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A Comparison of Head and Manual Control for a Position-Control Pursuit Tracking Task

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ABSTRACT

Head control was compared with manual control in a pursuit tracking task involving proportional controlled-element dynamics. An integrated control/display system was used to explore tracking effectiveness in horizontal and vertical axes tracked singly and concurrently. Compared with manual tracking, head tracking resulted in a 50% greater rms error score, lower pilot gain, greater high-frequency phase lag and greater low-frequency remnant. These differences were statistically significant, but differences between horizontal- and vertical-axis tracking and between 1- and 2-axis tracking were generally small and not highly significant. Manual tracking results were matched with the optimal control model using pilot-related parameters typical of those found in previous manual control studies. Head tracking performance was predicted with good accuracy using the manual tracking model plus a model for head/neck response dynamics obtained from the literature.

Objectives

An extensive research program is underway in the Air Force to develop predictive models for pilot control behavior for use in the design of advanced aircraft and ground-based flight simulators. Such models must be applicable to a variety of task environments, including (a) steady-state and non-steady-state control problems, (b) cockpit instruments and extra-cockpit visual scenes, and (c) manual and head control modes. Use of the head as a control effector is of particular relevance to tasks, such as airborne weapons delivery, where the operator may be required to perform multiple control tasks.

This paper summarizes the analytical work performed by Bolt Beranek and Newman Inc. (BBN) in support of an experimental study conducted by the Air Force to compare head and manual control performance. Additional details are documented in [1]. Model analysis was performed with the optimal control model (OCM) of the human operator. This model was selected because of its demonstrated predictive capabilities across a broad spectrum of task environments [2]. As shown later, the model provides a consistent treatment of the head and manual control results obtained in the Air Force study.

Background

The use of the head as a control effector in continuous tracking tasks has not been explored to a great extent. Studies of head tracking have not, in general, used the full range of performance assessment techniques often employed in studies of manual control, nor have they proposed or validated mathematical models. Furthermore, experimental results run counter to what we would expect on the basis of manual control results.

A comparison of head and manual tracking is provided by Chouet and Young in a study employing both time- and frequency-response performance measures [3]. A set of spatial orientation tasks were performed which required the subjects to regulate the attitude of a moving simulator cab in the presence of a pseudo-random disturbance input. Rate control of the cab was implemented.

Head tracking compared favorably on the average with manual control in the pitch and yaw axes but was less effective in the roll axis. Compared with manual tracking, the gain crossover frequency* for head control was the same in the yaw axis and about 20% less in the pitch axis. Integral squared tracking error, averaged over these two axes, was about 16% greater for head tracking.

Shirachi, Monk, and Black [4] studied the head control effector in a proportional-control pursuit tracking task. Control was performed singly and jointly in the horizontal and vertical axes. Manual control was not explored, and only frequency-response measures were obtained.

Differences between axes and between 1- and 2-axis conditions were found. Pilot gain was substantially greater in the vertical axis, whereas pilot response was more highly correlated with the tracking input in the horizontal axis. Dual-axis tracking appeared to be more efficient than single-axis tracking: specifically, pilot gain and response coherency were greater, and phase lag was smaller, for the dual-axis task.

A number of the findings reported in these two studies are surprising in light of other studies of human controller behavior. First, since the

* The gain-crossover frequency is the frequency at which the combined transfer characteristic of the operator and controlled element is unity (0 dB).

hand is less massive than the head, one would expect manual control to be of wider bandwidth -- and thus more effective -- than head control. Second, previous manual control studies have shown similar tracking effectiveness in vertical and horizontal axes when the control tasks have been statistically identical on the two axes [5,6]. Finally, studies of multi-axis manual control have shown that performance on a given axis either stays about the same or degrades when another axis is tracked concurrently; it does not tend to improve. The experimental program summarized in this paper was conducted, in part, to resolve these discrepancies as well as to develop and test a predictive model for head tracking.

As an initial working hypothesis, we adopted a model of head/neck dynamics similar to that proposed by Morasso et al [7], which was based on the response of the head to passive displacement. They fitted the observed response with a second-order system having a natural frequency of 9 rad/sec and a damping ratio of 0.55. They also added a 20 msec delay and a first-order low-pass filter having a time constant of 0.18 sec to reflect additional neuromuscular response mechanisms.

DESCRIPTION OF EXPERIMENT

An experimental program was conducted to explore the ability of the human operator to perform a pursuit tracking task using the head as the control effector; manual tracking with a nearly isometric control stick was also explored to provide a point of reference. The output of the controlled element ("plant") was proportional to the operator's control input. Plant position and target displacement were explicitly displayed to the operator. Tracking was performed in three modes: (1) horizontal axis only, with vertical error clamped electronically at zero; (2) vertical axis only, with horizontal error clamped at zero; and (3) combined horizontal and vertical axes.

Half the experimental trials were performed with the subject controlling the cursor by appropriate head movements. A helmet-mounted sight was used to sense the subject's head angles as he tracked the target and was calibrated electrically so that one degree of head rotation produced one degree of cursor displacement. A nearly isometric control stick was used as the manual input in the remaining trials. In order to facilitate comparison of pilot response characteristics obtained in the two control modes, system gains were adjusted so that one volt of recorded control input always corresponded to 1 degree of cursor displacement. One control volt represented one degree of head motion, or 1/8 lb control force.

Forcing functions were constructed from 11 sinewaves whose amplitudes were selected to simulate a white noise process passed through a second-order filter having a double pole at 2 rad/sec. Frequencies were spaced at approximately half-octave intervals. Horizontal-axis input frequencies were interleaved with vertical-axis frequencies to allow for differentiation between horizontal-axis and vertical-axis response characteristics during 2-axis tracking.

Eight university students served as subjects for this experiment. Each subject served in all six conditions of control mode (head or manual) and target motion (horizontal only, vertical only, and 2-axis). Half the subjects were first trained and tested with the joystick and were then trained and tested on the head motion system; half were trained in the reverse manner.

A tracking session consisted of three sets of four 100-sec trials, one set with each type of target motion. The first 9 seconds of each run were considered as "start up" time; the remaining 91 seconds were recorded and scored. A 1-minute rest period was provided between each trial within a set of four trails, and a 5-minute rest was provided between each set. Subjects were instructed to minimize the circular error probability (CEP)* and were given their CEP scores at the end of each run. Order of presentation was counterbalanced over subjects.

Each subject was trained until a performance asymptote was reached, where "asymptote" was defined as an improvement of 5% or less averaged over all trials in a session on two consecutive days. On the average, the subjects received about 100 practice trials total. Experimental data were taken on the day following the day a subject reached asymptote. Each subject provided 24 trials of experimental data: 2 control modes, 3 target conditions, 4 replications each.

EXPERIMENTAL RESULTS

The analysis procedure followed in numerous previous studies was again followed here. First, the time histories were analyzed to provide various time- and frequency-domain measures of tracking performance. Second, these results were averaged across subjects and then subjected to model analysis to identify (i.e., quantify) parameters relating to operator response limitations. Emphasis was placed on testing a predictive model for head tracking.

Primary Data Reduction

Tracking error and control input time histories from each experimental trial were subjected to fast-Fourier transform (FFT) analysis to yield,

* The CEP score was defined as the radius of an imaginary circle drawn around the target such that the cursor was within this circle 50% of the time. For a Gaussian tracking error distribution, the CEP is proportional to rms tracking error.

among other measures, estimates of power spectra. These spectra were then integrated to obtain estimates of error and control variance. These same spectra were also multiplied at each FFT frequency by the square of the frequency (in rad/sec) and again integrated to obtain estimates of error-rate and control-rate variance.

RMS performance scores, obtained by taking the square root of the population mean for each variance score, are presented in Figure 1. Tracking error scores were nearly identical for horizontal- and vertical-axis tracking and were little influenced by the number of axes tracked simultaneously. Error scores associated with head tracking, however, were about 50% greater than manual tracking scores. Results of paired t-tests performed on variance scores, reveals that head/hand differences in tracking error were statistically significant at the 0.001 level. Head/hand differences in other rms performance measures were inconsistent and generally not statistically significant.

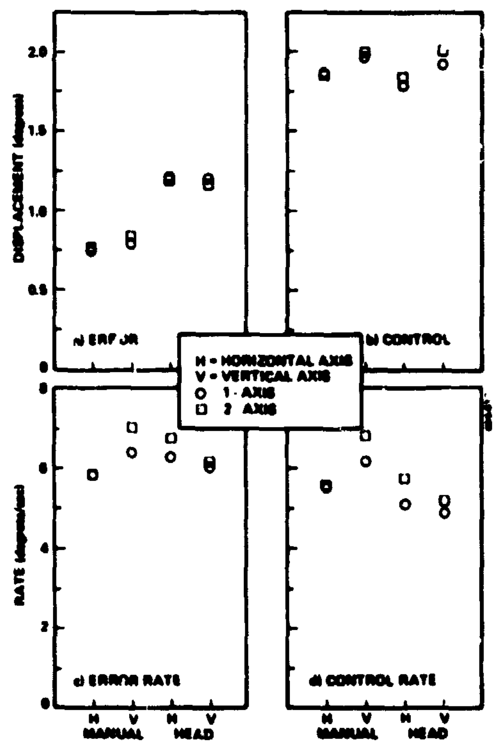

Figure 1. RMS Performance Measures
Average of 8 subjects, 4 trials/subject

Horizontal/vertical differences on the order of 5 to 20% were observed for the remaining three performance measures. For the most part, however, these differences (as well as 1-axis/2-axis differences) were not strongly significant.

Results of the FFT analysis were used to compute estimates of the pilot describing function and remnant spectrum for each experimental trial. Two sets of measures -- one for each axis -- were obtained for 2-axis trials. The describing function was expressed in terms of amplitude ratio ("gain") and relative phase shift, whereas the portion of the closed-loop control spectrum not linearly correlated with the tracking input served as the measure of pilot remnant.

Amplitude ratio and phase measures were very nearly similar for the horizontal and vertical axes and for single- and dual-axis tasks (see Levison et al [1]). The frequency dependency of the remnant spectrum was virtually unchanged, but the magnitude was about 1-2 dB greater for vertical tracking. The remnant spectrum (for a given axis) was also about 1-2 dB greater for dual- than for single-axis tracking. Thus, the small differences in tracking performance related to axis orientation and to number of concurrent axes appears to stem from differences in the "noisiness" of the pilot's response.

Considerably greater differences in tracking performance were associated with the mode of tracking. Figure 2 shows that, in comparison to manual tracking, head tracking yielded lower amplitude ratio and higher remnant at low and mid frequencies, and larger phase shift at high frequencies. These differences were highly significant [1]. As shown by the model analysis below, the differences shown in Figure 2, as well as the head/hand differences in performance scores discussed above, are interrelated and reflect a consistent cause-and-effect relationship.

Model Analysis

The Optimal Control Model (OCM) of the human operator was employed to provide a theoretical framework to account for the effects of control mode (head or hand) on pilot response behavior. Our objective was to seek a consistent modeling philosophy that would replicate manual and head tracking performance. Readers unfamiliar with this model are directed to the review article by Baron and Levison [2], and the citations listed therein, for a description of the model structure and parameterization.

Because control mode was the only experimental variable to yield performance differences that were significant in both the practical and statistical sense, model analysis was directed toward explaining head/hand differences. Average data obtained for the single-axis horizontal tracking task were used to identify pilot-related model parameters and to test the predictive capability of the model.

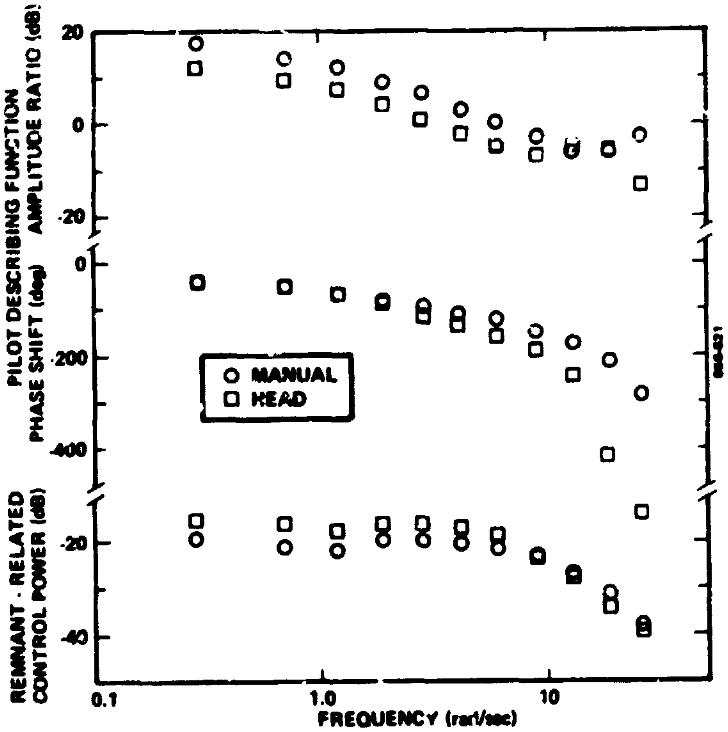

Figure 2. Effect of Tracking Mode on Frequency Response
1-axis horizontal tracking.

Average of 8 subjects, 4 trials/subject

Parameters for the manual control task were first identified using the gradient search scheme reported by Lancraft and Kleinman [8] and modified by Levison [9]. This scheme required the definition of a scalar "matching error" that consists of normalized squared differences between model predictions and experimental measurements. Variance scores, describing function gain, describing function phase shift, and pilot remnant measurements were used in computing this matching error.

Each model-data mismatch was normalized with respect to the (across-subject) standard deviation of the experimental mean so that: (a) a set of dimensionless quantities would result, allowing their accumulation into an overall scalar matching error, and (b) each component matching error would contribute to the total in proportion to the reliability of the data.

This gradient search scheme identified the parameter values shown in the first column of Table 1. These values were then "rounded off" as shown in the second column of Table 1 and tested against the same matching criterion. As the resulting matching error was within 12% of that obtained by the gradient search, the latter set of parameter values were used to model the head tracking data.

A model for the head/neck system similar to that proposed by Morasso et al [7] was tested against the head tracking data obtained in this experimental study (1-axis, horizontal task). To model this task, the system dynamics were augmented by a second-order filter having a natural frequency of 9 rad/sec and a damping ratio of 0.55, plus a first-order lag of 0.18 seconds. The output of this third-order system was considered as the operator's control signal for purposes of predicting the pilot describing function and remnant spectrum.

This modified pilot model was tested against the experimental head tracking data with pilot parameters adjusted as indicated in the second column of Table 1. As shown in Figure 3, a good match between model and experiment was obtained over much of the measurement bandwidth.

Experimental and predicted rms performance scores are compared for both the manual and the head tracking tasks in Figure 3a. Brackets indicate one standard deviation as measured across subjects. The "approximate" pilot parameters shown in Table 1 were used for both comparisons. Because the model results for the head tracking tasks are based on parameters identified for the manual task, plus a model for head dynamics taken from the literature, these results are true predictions.

All four rms performance scores obtained from the manual control data were matched to within one standard deviation. Although the head-tracking scores were predicted less accurately, all predictions were within 12% of the experimental mean, and rms tracking error was predicted to within 5%.

Figure 3b shows a very close match to frequency response measurements obtained from the manual tracking data. Measurements at mid frequencies -- where response behavior is critical in terms of overall system behavior -- were predicted with high accuracy for the head control task. Prediction errors were greatest for low-frequency amplitude ratio and phase shift, and high-frequency amplitude ratio and remnant.

DISCUSSION

The parameters identified for the manual task are consistent with values found in earlier studies using proportional control systems [2].*

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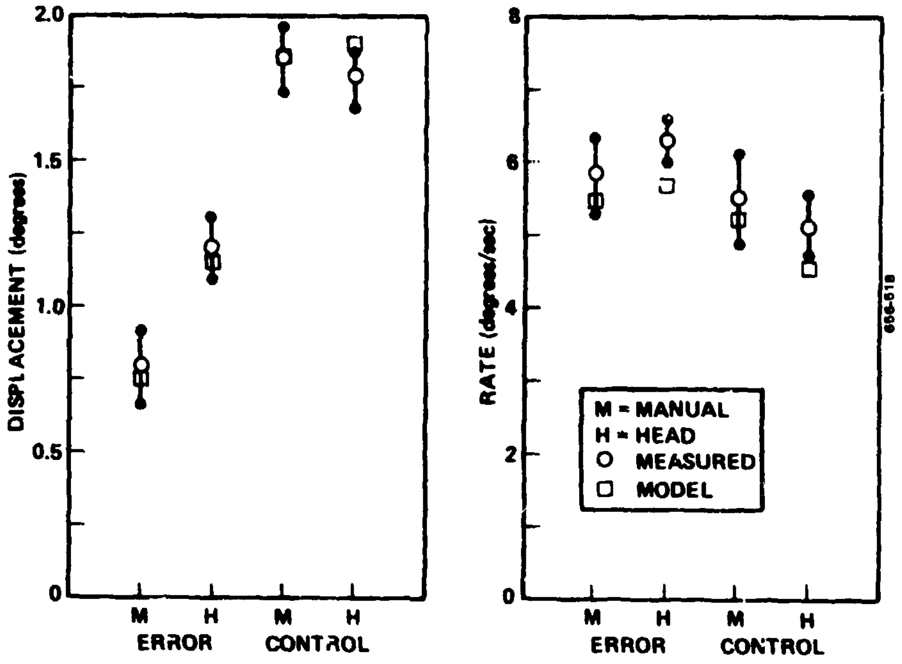
* This is true for all parameters except motor noise/signal ratio, which cannot be meaningfully compared with previous results because of the different treatment of motor noise [1].

a) RMS Performance Scores



b) Frequency Response

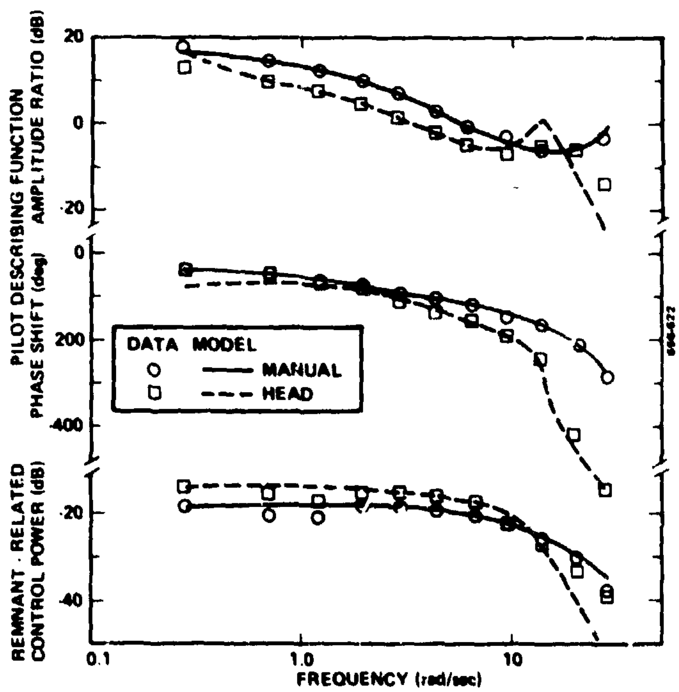


Figure 3. Comparison of Model and Experimental Results
1-axis horizontal tracking.
Average of 8 subjects, 4 trials/subject

Table 2

Identified Values for Pilot-Related Model Parameters

Parameter	Best Fit	Approximate Value
Matching error	0.840	.937
P_e	-21.0	-20
$P_{\dot{e}}$	-19.5	-20
P_u	-26.0	-25
TD	0.169	0.17
TN	0.082	0.08

P_e = observation noise/signal ratio, error (dB)

$P_{\dot{e}}$ = observation noise/signal ratio, error rate (dB)

P_u = motor noise/signal ratio (dB)

TD = time delay (seconds)

TN = motor time constant (seconds)

Single-axis, horizontal, manual control task.
Average of 8 subjects, 4 trials/subject

The ability to predict head tracking data with these parameter values, plus a model for head/neck response dynamics obtained from the literature, suggests that the optimal control model provides a mechanism for generalizing the results of this study to other tasks. Specifically, we would expect this model to be valid for tasks in which overall system performance is relatively insensitive to pilot response behavior at frequencies less than 0.5 rad/sec or greater than 10 rad/sec. Although one could probably improve the match at the high and low end of the measurement band, through readjustment of the pilot-related parameters, we submit that a more meaningful approach -- one having greater predictive potential -- would be to revise the model for head/neck response dynamics.

The reader is cautioned against generalizing head/hand differences on the basis of the performance differences obtained in this study. In general, head/hand differences can be expected to depend on the details of the task environment, including controlled element dynamics, external forcing function characteristics, and possibly performance requirements. It is these potential interactions that provide the primary motivation for model development.

The lack of 1-axis, 2-axis differences reported here are consistent with earlier studies involving "integrated" controls and displays which employ (a) a single manipulator having similar characteristics in two dimensions, and (b) a single error indicator that moves in two dimensions [5]. Were the display to be non-integrated such that separate display elements indicated horizontal and vertical tracking error, significant 1-axis, 2-axis performance differences would be expected [6].

We cannot explain the differences between the results of this study and some of the counterintuitive results reported in previous studies of head tracking; published information is inadequate to allow complete reconstruction of the earlier studies. We can only point out that care was taken in this study to provide the subjects with knowledge of performance after each practice trial, and to train them until apparent asymptotic performance. We assume that this training procedure motivated the subjects to minimize their error scores whatever the task conditions.

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