

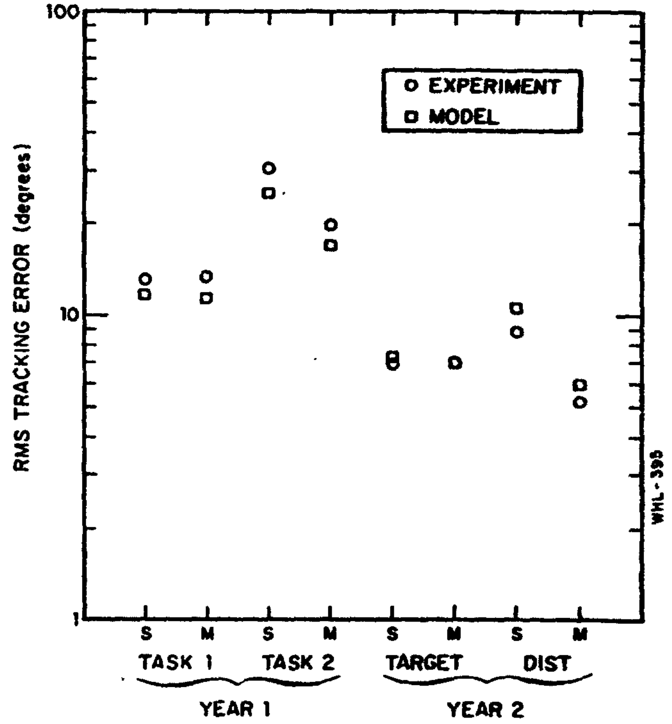

Figure 6. Comparison of Model and Experimental RMS Error Scores for Two Studies

S=static condition, M=motion condition.

5. Variations in model parameters relating to motion-cue availability and attention-sharing are sufficient to enable the model to replicate the effects of motion on all performance metrics for the tasks explored in this study.

6. Using the model for motion-cue utilization defined above, plus a single "typical" set of pilot-related model parameters, one can obtain accurate model predictions of rms tracking error scores for all task configurations explored in this study and in the preceding study.

7. There is some evidence that low-quality acceleration information can be obtained directly from the visual display in some tasks. The influence of such information processing on tracking performance appears to be minimal, however.

8. Use of acceleration-rate information appears to allow a modest reduction in rms tracking error in some tasks.

9. Results are consistent with existing models for motion perception by vestibular sensors. Such models are not needed to explain the data obtained in this study, however.

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