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A DISPLAY EVALUATION METHODOLOGY APPLIED TO VERTICAL SITUATION DISPLAYS*

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1. INTRODUCTION

In spite of vast efforts in display design and evaluation, there do not appear to be standardized procedures for evaluating aircraft displays. Instead, a variety of techniques are employed in the several stages leading to an acceptable display configuration, with man-in-the-loop real-time simulation experiments playing a central role. While there are a number of valid reasons for the techniques that have been used [1], it seems fair to say that there exists a need for unifying concepts and approaches.

Analytical models of the pilot-vehicle-display system appear to offer the possibility of a systematic, well-defined and comprehensive approach to display evaluation. Such models allow one to examine the interactions of displayed information with vehicle dynamics, disturbances, mission criteria and human performance. They may be used to provide early and preliminary evaluation of competing configurations without the necessity for expensive simulation; in later stages of display development, the models can serve as powerful diagnostic and extrapolative adjuncts to the necessary simulations.

The advantages of analytical models for display evaluation have been well-understood for some time and considerable effort has been expended in their development. Perhaps the most extensive effort to date is represented by the work of Allen, Clement and Jex [2] and McRuer, et al. [3]. They attempted to synthesize the human operator scanning model of Senders [4], multi-loop describing function theory [5] and Clement's theory of human signal reconstruction [6] into a theory for displays in manual control.

In this paper, an approach to display evaluation based on the optimal-control or state-variable model of the human operator [7-10] is described. The approach has evolved over the past several years [11-14] and we believe it has significant advantages for display evaluation. In the remainder of the paper, we describe

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briefly the foundations of the methodology* and present results of its application to the analysis of vertical situation display for STOL approach. This analysis includes the effects of both status and command displays on pilot workload and system performance. More detail concerning the results and ideas presented here can be found in [15].

2. DISPLAY EVALUATION METHODOLOGY

The following four steps are fundamental in the application of the display evaluation methodology:

1. Specification of system dynamics, disturbances, and task requirements in terms of a linear-quadratic-gaussian optimization problem suitable for application of the optimal control model of the human operator [8, 10].

2. Analysis of proposed display configuration with respect to display characteristics and their relation to parameters of the human operator model.

3. Determine performance with given configuration and investigate the effects of elimination of display limitations.

4. Analyze display workload-performance tradeoffs via sensitivity analysis.

System Specification

System dynamics are approximated by the following linear state equation:

$$\dot{\underline{x}} = \underline{A}\,\underline{x} + \underline{B}\,\underline{u} + \underline{E}\,\underline{w} \qquad (1)$$

where $\underline{x}(t)$ is the vector of system states, $\underline{u}(t)$ the vector of pilot control inputs and $\underline{w}(t)$ the vector of linearly independent white gaussian noises. If external forcing functions are rational gaussian noise spectra of first order or higher as is the case for most turbulence models [16], they are represented by white noise ($\underline{w}$) passed through a linear filter and the system dynamics are augmented by those of the filter. Disturbances such as constant winds or wind-shears are modelled, essentially, by adding non-zero mean components to $\underline{w}$ [14, 15].

*A detailed description of the optimal control model of the human operator is not given as it has already been well-documented [7-10, e.g.].

The display-variables are assumed to be linear combinations of the state and control variables and are given by the "display-vector"

$$\underline{y}(t) = \underline{C}\ \underline{x}(t) + \underline{D}\ \underline{u}(t) \qquad (2)$$

As with the input, display dynamics are included by introducing additional system states and augmenting the matrices in Equation (1). Such is required, for example, in analyzing certain flight director configurations.

Task requirements are stated in terms of "cost weightings" associated with various system variables in a quadratic cost functional of the form

$$J(\underline{u}) = E\ \{\underline{y}'\ \underline{Q}\ \underline{y} + \underline{u}'\ \underline{R}\ \underline{u} + \dot{\underline{u}}'\ \underline{G}\ \dot{\underline{u}}\} \qquad (3)$$

It is assumed that the pilot selects his control response to minimize the appropriate J. For relatively simple, single-variable control situations, good approximations to experimental measurements have been obtained with a cost functional consisting simply of a weighted sum of system error variance plus control-rate variance [5]. The cost on control-rate represents, in part, a subjective penalty imposed by the controller on making rapid control motions and may account, indirectly, for physiological limitations on the pilot's bandwidth.

For complex multi-input, multi-output tasks, the cost weightings may not be chosen in so simple a fashion. One approach is to select values for the weightings so as to keep mean-squared output levels within prescribed tolerances [17]. A unit amount of "cost" is associated with a given variable when the magnitude of the "error" equals the nominal limit, and the weighting coefficient for each variable is simply the inverse of the square of the corresponding limit. This approach was used in the application to be discussed later.

For the present paper, the matrices introduced in Equations 1-3 are assumed constant. This corresponds to a condition for which we have the most validation data but it is not a necessary restriction. For example, in a companion paper [18] and in [15], range (time)-varying display gains and cost functional weightings are included in the analysis.

Analysis of Display Configuration

A basic assumption of the optimal control model of the human operator is that the human perceives a noisy, delayed version of the displayed variables; i.e., if $\underline{y}_p(t)$ is the vector of perceived variables, then

$$\underline{y}_p(t) = \underline{y}(t-\tau) + \underline{v}_y(t-\tau) \qquad (4)$$

where $\underline{y}$ is defined by Equation 3, and $\underline{v}_y$ is a vector of white, gaussian observation noises.* When the displays have been optimally designed as is the case in many laboratory situations, central processing sources of pilot randomness appear to be the principal determinant of $\underline{v}_y$. Thus, we find for manual control situations in which the displayed signal is large enough to negate the effects of visual resolution ("threshold") limitations, the autocovariance of each observation noise component appears to vary proportionally with mean squared signal level and may be represented as

$$\begin{aligned} V_{y_i}(t) &= \pi\ P_i \cdot E(y_i^2(t)) \\ &= \pi\ P_i\ \sigma_{y_i}^2(t) \end{aligned} \qquad (5)$$

where P is the "noise/signal ratio" and has units of normalized power per rad/sec. Numerical values for P_i of 0.01 (i.e., -20 dB) have been found to be typical of single-variable control situations [9, 10].

When display characteristics are not ideal it is necessary to modify the expression for the observation noise covariance associated with a particular display variable. In this study, two display limitations were important under certain circumstances, namely threshold limitations and the lack of a zero reference. We account for these phenomena by letting the autocovariance for each observation noise process be

$$V_i(t) = P_i \left(\frac{\sigma_i^2}{K_i^2\ (\sigma_i, a_i)} + \sigma_{i_o}^2 \right) \qquad (6)$$

where the subscript i refers to the i^{th} display-variable. The quantity $K(\sigma_i, a_i)$ in Equation 6 is the describing function gain associated with a threshold device

$$K(\sigma, a) = \frac{2}{\sqrt{\pi}} \int_{-\infty}^{-\frac{a}{\sigma\sqrt{2}}} e^{-x^2}\ dx$$

where "a" is the threshold and σ is the standard deviation of the "input" to the threshold device.** This factor is used primarily to account for threshold-type phenomena associated with viewing

*The human's time delay, τ, is a parameter of the model; typically, τ = .15 - .2 sec.

**For non-zero mean signals this expression must be modified [14].

the display, but "indifference" thresholds will have an indistinguishable effect. Essentially, its effect is to cause the observation noise covariance to become greater as the signal becomes smaller relative to the threshold.

The term $\sigma_{i_0}^2$ in (6) is a residual-noise covariance and, in many cases, is similar in effect to a threshold. However, it can be viewed as a separate parameter and used to account for observed degradation in tracking performance that results from lack of reference indicators [15].

Performance Evaluation

Once the system and human parameters have been chosen, performance can be evaluated. Although, for model development, task requirements are specified in terms of the quadratic cost functional J of Equation 3, other measures of performance are important in problem analysis. For many problems a useful system metric relates to performance reliability, or the probability of achieving mission objectives successfully. The success of a mission (segment) can often be stated in terms of constraints that the system states (or outputs, or controls, or functions of these variables) must satisfy. In other words, mission success may be equated with $\underline{y} \in X$. Then, the probability of success is, simply,

$$\Pr\{\underline{x} \in X\} = \int_{\underline{x} \in X} p(\underline{x}) d\underline{x} \qquad (7)$$

where $p(\underline{x})$ is the probability density function for $\underline{x}$. An example where such a specification of success is meaningful is approach to landing (see below). Because of the lineari y and gaussian assumptions, $p(\underline{x})$ (and $p(\underline{y})$, $p(\underline{u})$, etc.) is obtained in a single run of the optimal control model for the human operator.

The probability of success, as defined in Equation 7, is for the total man-machine system and the particular mission segment being analyzed. This probability is, in fact, a conditional one in that its computation depends on the particular system and model parameters chosen in Equations 1-6. Thus, through model analyses, success or failure probabilities may be determined as functions of any parameter(s) of interest. In particular, for display evaluation, one can investigate systematically the effects on performance reliability of changes in display characteristics. Because of the structure of the model, one can also compute the performance that could be attained with an idealized display; this provides a useful basis for comparison and analysis.

Workload Analysis

As noted earlier, the observation noise/signal ratio, P_i, seems to be associated with the operator's central processing capabilities. This association leads to a relatively straightforward model for task interference and operator workload. The details of this model are given in [19]. Very briefly, we consider, for convenience, that attention-sharing may be required at three levels: between manual control and non-control tasks; between sub-tasks within the manual control task; and between displays associated with performing a given sub-task. For example, a pilot might share attention between control and communication, between longitudinal and lateral control and between flight path and attitude displays. Thus, we define

f_t = fraction of attention devoted to the control task as a whole
f_s^t = fraction of attention devoted to sub-task s
f_i^s = fraction of attention devoted to i^{th} display in sub-task s

Then, the effects of attention-sharing are modelled by an increase in the "nominal" noise/signal ratio, i.e., by

$$P_i = P_o \cdot \frac{1}{f_t} \cdot \frac{1}{f_s} \cdot \frac{1}{f_i} \qquad (8)$$

where P_i is the noise/signal ratio associated with the i^{th} display when attention is being shared and P_o is the noise/signal ratio associated with full attention to the display.

To predict the effect on specific tasks of sharing attention, Equation 8 is used to establish the appropriate observation noise-signal ratios and the model equations are solved using this value. If the pilot's allocation of attention is unknown beforehand, model solutions may be used to determine the optimum allocation of attention, which, in line with the fundamental optimality hypothesis, may be taken as a prediction of the pilot's allocation.

Building on the model for attention, we define a "workload index" as the fraction of attention required to achieve a specified criterion level of performance on the control task. Thus,

Workload Index = f_{t_c}

where f_{t_c} is the minimum fraction of attention for which performance can be maintained within the criterion level. In order to predict the workload index, it is necessary to specify a relevant performance measure, the required level of performance, and the "reference" noise/signal ratio P_o. Ideally, we would like P_o to correspond to full attention, but we cannot conduct an experiment in which the pilot is guaranteed to use his total information-processing capability. Therefore, we let P_o correspond to the noise/signal ratio (namely, .01 or -20 dB) obtained in a standardized laboratory situation in which the pilot is motivated to minimize his tracking errors. We know that this value does not correspond to "full capacity", because *significantly lower* noise-ratios have been found experimentally [19]. However, based on our laboratory experience, P_o = -20 dB does appear to correspond to a high workload condition, and "operation" at this level for any prolonged time would undoubtedly be unacceptable. Of course, when we are interested primarily in the relative *change* in workload requirements from one situation to the next, the value for P_o is not too critical.

3. ANALYSIS OF VERTICAL SITUATION DISPLAYS FOR STOL APPROACH

The display evaluation methodology has been used to analyze basic status displays and director displays for the steep (7.5°) approach to landing of the Augmentor Wing Jet STOL Research Aircraft (AWJSRA). The displays were analyzed primarily with respect to steady-state, gust regulation performance at the decision height (approximately 30m), though other supporting studies were also conducted [15, 18]. Here, we describe the basic display configuration that was investigated and present some of the more interesting and more important results. Performance predictions are presented for lateral control and for combined lateral-longitudinal control. Results for the longitudinal control case are given in [5]. Details concerning vehicle dynamics, turbulence spectra, cost-functional weightings, and other parameters of the system-human operator model are given in [15], where more extensive presentation and discussion of results may also be found.

An abstraction of the relevant features of the STOLAND-EADI status display [20] considered here is shown in Figure 1. This display provides the pilot with glide path and localizer errors as well as attitude information. From such a display the pilot can also obtain the rates of change of these variables. Although an airspeed error indicator is not shown in Figure 1, the pilot is displayed this quantity with the STOLAND-EADI and we will assume that airspeed error is available in our analysis.

Effective visual thresholds were computed for the aircraft at the 30-meter decision height. On the basis of previous analysis of approach performance [14], an "indifference threshold" of 0.1 degrees visual arc was associated with perception of height error. Previous analysis of pilot remnant data [13] suggested thresholds of 0.05 degrees visual arc for other indicator displacements and 0.18 arc-degrees/second for indicator-rate quantities. Display gains given in [20] were used to convert thresholds into units related to system quantities.

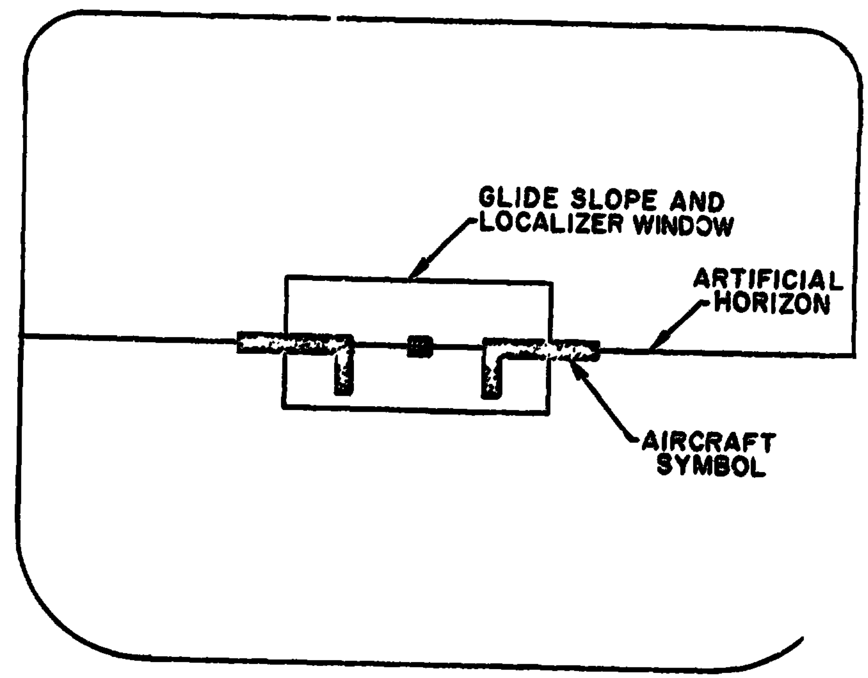

FIGURE 1. Display of Status Information

Non-zero rms residual noise terms were associated with height and sink-rate information. Because the display shows the height "window" of ±3.7 meters, a residual noise on height perception was needed to account for the lack of an explicit zero reference. To approximate the effects of the non-zero reference, the value of the residual noise was set equal to the amount of the reference offset (i.e., 3.7 meters). The residual noise on sink-rate information was included to account, in a rough way, for the resolution limitations of a Scanning Beam Instrument Landing System. However, the latter noise term was found to have no appreciable effect on predicted performance. A non-zero rms residual noise term was also associated with lateral offset error. This was set to a value of 5.4 meters, corresponding to the lateral dimensions of the "window". Studies of longitudinal control showed that the thresholds on attitude could be ignored, so in the analysis of lateral performance the thresholds associated with viewing the bank angle indicator were set to zero. Thresholds and residual noises for all displayed variables are summarized in Table 1.

Table 1

DISPLAY-RELATED PARAMETERS

Variable	Threshold	RMS Residual Noise
Altitude error (m)	0.48	3.7
Sink-rate (m/s)	0.85	1.1
Pitch (deg)	0.22	0.0
Pitch-rate (deg/s)	0.78	0.0
Airspeed error (m/s)	0.14	0.0
Lateral error (m)	.28	5.4
Lateral error rate (m/s)	.52	0
Bank angle (deg)	0	0
Roll rate (deg/s)	0	0

To evaluate various display configurations it was necessary to choose a performance metric. Although rms error scores were used as raw measures, it was decided to evaluate the displays in terms of the probability of not meeting Category II, approach window specifications, i.e., in terms of probability of a "missed approach". Of course, the missed approach probability is a function of gust intensity. Both, a worst-case wind- and a median-wind-condition, were investigated.* Because the relationship between rms performance and gust intensity is nearly linear [15] and the

*Given that turbulence occurs (P_T=.8), winds of intensity equal to or greater than that of the worst-case (median) wind will be encountered 1% (50%) of the time.

probability density for turbulence intensity is known [16], one can use the results for the two wind conditions to predict a measure of system performance that is averaged over all possible wind conditions. Such an overall system performance measure was also obtained in many cases.

Longitudinal and lateral displays were first analyzed separately. This was possible because of the decoupling inherent in the assumed linearized perturbation equations. Of course, the pilot must share his capacity between the longitudinal and lateral tasks, which implies some interference and a degradation in performance on each task. This interference was treated within the framework of the model of attention presented earlier.

To account for the interference, we define a combined cost functional

$$J_{TOT} = J_{LONG} + J_{LAT}$$

where J_{LONG} and J_{LAT} are the cost functionals for the longitudinal and lateral cases, respectively. The combined cost functional is meaningful because of the manner in which the weightings in the separate cost functionals were chosen. Now, if f_{LONG} is the fraction of attention devoted to the longitudinal task, then for control

$$f_{LAT} = 1 - f_{LONG}$$

It is therefore possible to determine how attention should be shared between the two control modes so as to minimize J_{TOTAL}.

Status Display

The first stage of the analysis of the lateral displays was a sensitivity study to determine the optimal allocation of attention between localizer and bank angle displays.* It was found that performance was not very sensitive to allocation of attention between these displays. Neverthess, about 75% attention to localizer, 25% to bank angle indicator was best in a high workload situation [15] and this attention-split was assumed for the remainder of the analysis.

Lateral tracking performance was computed for the worst-case and median winds and these rms scores were used to compute a composite score for an "all-winds" average. This was done for several levels of total attention devoted to the lateral task. The results in terms of missing the lateral approach window (5.4m) are given in Figure 2. They reveal that the lateral control task, even with the SAS-on, is very difficult. (The probability of missing the lateral window when averaged across all winds is 1.5 - 3 times as great as that for missing the longitudinal window at all levels of attention investigated.) If a 95%

*Because of the nature of the EADI overt visual scanning was not considered.

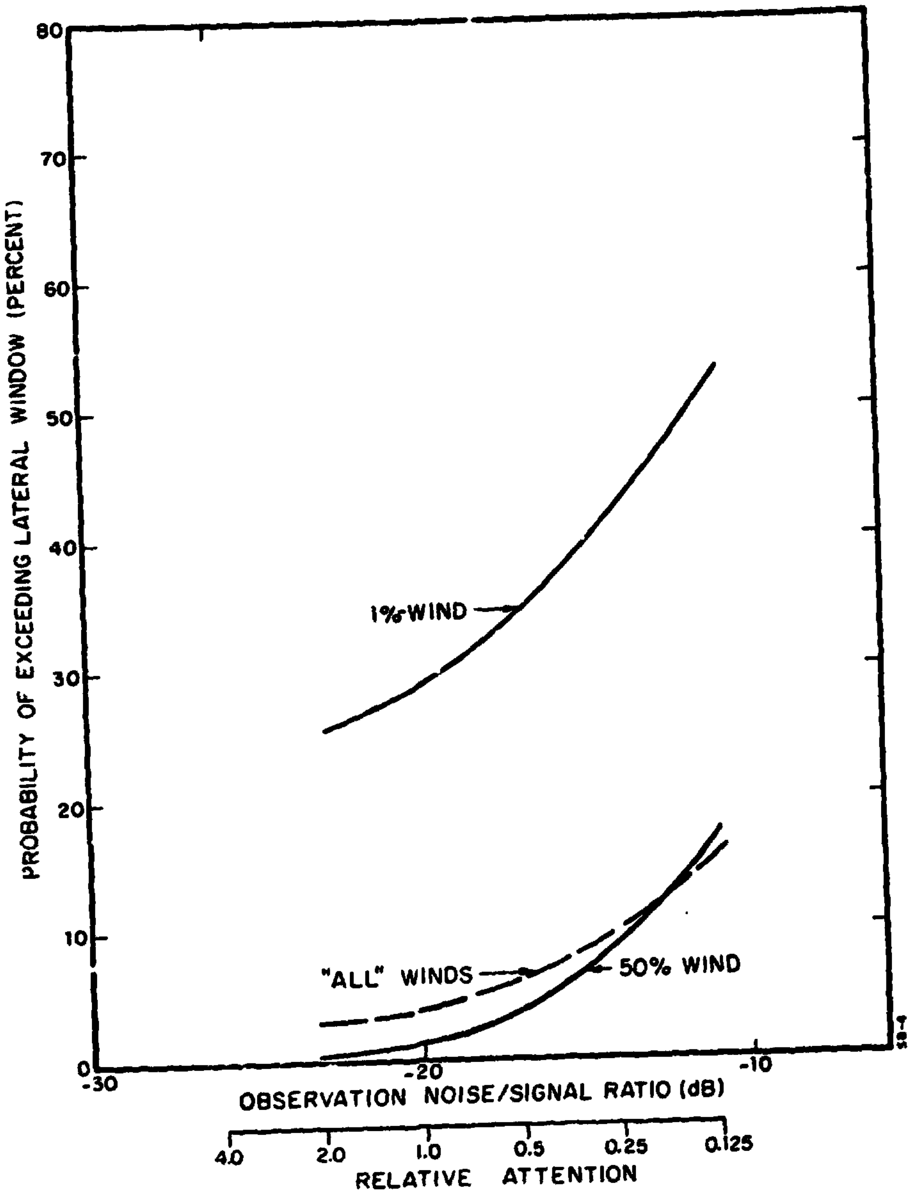

FIGURE 2. Effect of Attention on Lateral Window Performance

probability of a successful lateral approach is selected as a criterion level, the Workload Index for the lateral task for the 50% wind is about .4, and it is about .7 when the average of all winds are considered. For the 1% wind, it does not appear that a success probability of 95% is achievable within the limits of human behavior that we have observed heretofore.

The effects of sharing attention between longitudinal and lateral control tasks on window performance, averaged over all winds is shown in Figure 3. Using the probability of a missed approach as the measure of performance leads to the conclusion that approximately a 40/60 split of attention between longitudinal and lateral tasks is optimal. The corresponding overall probability of a missed approach (i.e., a miss on height <u>or</u> airspeed <u>or</u> lateral position) is about 8%. We can use these results <u>and</u> those for longitudinal control to obtain missed approach probabilities as functions of the relative attention devoted to the tracking task as a whole (assuming, for convenience that the pilot splits attention equally between the two tasks and that "full" attention = -20 dB). The result is plotted in Figure 4. This figure emphasizes the difficulty of the task. When all winds are considered, it does not appear possible to achieve a 95% approach success probability, at least within the range of pilot workload that is assumed acceptable. Even for the 50% wind condition, a success probability of 95% implies a Workload Index of about .9, hardly a desirable situation.

In an attempt to determine potential improvements in the lateral display, an analysis of the sensitivity of performance to changes in display parameters was conducted (for the worst-case wind and a high workload (P_o = -20 dB) condition). The following display improvements were considered in cumulative fashion: A) nominal EADI-Status Display; B) removal of residual noise associated with lateral error (providing a zero-reference); C) zero threshold for lateral error-rate; D) zero threshold for lateral error; E) no modification of noise/signal ratios for attention-sharing (display integration). The results of the analysis are given in Table 2.

Table 2

EFFECT OF DISPLAY PARAMETERS ON LATERAL PERFORMANCE

Condition	A	B	C	D	E
σ_y (m)	5.09	5.05	4.89	4.87	4.59
$\sigma_{\dot{y}}$ (m/s)	2.0	1.99	1.96	1.95	1.88
σ_ϕ (deg)	5.04	5.03	4.97	4.96	4.71
σ_{δ_w} (deg)	10.6	10.6	10.4	10.4	9.8

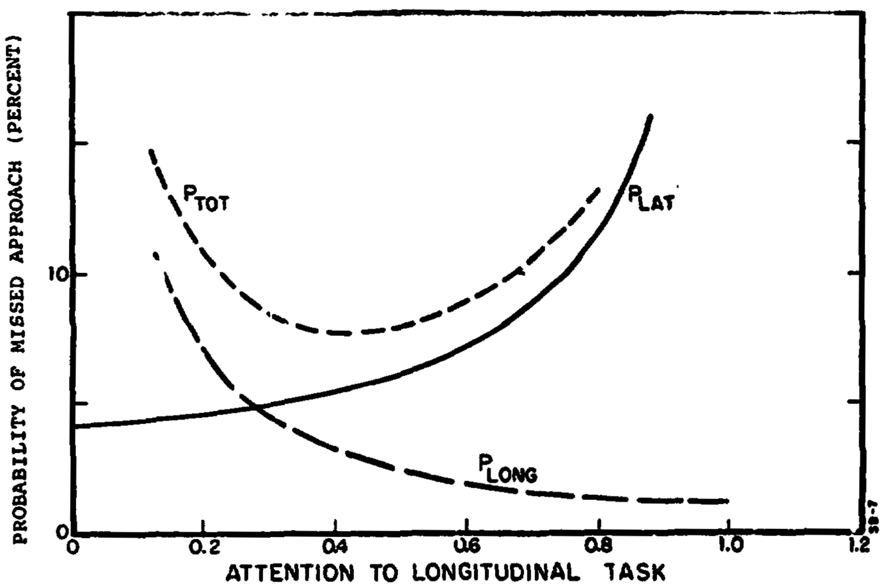

FIGURE 3. Effect on Approach Performance of Attention Sharing Between Longitudinal and Lateral Tasks

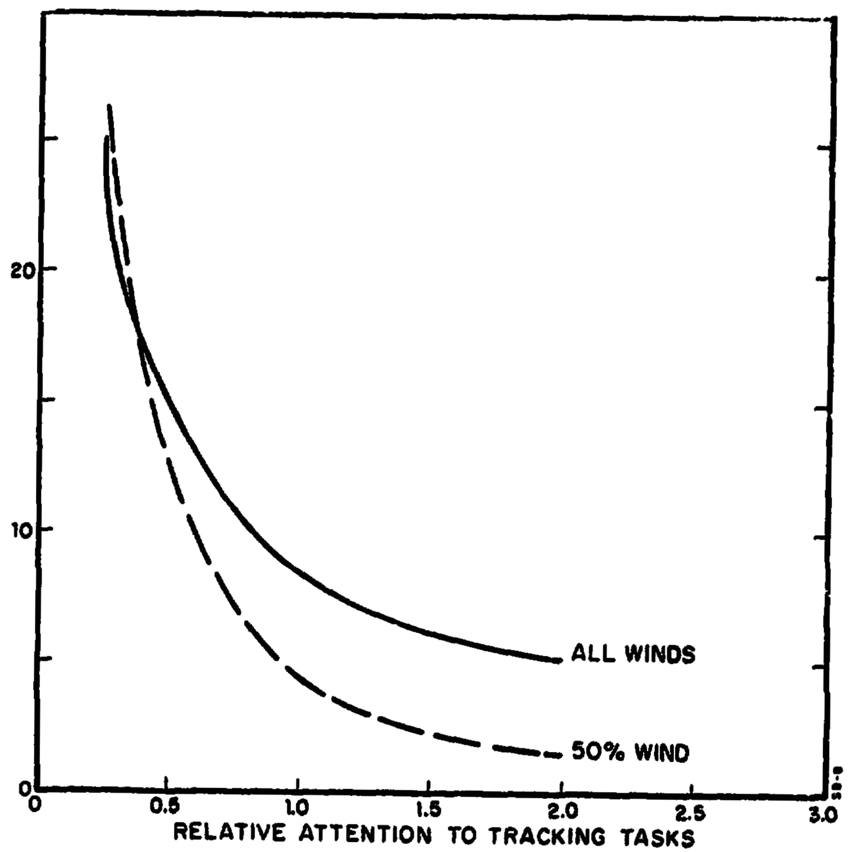

FIGURE 4. Effect of Attention on Missed Approach Probability

Performance improvements with display changes are not too dramatic, with the cumulative improvement in tracking performance being about 10%. Of the changes made, only two had any significant effect; namely, removing the lateral error rate threshold and removing the necessity for attention-sharing.

Director Display

A flight director display could remove threshold limitations and alleviate the requirement for display integration and, thus, realize the performance improvement possible with the *idealized* display of condition E. The actual performance improvement attained might not be substantial in terms of lateral error (about 10% according to Table 2). However, the flight director might allow achievement of similar performance at reduced workload, i.e., it might reduce the workload index.

An "interim" lateral flight director system for the AWJSRA has been described in [21]. We analyzed an approximate version of that system, as shown in Figure 5. It should be noted that we assume here that lateral flight path angle may be obtained directly rather than by means of the complementary filtering techniques of [21]. Although this assumption is somewhat unrealistic, the idealization should provide a bound on the performance improvements that can be expected of the more practical system. The gains for the lateral director system correspond to case 2F of [21].

The effects on rms performance of sharing attention between the lateral flight director and the lateral displays of the EADI-Status display (considered as an entity) were investigated. It was assumed that the portion of attention devoted to the status display was allocated between the localizer and bank angle indicators in the approximately optimal 3:1 ratio mentioned earlier. The results indicated that about 80-90% attention to the flight director is "optimal", but performance was very insensitive to changes in attention [15]. Results for the 80% division of attention were quite close to those for the idealized display; lateral error was about 3% greater for the flight director-status display combination and other variables were virtually identical. Even when only the flight director is available, there is not a significant increase in lateral error. In general, then, the attention-sharing results indicate that the "interim" lateral flight director comes close to achieving the improvements implicit in an idealized display. On the other hand, the improvements at the level of attention (-20 dB) and wind-condition (1%) investigated were not large indicating that, when working hard at the task, one can perform almost as well with the status displays as with the director.

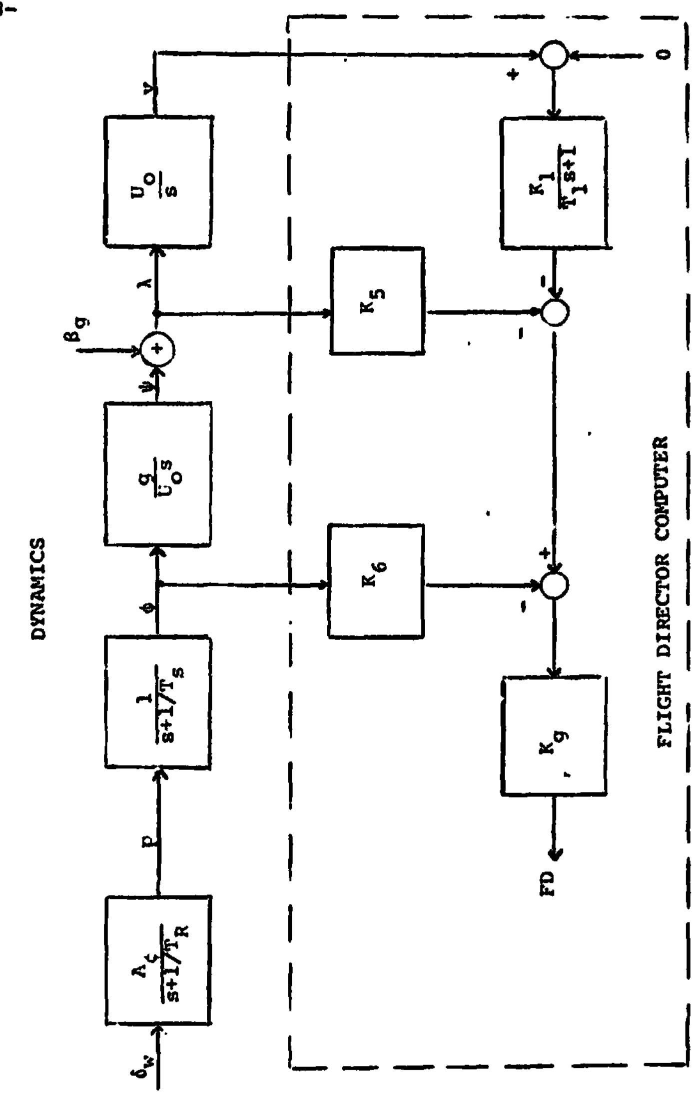

FIGURE 5. "Interim" Lateral Director System

The improvement provided by adding the lateral flight director to the status display at various "levels" of attention is shown in Figure 6. Averaged over all wind conditions, the probability of a missed approach without the flight director is 1.5 to 2 times greater than with it — at all levels of attention. Moreover, the improvement is greatest in the range of operation (attentions of .5 to .125 that are likely to be most important. For the 50%-wind (also shown in Figure 6), the flight director provides even more substantial improvement.

In terms of workload, an approach success probability of 99% is unattainable, with reasonable workload, when all winds are considered; for the 50%-wind, the flight director reduces the Workload Index from about 1.4 to about .3. For the all-winds average, a 95% success probability requires a workload index of about .7 in the no-director case as opposed to about .25 when the director is available. In general, the curves of Figure 6 indicate that addition of the flight director will reduce the lateral workload by a factor of 2-4 for success probabilities that can be achieved, with greatest improvement in the range of most interest.

The total longitudinal-lateral approach task with flight directors for both control tasks* was analyzed in exactly the same fashion as for the status display configuration. The results are presented in Figure 7. When the average of all-winds is considered, the addition of the flight-directors reduces the miss probability by about a factor of two, with the most improvement in the lower attention levels. Even greater improvement (4-7 times better) is evidenced for the 50%-wind condition. The missed approaches, for the all-winds average, are due largely to the lateral task; although not shown, this is even more true for the 50%-wind condition.

Figure 8 shows the tradeoff between workload and performance for the 50%-wind condition. The directors cut the workload by at least a third in the range of success probability of 95-99%. A similar reduction in workload is possible for the all-winds average, but the probability of success is much reduced. (The workload index for a 95% success probability is about .7 with the directors as opposed to 2 without them.)

4. CONCLUSIONS

A display evaluation methodology based on the optimal control model of the human operator has been described and applied to the analysis of vertical situation displays for STOL approach. The methodology appears to provide a powerful means for analyzing

*The "Interim" longitudinal directors for nozzle and elevator control were approximations [15] to those proposed in [21].

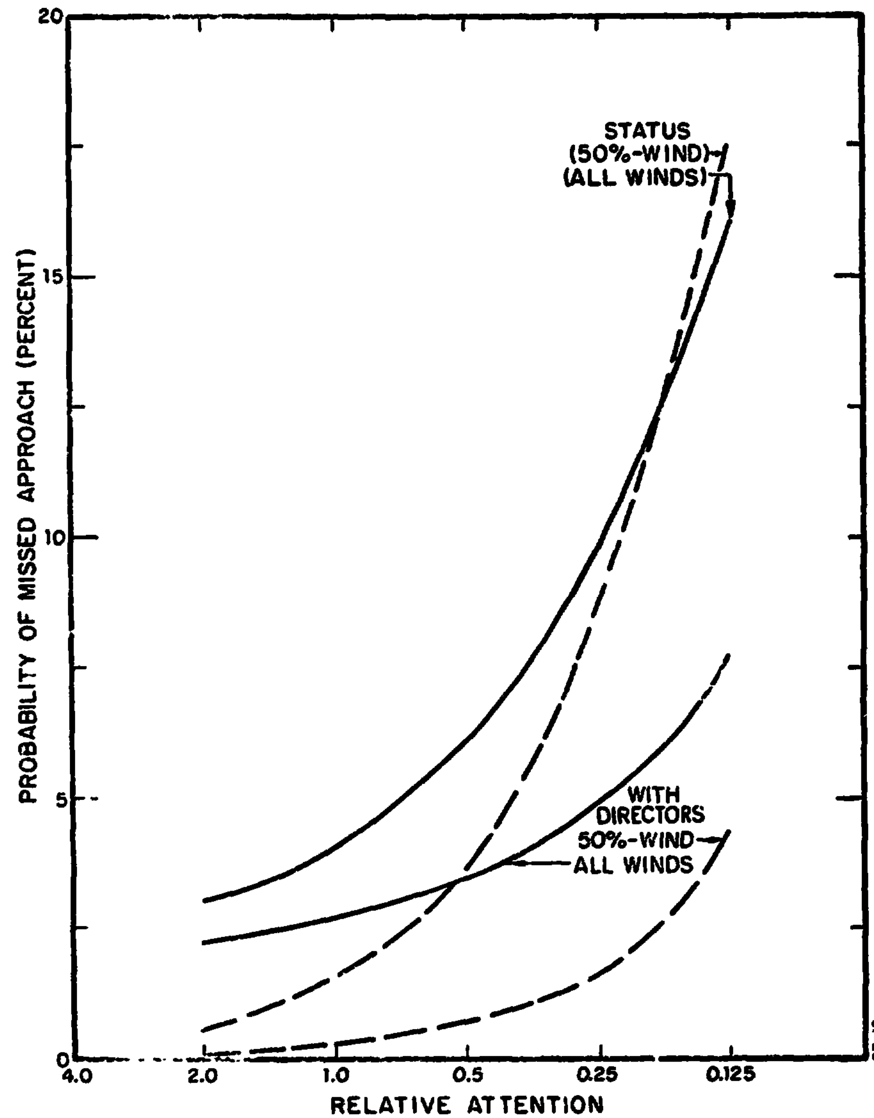

FIGURE 6. Effect of Lateral Director on Missed Approach Probability

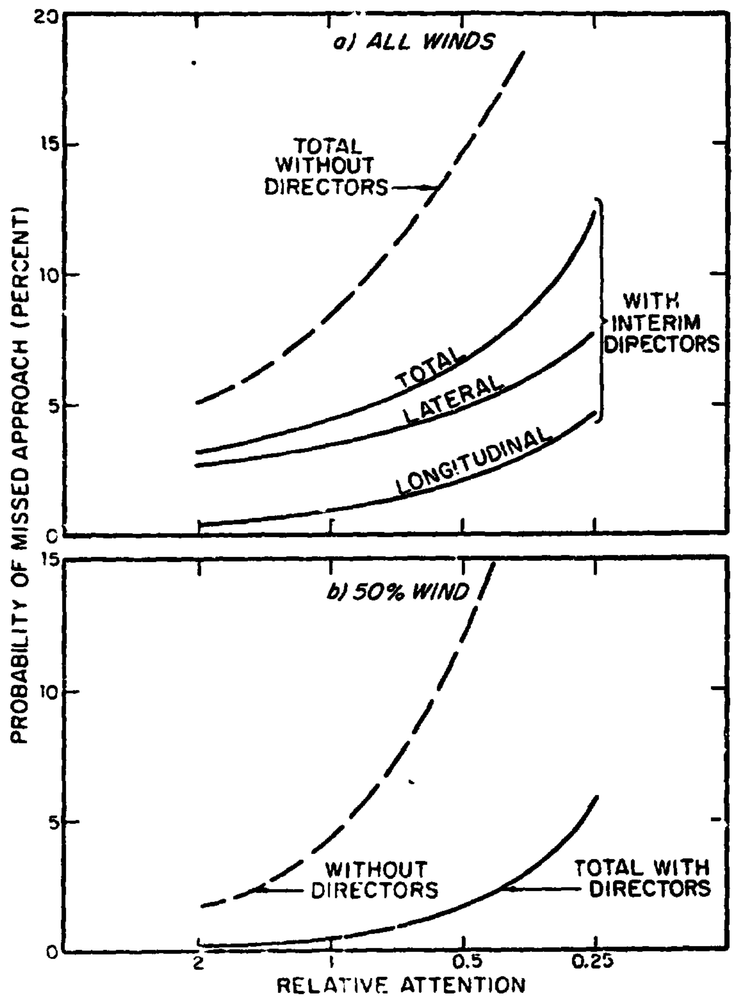

FIGURE 7. Effect of Director Systems on Combined Longitudinal/Lateral Approach Performance

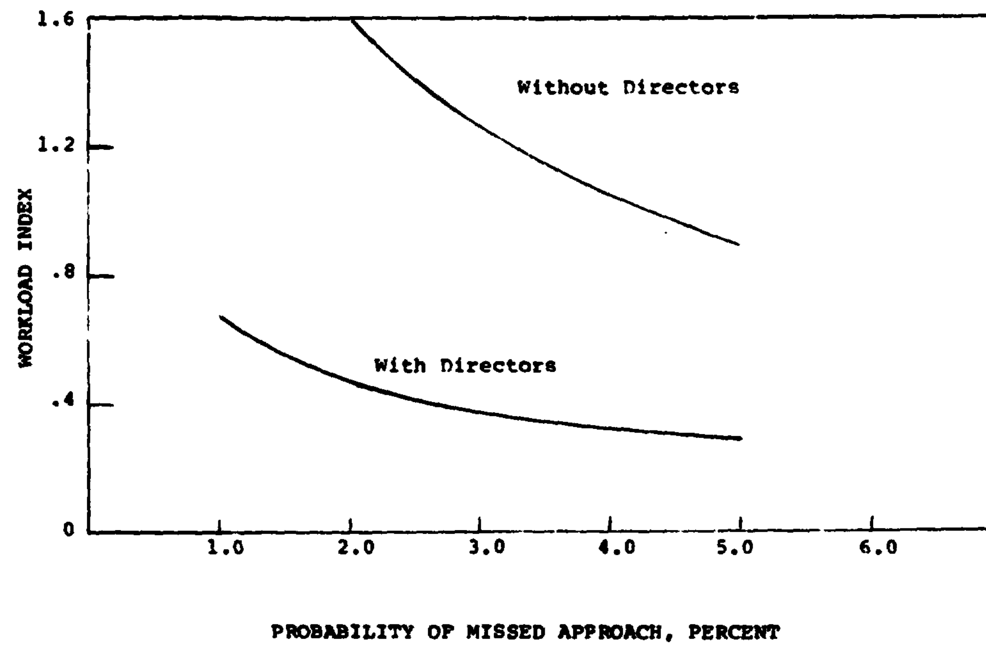

FIGURE 8. Effect of Flight Directors on Workload Index, 50%-Wind

displays and their effect on system performance and reliability. It may be used to determine bounds on expected display improvements via analysis of "idealized" displays. The model for task interference and workload permits linearized analysis of combined longitudinal and lateral performance in a rational and consistent manner. Interaction between axes is introduced via the limited capacity of the pilot and not through any vehicle coupling. The analysis techniques can also serve as a basis for director design. Such a (preliminary) procedure for design of a longitudinal director system, that considered only the gust-regulation problem, yielded a configuration that resulted in substantially reduced workload [22].

The performance of the AWJSRA with an "unaugmented" EADI-Status display was analyzed with respect to both "window" performance and pilot workload, for a range of turbulence conditions. The results indicate that with the basic display the overall task is quite difficult. When the median wind level is considered, a 95% success probability for approach requires a high workload. If performance is averaged over all possible winds, such a success-probability does not appear to be attainable within a reasonable range of workload. The lateral-directional task seems to be considerably more difficult than the longitudinal control task, even though stability augmentation is provided for lateral control. For a 95% probability of being within the respective approach window, the lateral task has a workload index about 2.5 times that for longitudinal control.

Potential improvements to the basic display were also explored. The greatest effects were observed when better error-rate (sink-rate, lateral error-rate) information was assumed, as might be provided, for example, by a display of longitudinal and lateral flight path angles. Significant effects were also observed when the requirements for attention-sharing were removed. These improvements, as well as a reduction in pilot workload, may be realizable with suitable flight-directors.

Analysis of suggested longitudinal and lateral flight director systems confirms that performance is improved and pilot workload is reduced by a significant amount. When the average of all-winds is considered, reducing the probability of a missed approach to 5% still requires a high workload. However, for a median-wind condition the directors reduce workload requirements to values that seem well within capabilities.

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