EVALUATION OF TACTUAL DISPLAYS FOP FLIGHT CONTROL*

by

William H. Levison
Robert B. Tanner
Thomas J. Triggs

Bolt Beranek and Newman Inc.
Cambridge, Massachusetts

Presented at the Ninth Annual Conference on
Manual Control, May 1973

ABSTRACT

A set of manual tracking experiments has been conducted to
determine the suitability of tactual displays for presenting
flight-control information in multi-task situations. Although
tracking error scores are considerably greater than scores
obtained with a continuous visual display, preliminary results
indicate that inter-task interference effects are substantially
less with the tactual display in situations that impose high
visual scanning workloads. The single-task performance degrada-
tion found with the tactual display appears to be a result of
the coding scheme rather than the use of the tactual sensory
mode per se. Analysis with the state-variable pilot/vehicle
model shows that reliable predictions of tracking errors can
be obtained for wide-band tracking systems once the pilot-related
model parameters have been adjusted to reflect the pilot-display
interaction.

PRECEDING PAGE BLANK NOT FILMED

I. INTRODUCTION

Objectives

In current aircraft, nearly all the flight parameter infor-
mation available to the pilot is transmitted to him visually,
whether under visual contact or instrument flying conditions.
It has long been recognized that during instrument flying condi-
tions the task of scanning just the essential instruments is a
taxing, fatiguing one. It may be that displays using information
from other modalities can alleviate the demands of this task.
Furthermore, the importance of maintaining continuous attention
to the visual scene outside the cockpit is being increasingly
realized for a number of situations. Traditional panel-mounted
visual displays do not permit this, whereas display of informa-
tion to other modalities could free the eyes substantially from
tasks inside the cockpit.

The goal of the study reported in this paper has been to
develop tactual displays that can be utilized for flight control.
The work has been conducted in three distinct phases: (a) review
and selection of elemental tactual transducers (tactors) for
operation in display arrays, (b) development of tactual display
configurations for flight control, and (c) evaluation of the
proposed tactual displays in a series of manual tracking experi-
ments utilizing the tactual arrays together with suitable dynamics
simulation of aircraft motions.

This paper summarizes the results of the tracking experiments.
Additional details on all phases of this project may be found in
[1].

Background

Both auditory and tactual displays have been applied to the
area of vehicle control. Perhaps the best known study in the area
of auditory displays was the program known as flying by auditory
reference (FLYBAR) [2, 3]. The attempt was to supply the pilot
with all the information he required to enable him to maintain a
required flight path. By so doing, he would be able to devote
more time to scanning the outside environment. Although initial
experimental success was achieved, an operational system was
never developed.

Tactual displays can offer two distinct advantages over auditory presentations. First, tactual displays should not interfere in any real way with speech communications. Second, the tactual modality is not limited in its ability to present information in a spatial pattern. Ballard and .essinger [4] report an early attempt to supply flight control information using just four vibrators mounted on one thumb. Hirsch and Yadushin [5] and Fenton [6] have both used tactual displays to supplement visual display information and have found an enhancement compared with using the visual display alone.

In addition to these studies relating specifically to vehicle control, there have been a number of studies dealing with the characteristics of tactual tracking. Most of these studies have displayed information to the more moveable parts of the body, such as the hand and arm [7-10] and the head and face [11-12]. Those investigators that have displayed information to the torso [13, 14] used just three vibrators per tracking dimension to indicate either zero error, left-right or up-down displacement. Hill et al. [7] suggested that tactile displays are correctly interpreted more frequently when located on body locations not involved with motion.

We considered that display-control compatibility would be an important variable in determining vehicle control performance. Because of this, we selected the chest and abdomen as the display area, since it is usually relatively immobile, and the display-control relationships are unlikely to be altered as the human operator performs his various functions. The torso also provides a relatively uniform display area for exploring various display sizes and geometries.

We also wished to evaluate a two-dimensional tracking display with minimal confusion between axes as well as high display-control compatibility without the use of large numbers of stimulators. Preliminary experimentation explored various configurations for possible use as flight control displays, and an X-Y display was selected with 7 stimulators on each dimension with a common stimulator shared at the point of the axis crossing. In order to enhance the pilot's ability to interpret the tactual information, X- and Y axis tracking errors were presented sequentially, rather than simultaneously.

Because of previously reported studies which indicated that simple intensity coding would not be adequate in a multi-task situation [13, 15], other coding dimensions were employed in this study. A ripple display was designed that used both number of tactors stimulated in a sequence as well as the rate of strobing to indicate the magnitude of the tracking error. Since preliminary experimentation indicated that pilots would have difficulty in distinguishing between different rates for ripple rates greater than 26 Hz, the ripple rate was varied continuously with error magnitude over a range of 2.6 to 26 Hz. (This range is lower than that found to be optimal by Hill [8] in his study with a ripple display, but we were using a different form of coding and a different type of stimulation.)

2. PROCEDURES

Description of the Task

The bulk of the experimental program was devoted to an investigation of continuous manual tracking performance with tactual and visual displays. In addition, combined tracking and visual monitoring tasks were studied in order to provide comparisons of tactual and visual tracking displays in situations imposing a high scanning workload.

Descriptions of the tracking and monitoring tasks are given below, followed by descriptions of the tracking displays and of the procedures used in analyzing the experimental data. Additional experimental details are provided in the discussion of experimental results (Section 3).

Tracking Tasks

Two very important constraints were placed on the selection of a tracking task. First, we wished to simulate the important aspects of a flight-control task. Secondly, it was important to obtain an accurate and complete characterization of the pilot-display interaction so that the results of this experiment could be extrapolated to other manual control tasks using tactual displays.

These two considerations led to the selection of a simulated attitude regulation task. A wings-level operating point was selected, thereby allowing the pitch and roll axes to be uncoupled. This task not only provided the required degree of face validity, but interpretation of the measurements was greatly facilitated by allowing each perceptual dimension of the tactual display to relate to an independent single-variable control task. In this manner we minimized the likelihood that the pilot's response to a particular tactual display variable would be confounded by his response to other tactual (or visual) display variables.

Simplified vehicle dynamics were selected to represent the response of a high-speed fighter aircraft having good handling qualities [16, 17]. Pitch dynamics were of the form

$$\frac{\theta}{x_e}(s) = \frac{K_\theta(s + 1/T_\theta)}{s(s^2 + 2\xi_o\omega_o s + \omega_o^2)} \qquad (1)$$

and the roll dynamics were

$$\frac{\phi}{x_a}(s) = \frac{K_\phi}{s(s + 1/T_r)} \qquad (2)$$

Values for the dynamic parameters were

$$T_\theta = 0.25 \text{ sec}*$$
$$\omega_o = 6.0 \text{ rad/sec}$$
$$\xi_o = 0.85$$
$$T_r = 0.3 \text{ sec}$$

and the control gains K_θ and K_ϕ were selected during training to provide acceptable system responsiveness.

The pitch and roll axes were perturbed by independent random-appearing inputs which were applied as vehicle disturbances. The transfer function relating pitch response to pitch-axis disturbance was the same as the pitch/control relationship shown in Equation (1) except that the numerator contained no root. The roll-axis disturbance was applied in parallel with the pilot's control input.

Both disturbance inputs were constructed by summing together 13 sinusoids of random phase relationships to simulate first-order Gaussian noise processes having break frequencies of 2.0 rad/sec. Input amplitudes were adjusted during training to yield nearly equal pitch and roll mean-squared error scores for the visual display condition.

A two-axis hand control provided independent control inputs to the pitch and roll axes. The control was primarily a force-sensitive device (.12 cm of stick motion per newton of force) and could be manipulated with wrist and finger motions.

---

*A T_θ on the order of 1.0 second is more commonly associated with high-speed pitch dynamics. But because the hand control used in these experiments allowed a very rapid control response, it was necessary to lower the value of T_θ to provide reasonable response dynamics.

Two instrument-rated pilot served as test subjects for the entire experimental program. Subject "A" was a commercial airline pilot with over 1000 hours of instrument flight time; subject "B" was a recent Navy pilot with over 300 hours of instrument time. Subject B had accomplished approximately 150 carrier-landings with medium-attack aircraft.

Visual Monitoring Task

A visual monitoring task was used in the final evaluation experiment to provide a substantial scanning workload. The pilot was required to scan between two meter movements and to depress a hand-held response button whenever either or both of the meter indicators was outside a clearly-marked "allowable" region. Separation between the meters and between each meter and the visual tracking display was sufficient to require overt visual scanning. The display panel for the combined monitoring and visual tracking task is diagrammed in Figure 1.

Each meter was driven by an independent simulated first-order noise process filtered by an additional first-order network having a break frequency of 1.0 rad/sec. Signal amplitudes — nominally equal for the two meters — were adjusted so that the two meter indicators were jointly within their allowable regions about 50% of the time. The rate at which the subjects had to change the state of the response button was determined experimentally to be about twice every three seconds. This relatively high response rate, coupled with the separation between displays, assured a high scanning workload whenever the visual monitoring task was performed.

Tracking Displays

Three tracking displays were employed in this experimental program: (1) a continuous visual display, (2) a tactual display, and (3) a quantized visual display that was designed to be a visual analog of the tactual display.

Continuous Visual Display

The continuous visual display consisted of a CRT presentation of an artificial horizon. Display motion was compatible with that found in an aircraft attitude instrument; i.e., a clockwise roll of the aircraft was represented by a counter-clockwise rotation of the display indicator, and a nose-down attitude was designated by an upward displacement of the indicator. The display panel was located approximately 30 inches from the subject's point of regard.

FIGURE 1. Diagram of Combined Tracking and Monitoring Display

7

Tactual Display

A variety of tactual display confiqurations were explored and evaluated during the initial traininq phase of this nrogram. Only the configuration used in the formal data-takinq sessions is described in this paper; details on the preliminary disrlay designs may be found in [1].

A diagram of the tactual display is given in Fiqure 2. Thirteen mechanical vibrators (bimorphs) were arranged in the shape of a cross with three tactors in each of the four arms and a single tactor at the junction. Tactors were concentrated towards the outer limits of each arm to provide a clear cue as to the directionality of the tracking error. The upper and lateral arms of the display were of equal dimensions, whereas the lower arm was compressed to enhance comfort in wearinq the display on the chest and abdomen.

The display was coded so that both the number of tactors excited and the rate at which successive tactors were stimulated (the "ripple rate") provided information related to the maqnitude of the trackinq error. When trackinq error was below a certain threshold level, only the center tactor was stimulated at infrequent intervals. For larqer errors, two or more tactors were stimulated in succession, with the interval between successive tactor stimulations beinq inversely proportional to the maqnitude of the error. The ripple rate, then, qave a siqnal proportional (within limits) to tracking error, whereas the number of tactors stimulated in a sinqle sweep gave a quantized indication of maqnitude.

A sinqle display sweep was always initiated at the center and proceeded outwards along one of the four display arms. Thus, an additional cue was provided in that the nortion of the anatomy stimulated by the tactors indicated the directionality of the signal. In order to maximize the ability of the pilot to interpret information obtained from the tactual display in a two-axis tracking situation, signals were presented sequentially, rather than simultaneously. The penalty for this codinq scheme, of course, was an increase in the effective perceptual delay time.

Operation of the tactual display is perhaps best visualized by reference to the timinq diagram of Fiqure 3. Assume that the X-axis and Y-axis errors are larqe enough to excite three tactors in each axis, and assume that the X-axis error is detected first. As soon as this error is detected, a 35.3-msec pulse (6 cycles of a 170 Hz waveform) is generated on the center tactor. An inter-stimulus-interval (ITI) proportional to the error at sample time is then generated, followed by stimulation of the second tactor. Another ITI is generated, followed by stimulation of the third tactor. Presentation of X-axis information is completed, and a pre-determined quiet interval (the IAI, or inter-axis-interval) follows.
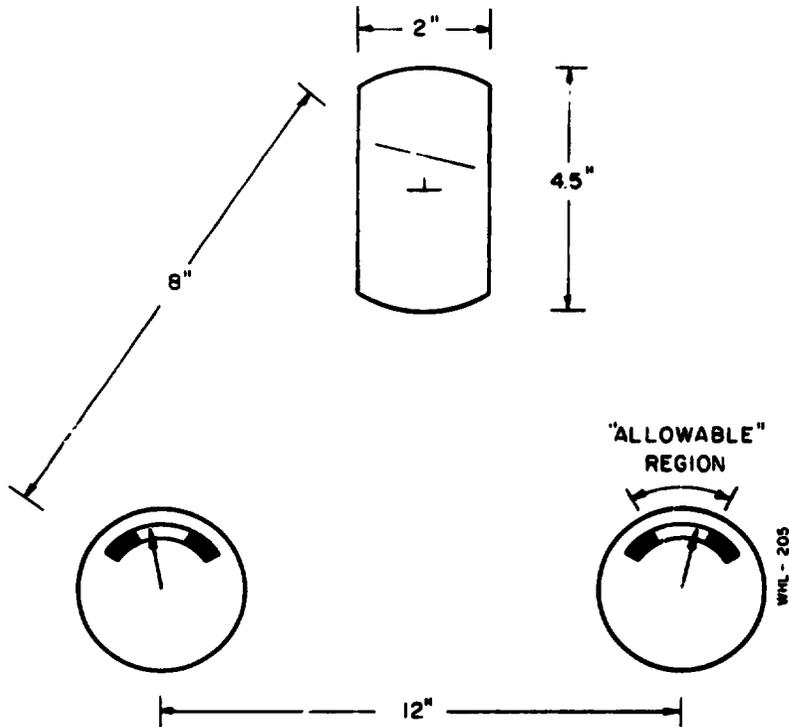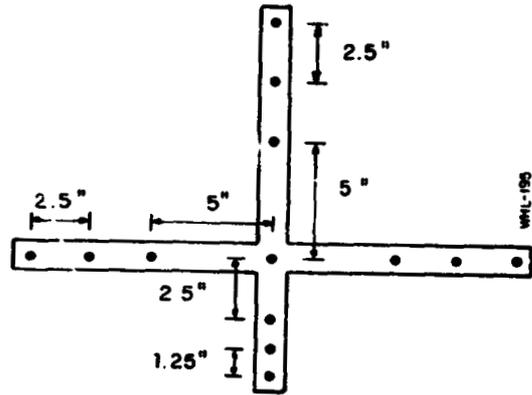
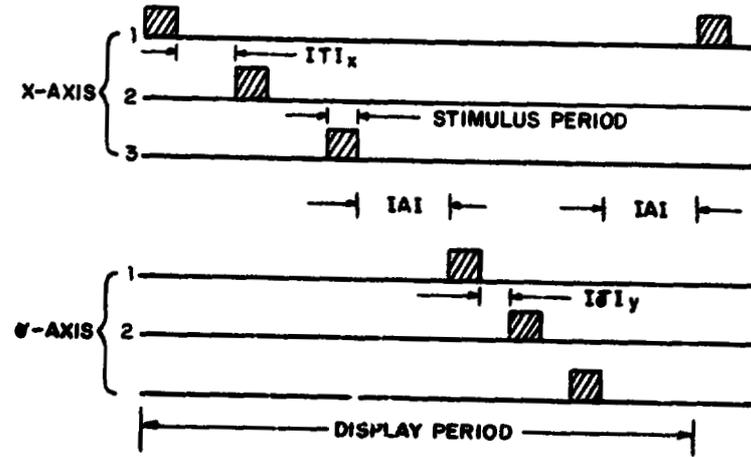FIGURE 2. Diagram of the Tactual Display

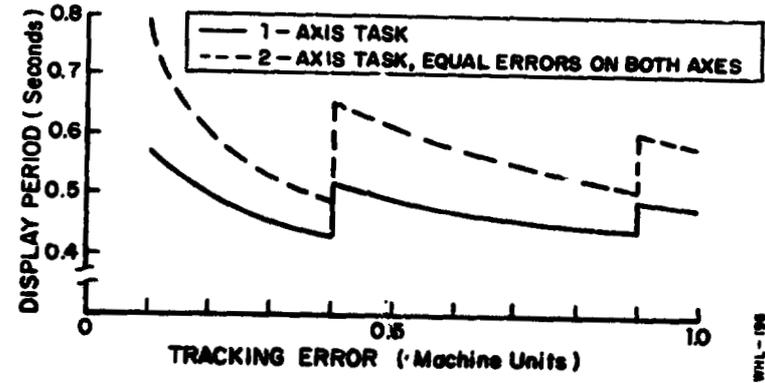FIGURE 3. Timing Diagram for Tactual Information

FIGURE 4. Relation Between Tactual Display Period and Tracking Error

During the IAI, the Y-axis error is sampled, and the process repeats itself for the Y-axis information while the X-axis tactors remain quiet. If only a single axis is tracked (i.e., if the error on one axis is insufficient to stimulate two tactors), successive sweeps are generated on a single display axis. In this case, the inter-sweep dwell period is automatically extended.

Independent inputs to the display control unit allowed individual control of the number of tactors stimulated as well as of the ripple rate. Thus, some flexibility was available in determining the relationship between tracking error and the various coding dimensions. A single such relationship was used during the course of the formal experiments.

The tactual display operated in a sample-and-hold fashion; the period of the sweep along a given axis was determined by the error sample obtained prior to the initiation of the sweep. Because X- and Y-axis information was presented sequentially, the "display period" (i.e., the time between initiations of successive presentations on a given axis) was a function of the error samples obtained from both axes.

Figure 4 shows the relationship between display period and tracking error for both one-axis and two-axis tracking situations. (Equal X and Y errors are assumed for the two-axis case.) The discontinuities in the curves occur at values of tracking error where an additional tactor is stimulated. Because of the greater inter-sweep dwell time for the 1-axis situation, the two-axis display periods are less than double the one-axis periods for a given tracking error.

In order to maximize transfer of learning between visual and tactual displays, tactual stimulation corresponded as closely as possible to motions of the artificial horizon. Accordingly, a nose-down attitude produced an upward ripple of the tactors, and a roll-left attitude produced a right-directed ripple.

Quantized Visual Display

A visual analog of the tactual display was used to distinguish performance degradations associated with the tactual sensory mode from degradations associated with the particular coding scheme. This display consisted of an array of thirteen light-emitting diodes (LED) arranged in an X-Y pattern. The coding for this display was identical to that of the tactual display; thus, stimulation of a given LED corresponded to stimulation of a particular tactor.

Analysis Procedures

Data analysis was performed in order to provide quantitative descriptions of tracking efficiency with regard to specific tasks explored in this study and to allow the results to be extrapolated to other flight-control situations. Primary data reduction yielded standard measures of system performance and pilot behavior for both the tracking and monitoring tasks. The reduced data were then compared with the outputs of the state-variable pilot/vehicle model developed at BBN [18, 19]. A model-adjustment procedure allowed the pilot-display interaction to be characterized in terms of pilot-related model parameters so that predictions of system performance in other tasks could then be obtained.

Primary Data Reduction

Mean-squared tracking error and mean-squared control effort were computed both during training and during the formal data sessions. In addition, means and standard deviations for these variables were computed from the formal data. These (and all other) performance measures were computed from approximately the middle 200 seconds of each 4-minute run.

Amplitude density functions were computed from selected time histories of tracking error and control input. Each such density function was normalized with respect to its mean and standard deviation to facilitate comparison with the normalized Gaussian density function.

Fast-Fourier transform techniques facilitated computation of power spectral density functions of error and control signals. Each "spectrum" so computed was separated into two components: (a) a portion linearly correlated with the external input disturbance, and (b) a "remnant-related" component associated with stochastic pilot response behavior not linearly related to the input. The input-correlated portions of error and control spectra were used in the computation of pilot describing functions; both input-correlated and remnant-related components of control spectra were used in the model-matching procedure.

Relative levels of remnant-related and input-correlated power provided an indication of measurement reliability. If the estimated input-correlated error and control power were not both at least 4 dB greater than corresponding estimates of remnant-related power, frequency-domain measures computed at this frequency were considered insufficiently reliable for model analysis.

The frequency-domain analysis techniques described above are similar to those employed in previous studies and are described in greater detail in [20, 21].

A performance score was obtained for the monitoring task which yielded a number proportional to the fraction of time that the pilot's response button was not in the appropriate state. The combined state of the stimulus meters was continuously monitored ("in" if both meter indications were in the allowable region, "out" if not), as was the instantaneous state of the subject's response button. An integrator was charged whenever the response was inappropriate. Only a single performance measure for the total search task was obtained; no attempt was made to distinguish between the various types and sources of monitoring error.

Model Analysis

In order to relate the pilot-display interaction to relevant pilot parameters, the tracking performance measures described above were compared with theoretical results from the state-variable (or "optimal-control") pilot/vehicle model. As this model has been well documented in the literature [18, 19], no detailed description is given in this paper. We shall, however, briefly review the pilot-related parameters of this model.

Three classes of model parameters characterize pilot limitations in laboratory tracking situations. First, an effective transport lag (i.e., "time delay") is associated with each perceptual variable. Current implementation of the model requires a single value for all such delays. Typical values range from 0.15 to 0.2 seconds.

Second, a "motor time constant" is associated with each control variable. Typical values range from about 0.08 to 0.10 for laboratory tasks.

Finally, one or more variables related to pilot remnant are required. Pilot remnant is accounted for in the model by a set of white-noise disturbances added to each sensory variable used by the pilot (i.e., "observation noise"). In addition, noise may also be considered to be added directly to the pilot's control (i.e., "motor noise").

In situations using idealized display and controls with optimally-selected display and control gains, each observation noise variance tends to scale with the variance of the associated display quantity [22]. The constant of proportionality is approximately the same for all inputs derived from a single display indicator (typically, indicator displacement and rate). In this case, pilot remnant can be related to an effective "observation noise/signal ratio". Experimental evidence suggests that this ratio

varies inversely with the amount of attention paid to the task [20, 23]. A value of 0.01π (i.e., -20 dB) is a typical observation noise/signal ratio for single-variable laboratory tracking tasks using stable vehicle dynamics.

Display-related sources of pilot remnant can be included to account for sensory threshold and resolution limitations in non-idealized display situations [21, 24, 25]. Typical values of effective "thresholds" for continuous CRT presentations are 0.05 degrees visual arc for indicator displacement and 0.2 degrees second visual arc for indicator rate limits.*

Motor noise has usually been found to contribute relatively little to pilot remnant and system error and has been included mainly to reflect the pilot's imperfect knowledge of his control inputs. A typical value for motor noise/signal ratio is -25 dB.

3. EXPERIMENTAL RESULTS

Initial Training

Prior to the first formal data session, the subjects were given considerable practice on the simulated pitch and roll tracking tasks described in Section 2. They were trained first with the continuous visual display to facilitate rapid learning of the system dynamics. Each subject received about thirty 4-minute trials with the visual display, which was enough training to yield reasonably stable performance scores on the order of what we had expected from past levels of pilot performance. Training then commenced with the tactual display.

Each subject received over 100 training trials with the various tactual display geometries and coding schemes explored in this study. On the basis of mean-squared error scores obtained during this phase of the program, the geometry and coding described in Section 2 were adopted for the remainder of the experimental program.

Although the subjects were trained mainly on the combined pitch/roll task, they also received training on each component task individually. Subjects were instructed to minimize mean-squared tracking error when tracking a single axis and to minimize the sum of the mean-squared pitch and roll errors when tracking two axes. Performance scores were reported after each training trial. Training was continued until performance under each condition appeared to reach a reasonably stable level..

*Threshold-like effects are handled by a statistical linearization procedure. The observation noise variance associated with a given display variable is incremented whenever the predicted rms signal level fails to be large relative to the assumed threshold. The noise-adjustment procedure is described in [24].

Experirent 1: Tactual Tracking Performance

The primary objective of the first formal experiment was to
quantify the interaction between the pilot and the tactual display
in terms of pilot-related model parameters. A secondary objective
was to provide a comparison of tactual tracking performance to per-
formance with a continuous visual display.

Experimental Conditions

The sirulated attitude-regulation task was performed
alternately with the tactual and continuous visual displays.
Performance measures were obtained for each axis tracked separa-
tely as well as for the combined pitch/roll task.

Two levels of input amplitude were employed for tactual
tracking so that display-related threshold effects could be
quantified. Because of the large performance scores obtained
with the tactual display, input amplitudes used with this display
were lower than the level used with the visual display.

The various conditions explored in this experiment are
listed in Table 1. Input amplitudes are shown relative to the
amplitude used with the visual display. To the extent possible,
the various tasks were presented in a balanced order.

Table 1

Conditions Explored in Experiment 1

Display	Tasks (P=Pitch,R=Roll)	Rel. Input Amplitude	No.Replications Per Condition Per Subject
Visual	P, R, P + P	1.	2
Tactual	P, R, P + P	.5	3
Tactual	P, R, P + R	.25	3

Tracking Performance

Average standard deviation (SD) scores for tracking error
are shown in Figure 5. (Mean errors were negligible, for the
most part, and are not shown here.) The performance scores shown
in this figure and throughout the paper are given in terms of
analog machine units. One machine unit of error corresponds to
2 cm vertical deflection of the visual error presentation for
pitch and about 50° rotation for roll. One unit of control
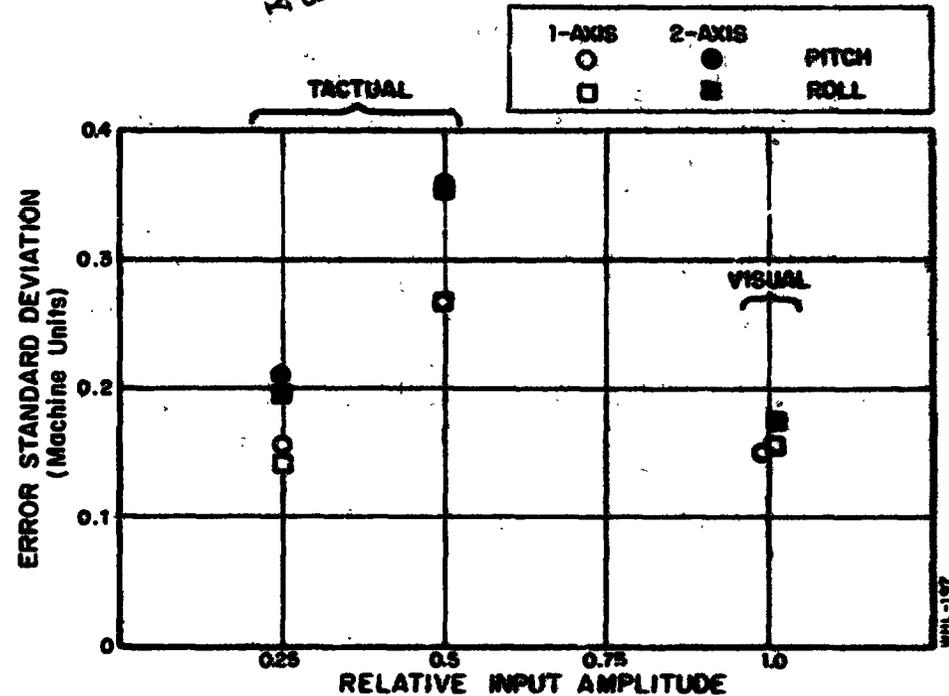effort represents approximately 7.7 newtons of force.

FIGURE 5.   Effect of Input Amplitude on Error SD Scores
(Average of Two Subjects)

As expected from considerations of the display coding scheme, tactual tracking performance was considerably less efficient than performance with the visual display. When corrected for differences in input amplitude, the single-axis tactual scores were found to be about 3.5 times as large as the visual scores. Also as expected, the scores associated with the tactual display did not vary proportionally with input amplitude. Extrapolation to zero input yields a (positive) non-zero error score, which suggests the presence of threshold-like effects.

No significant inter-axis interference effects were found with the visual display. The 1-axis and 2-axis pitch error scores were virtually identical; the small increment (about 15%) associated with the 2-axis roll score was not found to be statistically significant.*

Interference effects with the tactual display were larger, more consistent, and statistically significant. Two-axis standard deviations were about 35% greater for both pitch and roll. This relative difference was unaffected by input amplitude. As shown later in the paper, a good portion of the interference effects seen with the tactual display can be predicted from analysis of the coding scheme.

Use of the tactual display resulted in pulse-like control inputs, whereas the visual display allowed continuous-looking control activity. Both subjects commented that the pulse-like behavior reflected a "wait-and-see" strategy that was dictated by the relatively long time delay associated with the tactual presentation.

Sample time histories of error and control signals in a 2-axis training session are shown in Figure 6. Control pulses were applied singly and in bursts at irregular intervals. Pulses within a single burst were separated by about 0.4 seconds, and intervals between bursts of activity with a given control input ranged up to 5 seconds. Figure 6 shows that the pitch and roll tasks were controlled sequentially.

Since the pilot/vehicle model used in this study is predicated on Gaussian tracking variables, amplitude density distributions were obtained for selected time histories to determine the extent to which this assumption was violated. Time histories for error and control (one per subject) were analyzed for the 1-axis, larger-input, pitch tracking task with tactual display. As expected, the control amplitude-density curves were highly non-Gaussian and had large peaks associated with zero control activity. The error amplitude densities, however, were much more nearly Gaussian in appearance.

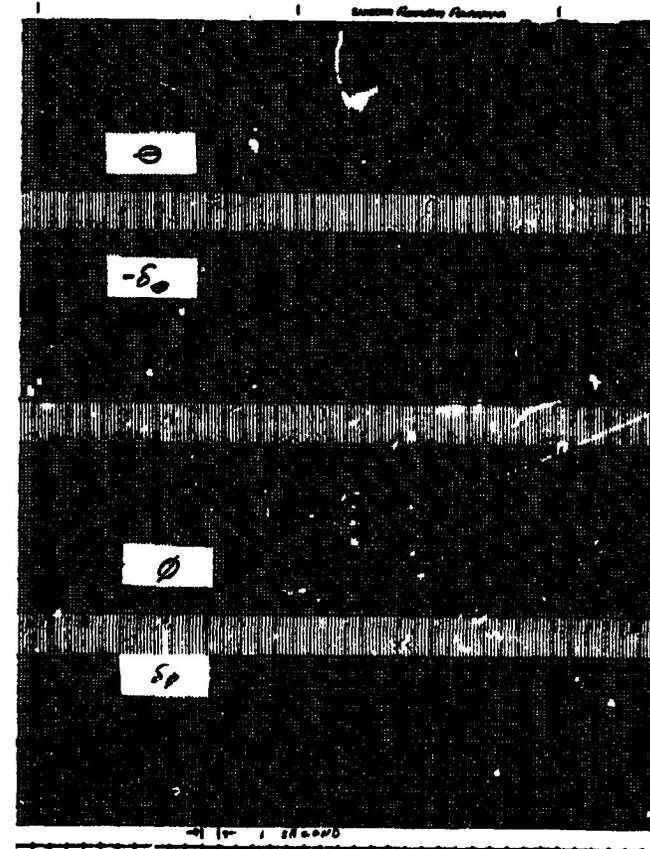*Statistical significance was tested by analysis-of-variance.

FIGURE 6. Time Histories of Error and Control Signals

Because of the non-Gaussian pilot response activity, the pilot/vehicle model must be applied with caution. Clearly, one cannot expect to obtain accurate predictions of detailed *control* behavior. It is possible, nevertheless, that reliable predictions of *tracking error* can be obtained, once the model parameters have been "calibrated" to account for the interaction between the pilot and the tactual display.

Model Analysis

Model analys' was undertaken with the following two objectives in mind: (1) obtain a representation of pilot-display interaction in terms of pilot-related model parameters, and (2) demonstrate the utility of the pilot/vehicle model in predicting system performance with the tactual display. Except for an initial calibration of display-related parameters, emphasis was on *predicting*, rather than *matching*, experimental results.

We adopted the following strategy for odel analysis:

1. Match the experimental measurements obtained for the single-axis pitch task with the visual display in order to determine pilot time delay, motor time constant, and observation noise/signal ratio.

2. Match the data from the single-axis, large-input pitch task with the tactual display in order to determine the changes in pilot-related parameters required to account for the pilot's interaction with the tactual display.

3. Use the parameter values determined above to predict the effects of input amplitude, multiple-tasks, and system dynamics on system performance.

Data-fitting was performed by an informal search of the model-parameter space and was terminated when visual inspection revealed a "good" match between model outputs and experimental measurements. In general, error and control scores were matched to within 10 percent, and pilot describing functions and control spectra were matched within 2 or 3 dB. All data used for comparison with model results represents average performance of the two test subjects.

An acceptable match to single-axis pitch performance was obtained with a time delay of 0.2 seconds, a motor time constant of about 0.11 seconds, an observation noise/signal ratio of approximately -21.5 dB, and a motor noise ratio of about -25 dB. These parameter values are consistent with previous analysis of single-variable laboratory tracking tasks [18, 19].

Comparison of experimental frequency-domain measures with model results is provided in Figure 7. Note that comparisons are shown for both the input-correlated and remnant-related components of the control spectrum.

Having quantified the pilot-related parameters on the basis of visual tracking, we then attempted to predict differences between visual and tactual tracking performance from an analysis of the tactual display properties alone. Since a minimum tracking error of 0.1 units was required to generate a sequence of two or more tactors, an effective threshold of 0.1 unit was assumed for perception of error displacement. An essentially infinite threshold was specified for error rate on the assumption that the sample-and-hold type of coding scheme programmed for the tactual display would prohibit the direct perception of useful rate information.

Perceptual time delay was incremented to account for the delay imposed by the tactual coding scheme. The size of the increment had to be recomputed for each experimental condition because of the dependent relationship between display-related time delay and tracking error. The display period associated with the error SD score was taken as a rough estimate of the required increment and was determined from the appropriate timing curve of Figure 4.

An incremental time delay of approximately 0.45 seconds was derived for the single-axis, large-input pitch task. This increment was added to the 0.2 seconds determined from the visual tracking data to yield a combined pilot-display time delay of 0.65 seconds.

Values for motor time constant and noise/signal ratios derived from the visual tracking experiments, along with the revised computations of time delay and perceptual thresholds, allowed a tentative prediction of tactual tracking performance. These predictions did not provide a satisfactory match to the data, however. Only slightly over half of the difference between visual and tactual errors was accounted for. Moreover, the model predicted a substantially lower control SD score than was actually measured for the tactual display. We found, however, that an increase in motor noise/signal ratio to about -14.5 dB allowed both error and control SD scores to be matched to within 10%. As the reader can judge from Figure 8, a good match to the frequency-domain measures was also obtained. Apparently, the unexpectedly large value of motor noise was needed to account for the way in which pulse-like control behavior influenced the measurements.
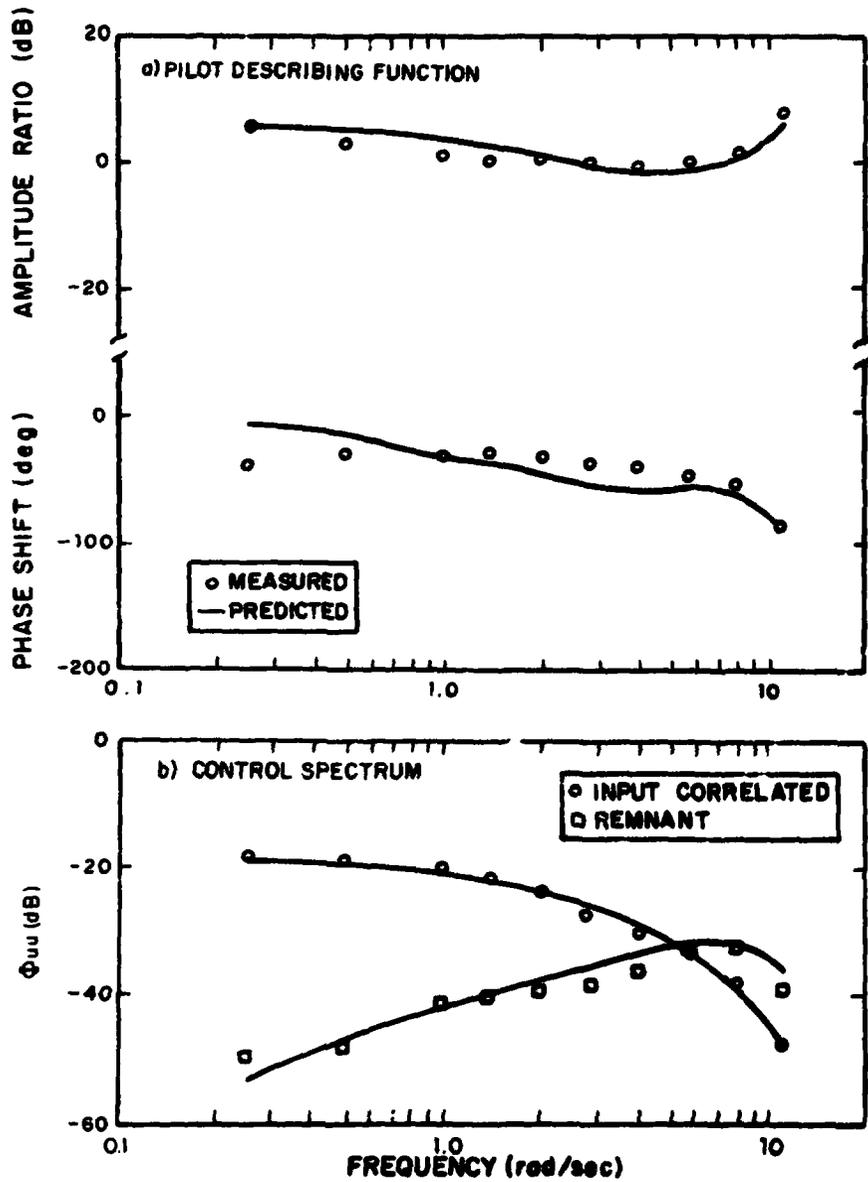
FIGURE 7. Frequency-Domain Measures for Visual Tracking, 1-axis Pitch
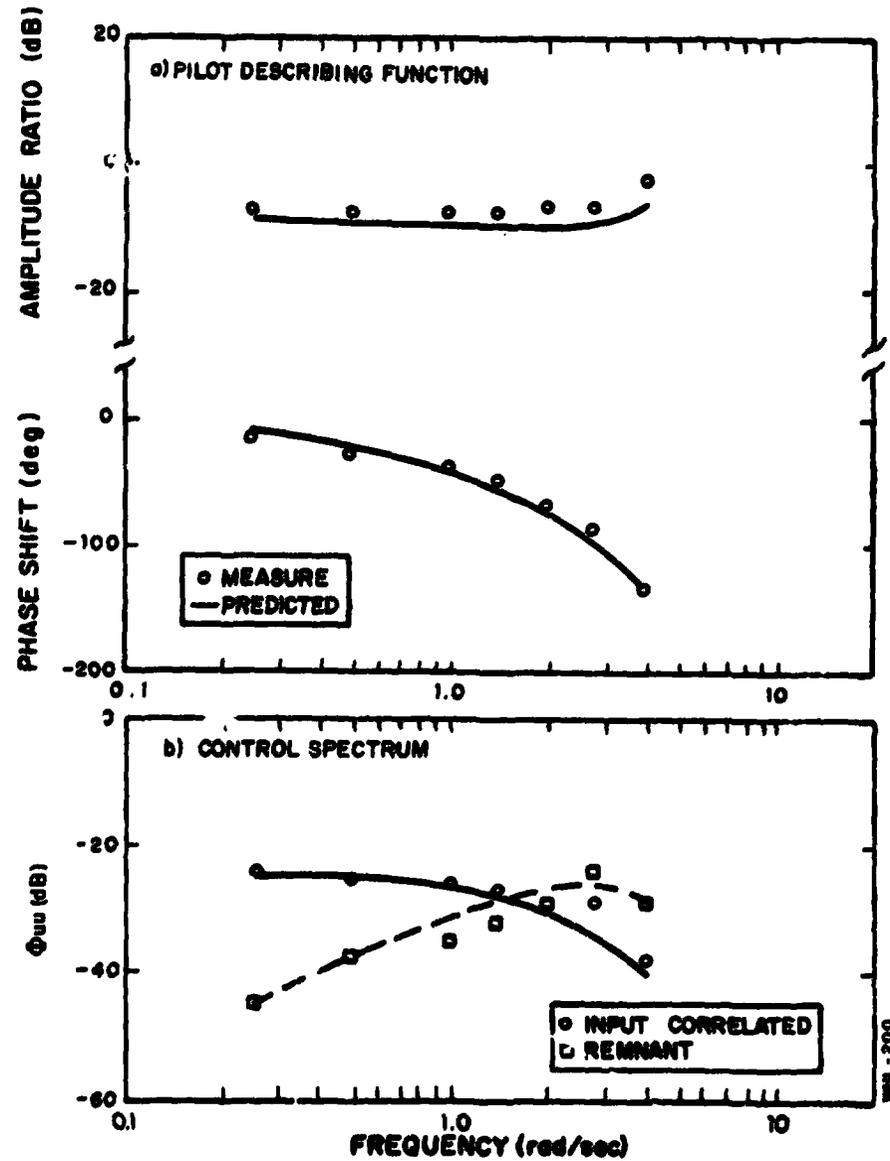(Average of 2 Subjects, 2 Trials/Subject)

FIGURE 8. Frequency-Domain Measures for Tactual Tracking, 1-axis Pitch
(Average of 2 Subjects,3 Trials/Subject)

Except as noted below, model parameter values determined in this calibration effort were used to predict the effects on system performance of (a) a change in input amplitude, (b) the addition of a second axis of tracking, and (c) the effects of changing the vehicle dynamics from pitch to roll. Time delay was recomputed in each case, and the effects of central attention-sharing in the two-axis task were represented by a doubling of the observation noise/signal ratio (see Refs. 20, 21). Parameter values used in obtaining these predictions, as well as those used in the preceding calibration efforts, are shown in Table 2.

Table 2

Values for Pilot-Related Model Parameters

Experimental Condition	τ	τ_n	v_o	$\dot{v}_o$	P_y	P_m
1-axis pitch, visual disp.	.20	.11	0.0	0.0	-21.5	-25
1-axis pitch, tactual disp., larger input	.65	.11	0.1	10.	-21.5	-14.5
1-axis pitch, tactual disp., smaller input	.72	.11	0.1	10.	-21.5	-14.5
2-axis pitch, tactual disp., larger input	.78	.11	0.1	10.	-18.5	-14.5
1-axis roll, tactual disp., larger input	.65	.11	0.1	10.	-21.5	-14.5

τ = effective perceptual time delay, second.
τ_n = rotor time constant, seconds.
v_o = displacement threshold, machine u.
$\dot{v}_o$ = rate threshold, machine units.
P_y = observation noise/signal ratio, dB.
P_m = rotor noise/signal ratio, dB.

A comparison of predicted and measured error and control SD scores is provided in Figure 9. Except for the 1-axis, larger-input pitch scores, all model results are true predictions; parameter values have not been readjusted to provide the best match in each case.

As expected, the SD scores for tracking error were predicted more accurately than the scores for control effort. Performance measures for the low-input, 1-axis pitch task were predicted most closely; the difference between predicted and measured SD scores for tracking error was negligible, and a good match to the frequency-domain measures (not shown here) was obtained.

The model accounted for about half of the increment in the pitch error score when the roll task was added, with a resulting matching error of about 15%. On the other hand, the model failed to account for the observed increase in control score. Comparison of the measured and predicted control spectra shown in Figure 10 suggests that the mismatch results from an under-prediction of the increase in controller remnant. The accurate prediction of the pilot describing function — particularly the phase-shift behavior — indicates that a reasonable approximation was made to the effective time delay imposed by the tactual display.

The 1-axis roll error score was predicted to within about 10% of its measured value. Inspection of the frequency-domain results (not shown here) indicates that modelling errors stemmed primarily from a too-high prediction of remnant-related control power.

Experiment 2: Comparison of Tactual and Quantized Visual Displays

The second formal experiment was designed to determine the extent to which the substantial performance decrement associated with the tactual display could be attributed to the coding scheme itself. Performance scores obtained with the tactual display were compared with those obtained with the quantized visual display described earlier. One- and two-axis pitch and roll performance was explored. Vehicle and input dynamics were identical to those used in the first experiment, and a single level of input amplitude (relative amplitude of 0.5) was used.

Average error and control SD scores are cross-plotted for the two displays in Figure 11. With one exception, performance scores obtained with the quantized visual display differed by less than 10% from corresponding measures obtained with the tactual display. Since these performance measures showed no apparent differences between displays, further analysis of the data obtained with the quantized visual display was considered to be redundant and, therefore, unnecessary.
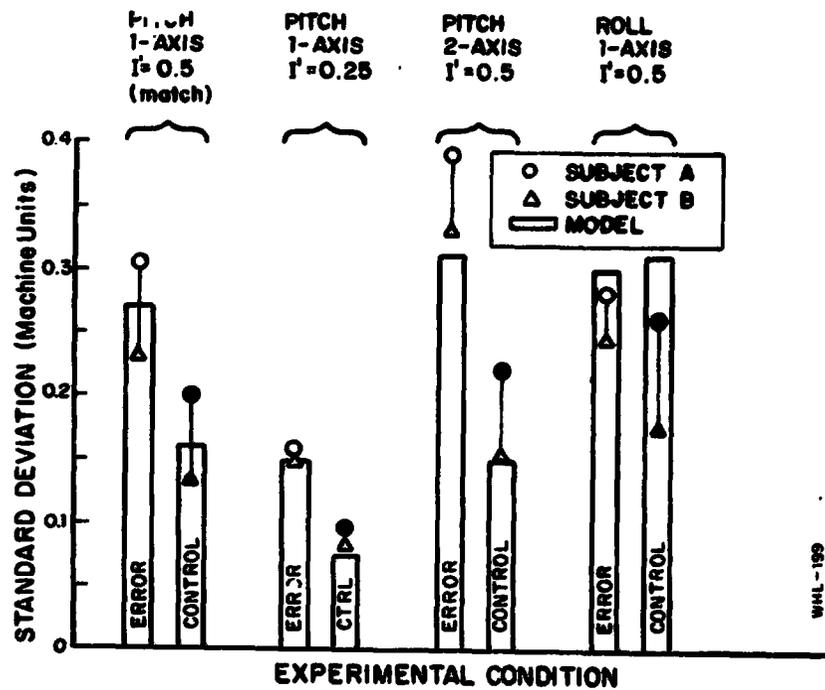
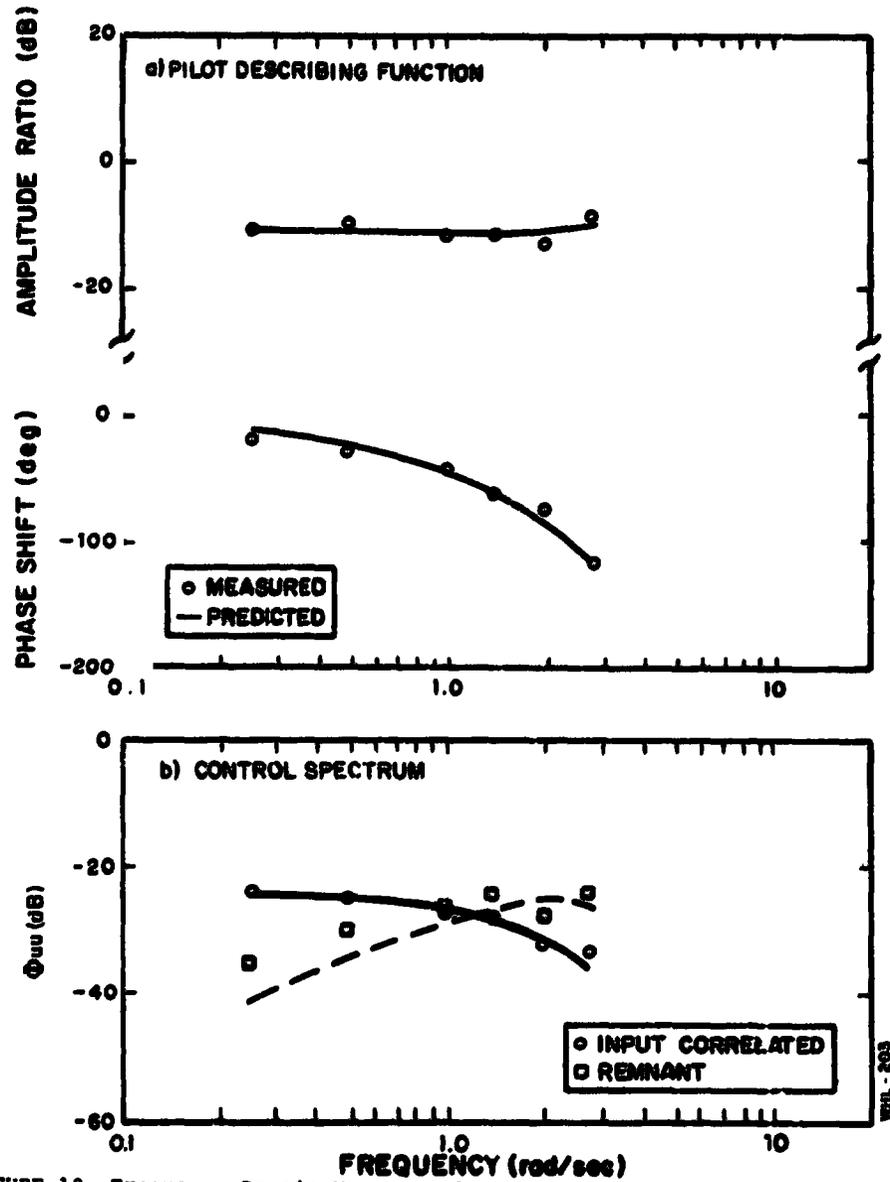FIGURE 9. Measured and Predicted SD Scores

FIGURE 10. Frequency-Domain Measures for Tactual Tracking, 2-axis Pitch
(Average of 2 Subjects, 3 Trials/Subject)

a, PITCH

1-AXIS 2-AXIS
O   ●   ERROR
□   ■   CONTROL

SD, TACTUAL DISPLAY
0.4
0.2
0

b, ROLL

SD, TACTUAL DISPLAY
0.4
0.2
0
0   0.2   0.4
SD, LED DISPLAY

WHL-205

FIGURE 11. Effect of Sensory Mode on SD Scores

On the basis of the results shown in Figure 11 we conclude that the degradation in tracking performance associated with the tactual display was due primarily to the coding scheme and not to the use of the tactual sensory mode per se. We do not rule out the possibility that such effects were present — asserting only that they were small compared to the effects of the coding scheme.
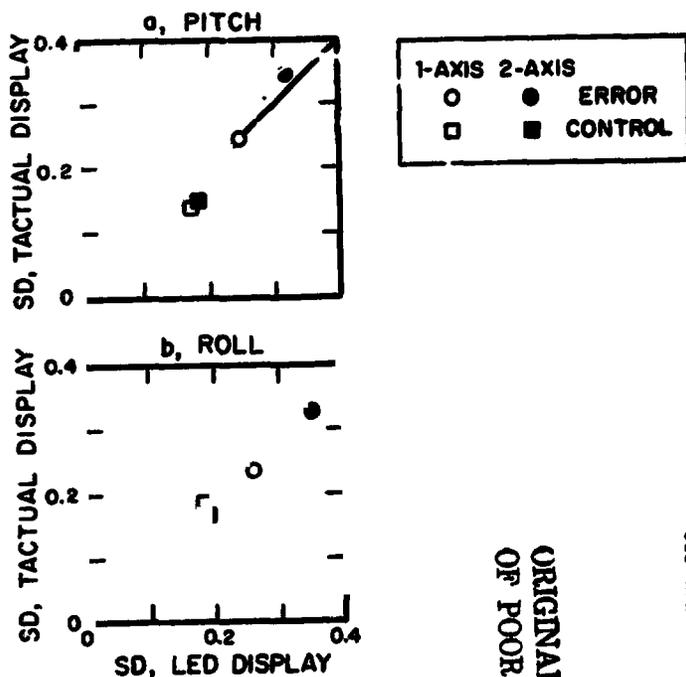
Experiment 2: Combined Tracking and Visual Monitoring

The visual monitoring task described in Section 2 was combined with a tracking task in order to determine the potential effectiveness of tactual displays in multi-task situations that impose a high visual scanning workload. The tracking task was modified to provide a lower-bandwidth task of the type to which a tactual display might reasonably be applied in practice. In order that we could explore a single source of task interference — namely, interference between tracking and monitoring — a single — axis tracking task was employed.

The roll-axis task was eliminated, and the simulated pitch dynamics used in the previous experiments were modified as follows: (a) the natural frequency of the second-order filter was reduced from 6 to 1 rad/sec, and (b) the zero in vehicle transfer function was eliminated. The disturbance input was the same as used in previous experiments and was added in parallel with the pilot's control input. One of the test subjects — the former Navy pilot — commented that the revised system behavior was similar to the response of the angle-of-attack indicator to control inputs during carrier approach. In order to reduce the disparity between tactual and visual tracking error scores, the input amplitude used for tactual tracking was 1/3 of that used for visual tracking.

The subjects were trained on the following five tasks: (a) monitoring only, (b) tracking-only with the continuous visual display, (c) tracking-only with the tactual display, (d) combined monitoring and tracking with the visual display, and (e) combined monitoring and tracking with the tactual display. Each subject received a minimum of 15 trials on each task, which appeared to be sufficient training to yield near-asymptotic levels of performance in the various tasks.

Tracking and monitoring scores are shown in Figure 12 for single- and combined-task situations. Tracking scores are given in terms of mean-squared error in machine units (1 machine unit = 2 cm indicator displacement); monitoring scores are in terms of fraction-of-time of incorrect response, divided by 5 to make the monitoring score numerically comparable to the tracking score.

PERFORMANCE SCORE (MACHINE UNITS)

0.08

0.06

0.04

0.02

0.00

■ T + M
□ T

T + M
▼▲
V + M

V + M ●

▽ M

V ○

TACTUAL
TRACKING
(T)

VISUAL
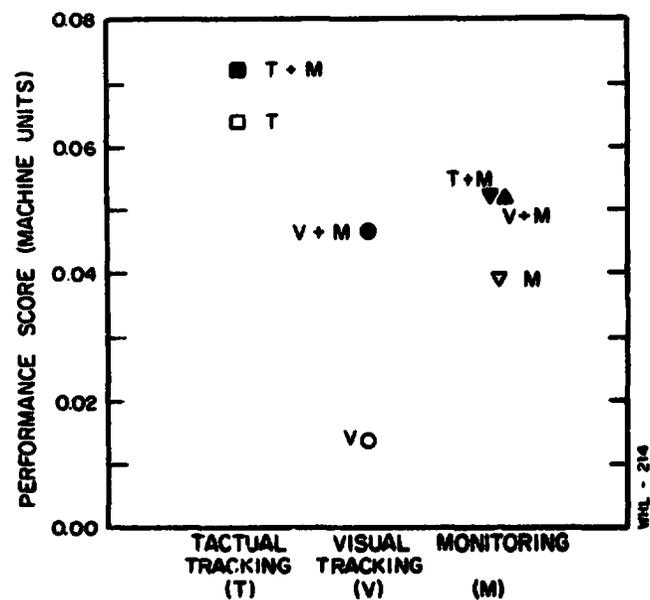TRACKING
(V)

MONITORING

(M)

WHL - 214

FIGURE 12.   Comparison of Single- and Combined-Task Tracking
and Monitoring Performance Scores

Average of 2 subjects, 3 trials/subject

Although visual tracking scores were consistently lower than corresponding tactual tracking scores, the interference of the monitoring task with tracking performance was considerably less when the tactual display was used. Single-task and combined-task tactual tracking scores differed on the average by about 12% — a difference that was not found by an analysis of variance to be statistically significant. The combined-task visual tracking score, on the other hand, was over three times as great as the single-task score. This difference was found to be statistically significant at the 0.001 level.

Interference in the reverse direction was also statistically significant; that is, the monitoring score increased significantly in the presence of the tracking task. The increase in score was about 35% (significant at the 0.01 level) and was the same whether the tactual or the visual display was used in the concurrent tracking task.

4. CONCLUSIONS

An experimental program was conducted to evaluate the suitability of a tactual display for aircraft flight control. The tactual display was configured in an X-Y format, and tracking error was indicated both by the number of vibrotactors excited in a sequence and by the rate at which successive tactors were excited. Tracking performance was observed in simulations of high-bandwidth and low-bandwidth aircraft dynamics, and combined tracking and visual-monitoring tasks were performed.

The experimental results lead to the following conclusions:

1. Interference between a tracking task and a visual monitoring task is considerably reduced when the tactual tracking display replaces a continuous visual tracking display.

2. Tracking errors obtained with the tactual display used in this study are substantially greater than errors obtained with a continuous visual display in a similar flight-control situation. Differences between 1-axis and 2-axis tracking performance are also greater for the tactual display.

3. Performance degradation of the tactual display is due primarily to the coding scheme adopted in this study — not to the use of the tactual sensory mode itself.

4. Tracking errors are corrected by intermittent pulse-like control inputs when the tactual display is used, apparently because of the large effective time lag imposed by the coding scheme.

5. The state-variable model for pilot/vehicle systems can be used to obtain reasonably accurate predictions of tracking error scores when the vehicle dynamics are wide-band, despite non-Gaussian pilot response behavior. Once the pilot-related model parameters have been adjusted to reflect the pilot-display interaction, the effect of changes in various aspects of the system configuration may be predicted.

Preliminary results suggest that the particular coding scheme used in this study has fulfilled our original expectations. At the cost of degraded single-task tracking performance, a tactual display has been designed which appears to allow relatively little interference between tracking and visual monitoring tasks. The question remains: can an alternative coding scheme be devised which provides improved single-task performance while maintaining minimum interference effects?

Tactual coding schemes that are more akin to simple intensity-coding have been found to provide superior single-task tracking efficiency. To our knowledge, however, such displays have not been shown to be effective in multi-task situations. Accordingly, we recommend that alternative coding schemes be explored in order to arrive at a tactual display design which best fulfills the twin objectives of good single-task performance and minimum task interference.

5. REFERENCES

1. Levison, W. H., R. Tanner, and T. Triggs, "Tactile Display for Aircraft Control", Semi-Annual Technical Report, Sanders Associates, Inc., Nashua, New Hampshire, January 1973.

2. Forbes, T. W., W. R. Garner and J. G. Howard, "Flying by Auditory Reference ("Flybar"). Psycho-Acoustic Laboratory", Harvard University, OSRD Report No. 5123, 1945.

3. Flynn, J. P., S. J. Goffard, I. P. Truscott and T. W. Forbes, "Auditory Factors in the Discrimination of Radio Range Signals: Collected Informal Reports", Psycho-Acoustic Laboratory, Harvard University, OSRD Report No. 6292, 1945.

4. Ballard, J. W. and R. W. Messinger, "Human-Engineered Electromechanical Tactual Sensory Control System", Elect. Manuf., 118-121, 1954.

5. Hirsch, J. and I. Kadushin, "Experiments in Tactile Control of Flying Vehicles", 6th Annual Conf. of Aviation and Astronautics, 64-68, 1968.

6. Fenton, R. E., "An Improved Man-Machine Interface for the Driver-Vehicle System", IEEE Trans. Human Factors in Electronics, 7, 150-157, 1966.

7. Hill, J. W., J. C. Bliss and K. W. Gardiner, "Applications of Tactile Displays for Pilot Cueing", Fifth Annual NASA-University Conference on Manual Control, NASA SP-215, 285-290, 1969.

8. Hill, J. W., "A Describing Function Analysis of Tracking Performance Using Two Tactile Displays", IEEE Transactions on Man-Machine Systems, 11, 92-101, 1970.

9. Weissenberger, S. and T. B. Sheridan, "Dynamics of Human Operator Control Systems Using Tactile Feedback", J. Basic Engr'g., 297-301, 1962.

10. Bliss, J. C., "Tactual Perception: Experiments and Models", Final Report, SRI Project 6070, Contract NAS2-3649, Stanford Research Institute, Menlo Park, California, 1967.

11. Seeley, H. F. and J. C. Bliss, "Compensatory Tracking with Visual and Tactile Displays", IEEE Transactions on Human Factors in Electronics, 7, 84-90, 1966.

12. Hoffman, M. A., "A Comparison of Visual, Auditory, and Electrocutaneous Displays in a Compensatory Tracking Task", unpublished doctoral dissertation, University of South Dakota, 1968.

13. Durr, L. B., "Effect of Error Amplitude Information", M. A. Thesis, University of Virginia, 1961.

14. Howell, W. C. and C. F. Briggs, "An Initial Evaluation of a Vibrotactile Display in Complex Control Tasks", Ohio State University Technical Report (813)-5, AD-320472, 1959.

15. Geldard, F. A., "Cutaneous Channels of Communication", In Sensory Communication, (W. A. Rosenblith, Ed), MIT Press, Cambridge, Massachusetts, 73-88, 1959.

16. Neal, T. P. and R. E. Smith, "An In-Flight Investigation to Develop Control System Design Criteria for Fighter Airplanes", Wright-Patterson Air Force Base, Ohio, AFFDL-TR-70-74, Volume 1, 1970.

17. Boothe, E. M. and M. L. Parrag, "Evaluation of Lateral-Directional Handling Qualities and Roll-Sideslip Coupling of Fighter Class Airplanes", Wright-Patterson Air Force Base, Ohio, AFFDL-TR-72-36, Volume 1, 1972.

18. Kleinman, D. L., S. Baron and W. H. Levison, "An Optimal Control Model of Human Response Part I: Theory and Validation, Automatica, 6, 357-369, 1970.

19. Kleinman, D. L., S. Baron and W. H. Levison, "A Control Theoretic Approach to Manned-Vehicle Systems Analysis", IFEE Transactions on Automatic Control, Volume AC-16, No. 6, 1971.

20. Levison, W. H., J. I. Elkind, and J. L. Ward, "Studies of Multivariable Manual Control Systems: A Model for Task Interference", NASA CR-1746, 1971.

21. Levison, W. H., "The Effects of Display Gain and Signal Bandwidth on Human Controller Remnant", AMRL-TP-70-93, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio, 1971.

22. Levison, W. H., S. Baron and D. L. Kleinman, " A Model for Human Controller Remnant", IEEE Trans. Man-Machine Systems, Vol. MMS-10, No. 4, 1969. Also NAS8-21136, 1968.

23. Levison, W. H., "A Model for Task Interference". International Symposium on Man-Machine Systems, September 1969, IEEE Conference Record No. 69C58-MMS.

24. Kleinman, D. L. and S. Baron, "Analytic Evaluation of Display Requirements for Approach to Landing", NASA CR-1952, 1971.

25. Baron, S. and W. H. Levison, "A Manual Control Theory Analysis of Vertical Situation Displays for STOL Aircraft", Bolt Beranek and Newman Inc., Cambridge, Mass., Rept. No. 2484, 1973.

THE DESIGN AND EVALUATION OF AN AURAL STALL WARNING SYSTEM (ASWS)

by

Professor Michael H. Redlin
Lieutenant P. E. Mullowney

·

The Aural Stall Warning System (ASWS) addresses itself to the prevention of stall and the resulting spin of high performance aircraft. Utilizing a distinctive yet simple aural display format, the ASWS not only warns the pilot of impending stall but also provides accurate angle of attack information in the high angle of attack region where visual presentation has heretofore proven to be inadequate. Small, lightweight ASWS prototypes have been designed, fabricated and evaluated in a laboratory environment and in the Air Combat Maneuvering (ACM) arena in the Differential Maneuvering Simulators located at the NASA Langley Research Center, Hampton, Virginia. Results obtained indicate a marked increase in pilot performance while in the ACM environment and a definite prevention of stall with the addition of the ASWS.