19. Effects of Display Format on Pilot Describing Function and Remnant*

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As part of a program to develop a comprehensive theory of manual control displays, six display formats were used by three instrument-rated pilots to regulate against random disturbances with a controlled element of $Y_c=K/s(s+2)$ (which requires mild lead equalization), under both foveal and 10° parafoveal viewing conditions. The six display formats were: CRT line, CRT thermometer bar, 14-bar quantized on a CRT, a rotary dial and pointer (meter movement), and two variations of a moving scale tape-drive (C-141 VSI). All were scaled to equivalent movement and apparent brightness. Measures included overall performance, describing functions, error remnant power spectra, "critical instability" scores, and subjective display ratings. Other controlled elements and parafoveal angles were partially investigated.

The results show that the main effect of display format is on the loop closure properties. Less desirable displays induce lower bandwidth closures with consequent effects on the closed-loop remnant and performance. The normalized injected error remnant remains roughly similar for all cases except quantized formats. The quantized display induces larger pilot lags and observation remnant. The moving tape display (off-reference case) could not be tracked parafoveally. Parafoveal viewing affected each display differently. The second-order critical instability task seems to provide a sensitive and convenient test for overall display format problems. Simple analytical models are presented which show good agreement with the preliminary-test data, and a tentative set of rules for estimating format effects of the display/pilot/vehicle system are given.

INTRODUCTION †

The complete program covered the three areas shown under "Scope" of table **1** which have been reported in full in STI Technical Report **191-1** (dated June **1971)** which will soon be released as an AMRL report (see ref. **1)**. Only the experiments are covered in this presentation.

Experimental Design for Display Format Experiment

The main features of this experiment are (see figs. **1** and 2)

- Standard single-axis setup in the STI fighter cockpit fixed-base simulator.
- Controlled elements were: $K/s(s+2)$ for the instrument format experiment, and K/s and K/s^2 for some preliminary experiments.
- Input: sum of five sinusoids.
- Measurements included: error performance σ_e^2, remnant error component $\sigma_{e_n}^2$; open- and closed-loop describing functions of pilot-controlled element-display; input-correlated and remnant error spectra at input frequencies (via serial segment technique, described in another Annual-Manual paper); subjective display rankings on a **1** to **5** scale from "best" to "worst;" and three sets of critical instability scores, including one set having the same lead equalization requirement as the tracking task.
- Viewing angles of 0° (foveal), 10°, 20° (parafoveal).
- Two to three instrument-rated pilots were

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† This is a summary of the points made on each slide of the informal presentation. These slides are now the tables and figures **of** this paper.

TABLE 1.—Display *Format Effects*

OBJECTIVE:
Effects of instrument display format on pilot's closed-loop behavior and performance
SPONSOR:
USAF AMRL/MRHD
SCOPE:
Reanalysis of extant remnant data for "ideal displays" in terms of recent "processing noise" concepts
Experiments with several display formats
Revised models and adaptation rules
REPORT:
STI–TR–191–1 (forthcoming USAF AMRL Rept. (ref. 1))

subjects; well trained on the task before measurement.

- At least two replications per cell were made.

The six instrument formats tested are shown on figure 2. The CRT line display served as a reference condition for the others. The coarsely "quantized" format had about **2** to **3** bars per 1a of error. The moving scale tape format was the fine-altitude scale of a standard C–141 VSI altimeter. The "on-reference" case was at the well marked white null, while the "off-reference" case required visual interpolation of the 270 ft position. All displays were scaled to the same linear sensitivity (for the dial at the pointer end) of 0.75 cm for 1a of input.

Typical Data for Error Spectra

The top half of figure **3** shows the closed-loop circulating error spectrum, Φ_{ee}, computed at input frequencies. The key points are

- The input-correlated component, Φ_{ee_i} is well above the remnant at all input frequencies, assuring accurate pilot describing functions.
- The remnant component, Φ_{ee_n} is usually well above the basic system noise level of -40 dB, except at the highest frequency.
- The mean square error is dominated by the closed-loop error peak near *2* to **3** rad/sec, and is thus sensitive to loop closure changes induced by the various formats.
- The data for successive replications is quite consistent for a given operator, but differs somewhat among subjects.

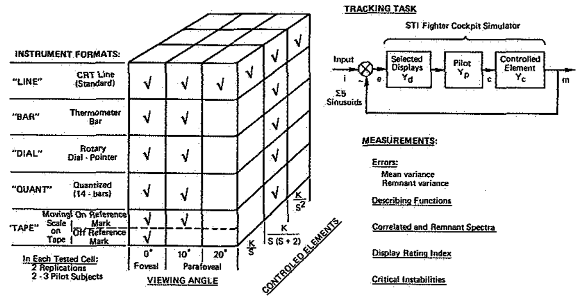

FIGURE 1.—Experimental design for display format exeriments.

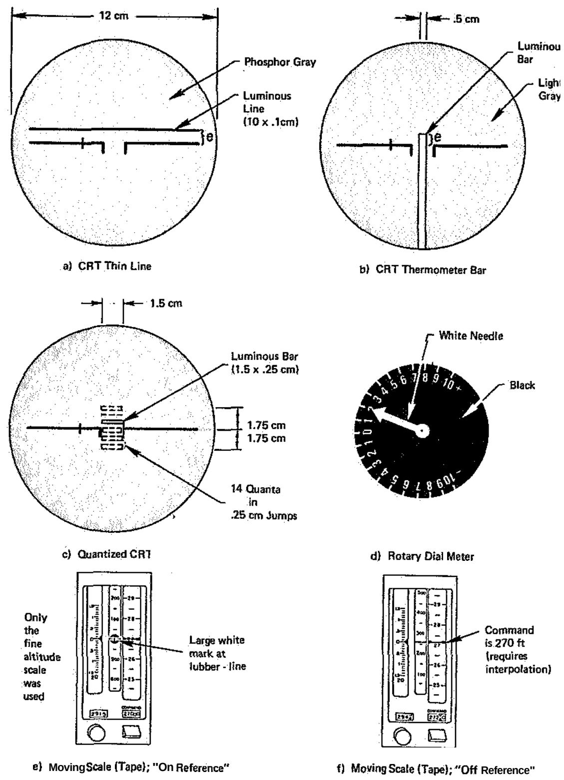

FIGURE 2.—Display formats investigated.

The normalized injected noise or processing remnant gradient ($\Phi'_{n_e} = \Phi_{nn_e}/\sigma_e^2$) is shown in the bottom half of figure **3.** The main points are

- The shape of Φ'_{nn_e} is typically not that of noise through a first-order filter.
- The level is typical of much prior and concurrent research at other laboratories.

(Display format effects on Φ'_{nu_e} will be shown later.)

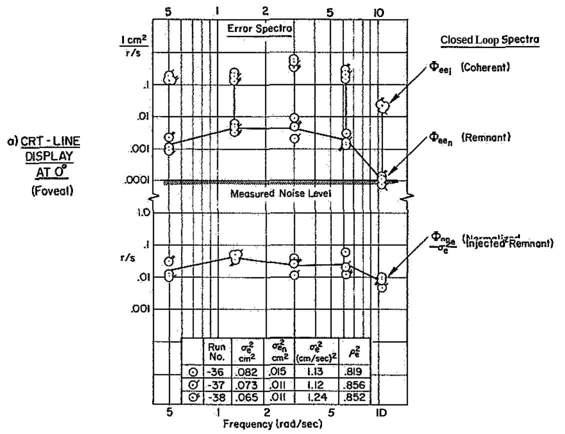

FIGURE 3.—Typical data **for error spectra.**

Error Performance Summary

The top of figure **4** shows total mean-square-error; the bottom shows the remnant component to an expanded scale. The bars show average. (Further data are in the Final Report (ref. 1).) The main points are

- Foveally, the line, bar, and dials (and tape: on-reference) were about equal in performance.
- Parafoveally, all formats suffered, but the line and dial held up best (dial's angular cue helped). Worst were quantized and tape: off-reference (latter could not be tracked at all).
- Remnant contributions due to format (foveal viewing) were small except for quantized display, where increase is on order of **1** quanta squared.
- Most of total error increases were due to the looser or lower stability closures induced by non-ideal formats (e.g., see quantized case).

Describing Function Parameter Summary

Detailed describing functions of figure 5 (shown also in Final Report (ref. **1**)) showed that all subjects generated sufficient lead to roughly cancel the controlled element lag at $(s+2)$, and the open-loop data were reasonably well fit by the extended crossover model:

$$Y_{OL}=Y_D Y_p Y_c \doteq \frac{\omega_c}{(j\omega)} e^{-j\left(\tau_e\omega+\frac{\alpha}{\omega}\right)}.$$

An interpolation routine, part of the post-run

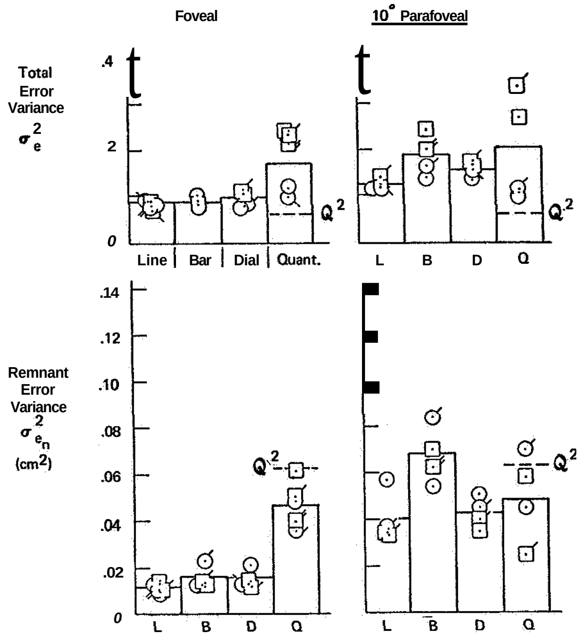

FIGURE 4.—Error performance summary.

data reduction, gave estimates of the parameters for the two frequencies nearest crossover, denoted by subscript c. The left side of figure 5 shows that format induced consistent effects in both subjects, in their delays and lead decrements (decrease in a, below the **0.3** to 0.4 value for the line case is associated with a similar decrease in the lead break frequency, which is well below the crossover region). Nonideal formats induce higher loop delays, and reduced displacement gains (hence lower lead break $(1/T_L \doteq K_D/K_R)$, evidenced here by lower a, and lower ω_c). Similar effects noted parafoveally, again Line and Dial held up best. One pilot used much more aggressive (and less typical) loop closure strategy parafoveally, evidenced by his higher gain and lower phase margin.

Φ'_{nn_e} Comparisons Across Displays and View Angles

In figure **6** the lines are averages of Φ'_{nn_e} (see fig. **3)** across subjects for each condition. The **left** side shows the the observation or noise, when normalized by the perceived signal variance, is remarkably insensitive to quite different formats.

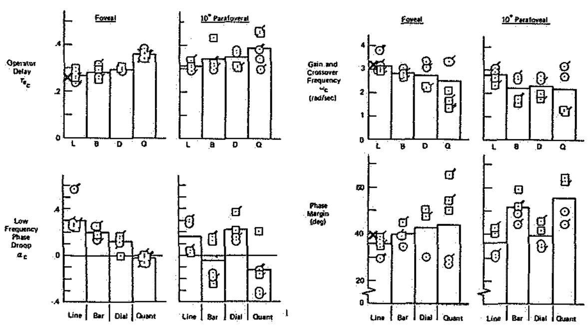

FIGURE 5.—Describing function parameter summary.

The right side shows that all data cover only a range of about 2:1 across the spectrum. This implies that a "processing noise" remnant source is dominant here.

Few of the shapes are clearly first-order, but a first-order noise model would represent typical effects adequately. The simple "Pew model" (so-named because Professor Pew pointed it out in the **1968** Annual Manual) ($\Phi'_{nn_e} = A\omega^B$, with $A \doteq 0.06$ rad/sec and $B \doteq -0.7$ or -7 dB/decade) is about as good a fit as any, albeit not very tractable analytically.

Other Measures

Scores for the "one-and-a-half-order" critical instability task (shown at bottom of table 2), which require the same lead as the tracking case, showed sensitive and significant decrements from the ideal CRT line format. These decreases in λ_c imply an increase in the apparent delay time, and correlate well with the increased crossover model delays, τ_{e_c}.

The critical instability task, with stable roots placed to induce the desired lead equalization, proved to be an easily learned, sensitive way to objectively rank an array of display formats. The subjective rankings (of overall suitability of each format for precision control purposes) corresponds to the critical task scores. Although the quantized format showed up poorly in performance and preference for tracking purposes, pilot comments revealed that its blinking action during a rate-of-change of error signal *was* readily perceivable parafoveally, even though its displacement was not.

TABLE 2.—*Other Measures*

Display	Critical instability [1]	Display rating [2]
Foveal case		
CRT line	3.9	1.0
Dial	3.4	2.5
Bar or tape (on ref.)	3.2	2.8
Quantized	2.5	3.7

[1] $Y_c = \frac{\lambda}{-(s+2)(s-\lambda)}$ (req'd $T_L \approx 0.5$ sec)
[2] Average ranking.

TABLE 3.—*Conclusions*

- Display-induced remnant is best modeled as a "processing-noise"

$$\Phi_{nn_e}(\omega) = \Phi_{nn_0}(\omega) + e^2\Phi'_{nn_e}(\omega)$$
(residual) (gradient)

- $\Phi'_{nn_e}(\omega)$ is similar to first-order white noise
  Data also fit Pew Model:

$$\Phi'_{nn_e} \doteq A\omega^B;\ A \approx .06;\ B \approx -.7$$

- Main effects of reasonable display formats are due to second-order decrements in loop closure tightness, and some increase in Φ'_{nn_e} for worst displays.
- Decrements due to format in critical task scores and subjective rankings correspond to describing function changes.

Conclusions

The following conclusions were reached (see table **3** for additional conclusions):

(1) The reanalysis of extant remnant data (not discussed here), as well as these experiments, verify that most display-induced remnant is best modeled as an injected '(processingnoise" :

$$\Phi_{nn_e}(\omega) = \Phi_{nn_0}(\omega) + e^2\cdot\ \Phi'_{nn_e}(\omega).$$
(residual) (gradient)

The gradient component is dominant for most cases of interest.

(2) The spectral shape and closed-loop effects of the processing remnant gradient can be modeled by white noise through a first-order filter, but out data are not closely first-order in shape. The simple Pew model with a slope of -7 dB/decade is about as good a data fit.

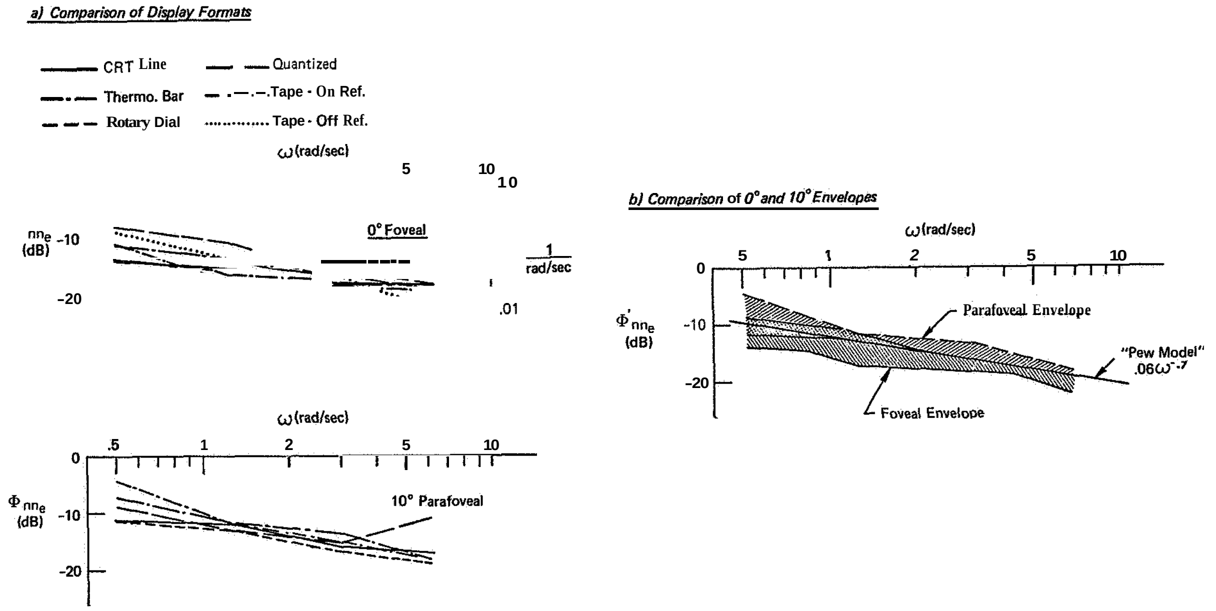

FIGURE 6.—Φ'_{nn_e} **comparisons across displays and view angles.**

(3) The main effects of nonideal tracking instrument format under nonscanned single-axis conditions are increased operator (and/or display motion) delays, which causes looser or less damped loop closures and, hence, poorer performance. The remnant gradient is also somewhat worse for nonideal formats or view angles, but represents second-order effects on the errors.

(4) There was a rough rank-order correlation among the subjective rankings, Critical Instability scores, and tracking parameters.

(5) When equally scaled, the CRT line and dial formats are roughly comparable, allowing for the extra lag in the dial instrument drive. The bar and moving tape displays suffered most under parafoveal viewing. Coarsely quantized displays (having only **2** to **3** quanta per desired 1σ of the error) should be avoided where lead generation is required.

(6) Further research on quantized displays is recommended using the efficient techniques developed during this program.

(7) Changes to the extant human operator models and adaptation rules to account for display format effects are discussed in the Final Report (ref. **1**).

REFERENCE

1. JEX, HENRY R.; ALLEN, R. WADE; AND MAGDALENO, RAYMOND E.: Display Format Effects on Precision Tracking Performance, Describing Functions, and Remnant. AMRL TR–71–63 (to be published). Obtainable by request from: Philip Kulwicki, 6570th AMRL/HED, Wright-Patterson AFB, Dayton, Ohio 45433.