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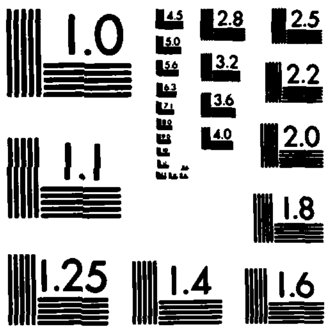

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AIR FORCE

HUMAN RESOURCES

PILOT-ORIENTED PERFORMANCE MEASUREMENT

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August 1985
Final Technical Paper for Period January 1983 - December 1983

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AD-A158 849

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NOTICE

This paper has been reviewed and is approved for publication.

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Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: Unclassified

1b. RESTRICTIVE MARKINGS:

2a. SECURITY CLASSIFICATION AUTHORITY:

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE:

3. DISTRIBUTION / AVAILABILITY OF REPORT: Approved for public release; distribution unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S): AFHRL-TP-85-18

5. MONITORING ORGANIZATION REPORT NUMBER(S):

6a. NAME OF PERFORMING ORGANIZATION: Operations Training Division

6b. OFFICE SYMBOL (If applicable): AFHRL/OT

7a. NAME OF MONITORING ORGANIZATION:

6c. ADDRESS (City, State, and ZIP Code): Air Force Human Resources Laboratory, Williams Air Force Base, Arizona 85240-6457

7b. ADDRESS (City, State, and ZIP Code):

8a. NAME OF FUNDING / SPONSORING ORGANIZATION: Air Force Human Resources Laboratory

8b. OFFICE SYMBOL (If applicable): HQ AFHRL

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER:

8c. ADDRESS (City, State, and ZIP Code): Brooks Air Force Base, Texas 78235-5601

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
61102F	2313	T3	12

11. TITLE (Include Security Classification): Pilot-Oriented Performance Measurement

12. PERSONAL AUTHOR(S): De Maio, J. Bell, H. H. Brunderman, J.

13a. TYPE OF REPORT: Final

13b. TIME COVERED: FROM Jan 83 TO Dec 83

14. DATE OF REPORT (Year, Month, Day): August 1985

15. PAGE COUNT: 15

16. SUPPLEMENTARY NOTATION:

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
05	08	
05	09	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number): altitude maintenance; flight simulation; performance measurements; task difficulty; visual simulation.

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

A prototype performance measurement system was developed to describe pilot performance in a simulator. The pilot's task was to maintain altitude at 200 feet both in straight and in turning flight. Pilot performance was sensitive to task difficulty and to visual scene quality. The strength of this performance measurement system was that it analyzed performance in terms of overall task performance and also specific pilot control inputs.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION:

22a. NAME OF RESPONSIBLE INDIVIDUAL: Nancy A. Perrigo, Chief, STINFO Office

22b. TELEPHONE (Include Area Code): (512) 536-3877

22c. OFFICE SYMBOL: AFHRL/TSR

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

Unclassified

AFHRL Technical Paper 85-18 August 1985

PILOT-ORIENTED PERFORMANCE MEASUREMENT

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This publication is primarily a working paper.
It is published solely to document work performed.

SUMMARY

Aircrew performance measurement is a critical problem in evaluating the quality of a visual simulation system and in determining the effectiveness of aircrew training devices. An effective performance measurement system must be able to separate performance into appropriate components and describe the relationship of these components. This paper describes a performance measurement system developed to analyze pilot performance in maintaining altitude in both straight and turning flight as a function of the object density of the simulated visual environment. The analysis indicates that pilot performance can be divided into perceptual and task difficulty factors and that the effect of the visual environment on each of these factors can be determined.

1473

PREFACE

This paper describes a performance measurement system designed to quantify pilot performance for simple simulator flight tasks. The work was performed by the Operations Training Division of the Air Force Human Resources Laboratory in support of the Aircrew Training Thrust and Aircrew Training Applications Subthrust. This effort was a part of Project 2313T312, Cognitive Aspects of Flight Training.

TABLE OF CONTENTS

LIST OF FIGURES

PILOT-ORIENTED PERFORMANCE MEASUREMENT

I. INTRODUCTION

The need for effective measurement of operator performance has increased dramatically as man-machine systems have become more complex and costly. Performance measurement systems (PMSs) are needed which will permit assessment not only of total man-machine system performance, but also of the component factors contributing to the total performance. To accomplish this assessment, measures are needed that permit the decomposition of performance into its perceptual, information processing, and physical control components.

The need to decompose overall performance into its components is particularly apparent when task difficulty interacts with other factors to affect performance. For example, Rinalducci (1981) examined the performance of pilots in maintaining level flight in an F-16 simulator. Rinalducci used two measures of performance; mean altitude above ground level (AGL) and root-mean-square (RMS) deviation from 200 feet AGL. Both measures were sensitive to the variables of visual cues, airspeed, and type of flight (i.e., straight or turning). In addition, both measures were sensitive to interactions among these variables. One variable, visual cues, is clearly a perceptual/informational factor. Neither of the other two variables (airspeed and type of flight) nor the interactions are as amenable to intuitive labeling. The performance measures used by Rinalducci did not permit analysis of the component processes; consequently all that can be shown is that these variables affect performance, but not how they do so.

Attempts to decompose performance into its components have followed two general approaches. One approach uses a discrete stimulus such as a cross-wind gust to elicit a control input (Wierwille, Casali, & Repa, 1983). Because the input is elicited by a discrete stimulus, it is possible to obtain timing information showing the contribution of perceptual, subject, and control task factors to the latency and effectiveness of control inputs. This approach provides information not only about how well a pilot controls the aircraft but also about the effectiveness of the pilot's response. The limitation of this approach is that it can be applied only when inputs are made in response to discrete environmental changes.

The second approach focuses on the ad lib control inputs which operators frequently make in unperturbed, steady-state operation. The typical measure used to study these ad lib control inputs is simply the rate of control inputs. For example, an input rate measure which has been used in driving an automobile is steering reversal rate (SRR), the rate at which the steering wheel is reversed through a small finite arc. This measure of performance is sensitive to traffic density (Greenshelds, 1963), lane width, speed, and preview (McLean & Hoffman, 1973) and to control task difficulty (Hicks & Wierwille, 1979). Although SRR is sensitive to the effects of both perceptual and task variables, it has drawbacks. MacDonald and Hoffman (1980) found that the addition of a secondary task affected SRR differently in simulated than in actual driving. More importantly, SRR is often uncorrelated with overall steering performance (MacDonald & Hoffman, 1980).

Similar control reversal rates have been employed in flight research to measure ad lib control inputs. As in driving control, such measures are sensitive to flying task difficulty, but the reasons for this sensitivity are not clear. For example, Blomberg, Pepler, and Speyer (1983) used elevator position reversal rate (EPRR) to measure control performance in the A-300 aircraft. They found the introduction of an electronic flight information system (EFIS) increased EPRR, while other measures of flying performance showed the EFIS improved pilot performance. Introduction of an autopilot, to control horizontal position and thereby reduce aircraft task difficulty, caused the EPRR to decrease.

For measures of ad lib control inputs to be useful, indices of input effectiveness, similar to those available for elicited control inputs, are needed. The PMS presented here measures both overall flight task performance and the effectiveness of ad lib inputs. Two assumptions underlie this PMS: first, the control inputs are elicited by specific flight conditions, and second, the qualitative effect of the input reflects the pilot's intention. That is, if an input causes the aircraft to change direction of travel, then the pilot's intention was to change direction. Based on these assumptions, flight control performance was broken down into a perceptual task component and a physical control task component.

In this paper, following a description of the PMS, data are presented to show the effects of perceptual and control task difficulty on the performance measures. These data were gathered in a flight simulator visual data base evaluation, the results of which are presented by De Maio, Rinalducci, Brooks, and Brunderman (1983).

II. THE MEASUREMENT SYSTEM

The PMS must provide measures of performance that are sensitive to the pilot's intentions moment by moment; therefore, both overall and component performance measures must be defined specifically for the flying task considered. The PMS discussed in the paper evaluated control performance in maintaining level flight at a specified altitude.

Four performance measures were employed. Two measures related to overall control performance: Target Altitude (TA), defined as the mean of the local altitude minima and maxima, and Altitude Range (AR), defined as the mean difference between local maxima and minima; these measures give the altitude the pilot was attempting to maintain and the degree to which the aircraft varied about that altitude. The remaining two measures, Smoothness (S) and Critical Error Rate (CER), are based on individual control inputs and were used to decompose performance into its components.

This PMS employs a functional criterion for defining a control input. The control inputs of interest were those made through the aircraft stick. The effectiveness of these control inputs was determined from their effect on the aircraft vertical velocity vector.

Since the control inputs that were examined affected the vertical velocity vector, they can be classified in only two categories: first, critical control inputs which changed the aircraft's direction of travel and, second, noncritical control inputs that did not change the direction of travel.

Operationally, a critical control input was designated by a change in sign of the aircraft's vertical acceleration. For example, if the vertical acceleration was positive (increasing rate of climb), a critical control input was one which caused the vertical acceleration to become negative (decreasing rate of climb). This definition is analogous to that used for SRR. This functional criterion makes the PMS highly sensitive, since control inputs are identified according to a task relevant criterion.

Efficient control would be expected to involve a relatively large proportion of critical inputs. A greater proportion of noncritical inputs might result in less efficient control since many of these inputs do not result in error reduction. Based on this distinction between critical and noncritical inputs, two component performance measures were defined. One measure, Smoothness (S), is the proportion of critical to the sum of critical and noncritical control inputs. Smoothness has a value of 1.0 when all inputs are critical and a value of 0.0 when no inputs are critical. A higher value of S represents more efficient control.

The other measure, Critical Error Rate (CER), is the horizontal distance traveled from critical control input to vertical acceleration sign change divided by the time from critical control input to vertical acceleration sign change. The more effective the critical control input, the smaller the value of the CER. This measure reflects the effectiveness of a critical control input by measuring the rate at which error continues to accumulate following the input. Effective control inputs are those which result in low rates of error accumulation.

These two measures, S and CER, permit the breakdown of control performance into its behavioral components. For this decomposition to be useful, two things are necessary: first, the component measures must be tied to psychologically relevant processes, and second, the contribution of the performance components to overall performance must be determined. The following analysis of control performance in a flight simulator addresses these issues through examination of flying performance in straight and turning flight under varying conditions of environmental visual cue quality.

III. SIMULATOR FLYING PERFORMANCE EVALUATION

In the simulator flying performance evaluation, the effect of two task difficulty factors on the measures of performance was examined. One of the task difficulty factors addressed was the quality of out-of-the-cockpit visual cues provided the pilot. De Maio et al. (1983) and De Maio and Brooks (1982) have used the slope, b, of the altitude estimation function relating the actual simulated altitude to the judged altitude as a measure of the altitude cueing effectiveness of simulator visual environments. The closer that b is to 1.0, the more effective the visual cues in simulated environment are for estimating altitude. The PMS was applied to flying performance data obtained in five simulated visual environments, whose altitude cueing effectiveness produced slopes ranging from b =.2 to b =.8.

The second task difficulty factor was the type of flight, either straight or turning. When an airplane is in wings level flight, the force of gravity is counterbalanced directly by the lift vector. When the aircraft is banked, a cosine component enters the lift equation. This cosine component increases the difficulty of the control task in proportion to the size of the bank angle up to 90^{o}.

The first step in the performance analysis was to look at overall task performance as measured by TA. Figure 1 shows that, for both straight and turning flight, TA was inversely related to the visual cueing effectiveness as reflected by the slope of the altitude estimation function for the different simulator visual environments. The data indicated that performance improved greatly when the slope of the altitude estimation function exceeded 0.7. In addition, Figure 1 shows that turning caused an increase in TA at all levels of altitude cueing effectiveness. These data indicate that TA is affected by both the quality of the visual environment and the difficulty of the flight task.

An understanding of why pilots raise TA with increased task difficulty requires examination of another measure of overall task performance: Altitude Range (AR). Figure 2 shows the effect of both altitude cueing effectiveness and task difficulty on AR. An inspection of Figure 2 indicates that AR was also inversely related to altitude cueing effectiveness and task difficulty. Since AR measures how precisely the pilot controls altitude, it affects TA in that TA must be at least sufficiently large to preclude collision with the ground on minimum altitude excursions.

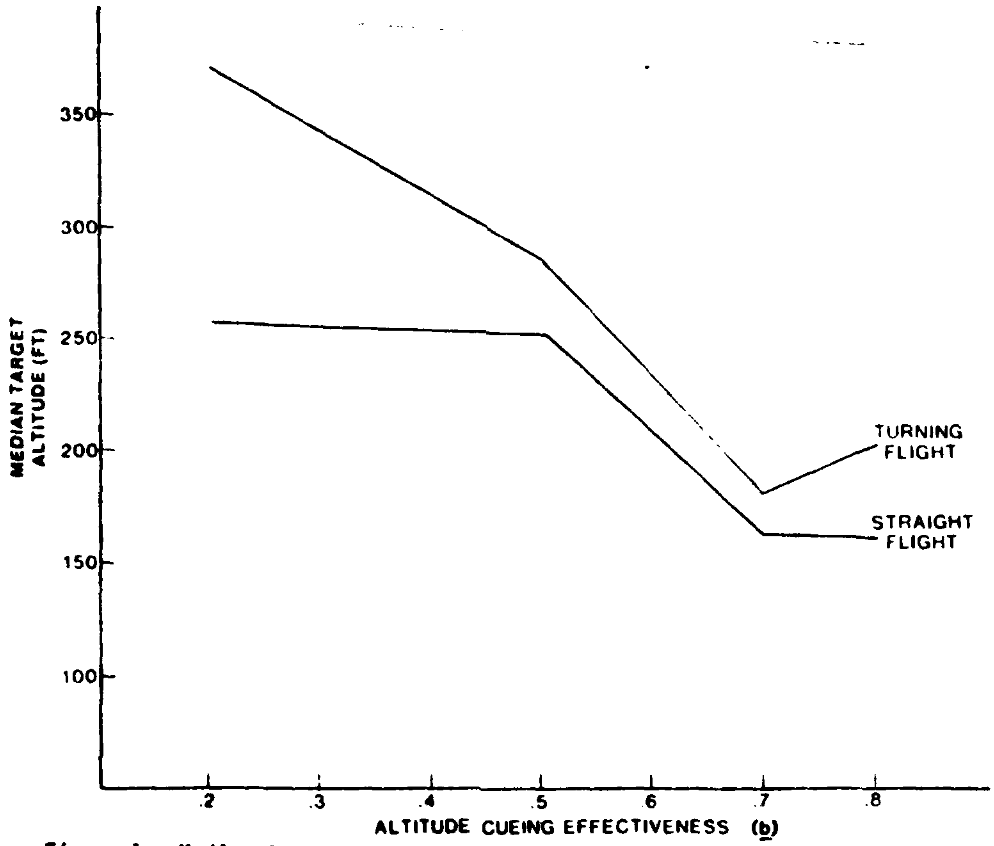

Figure 1. Median Target Altitude for Straight and Turning Flight as a Function of Altitude Cueing Effectiveness.

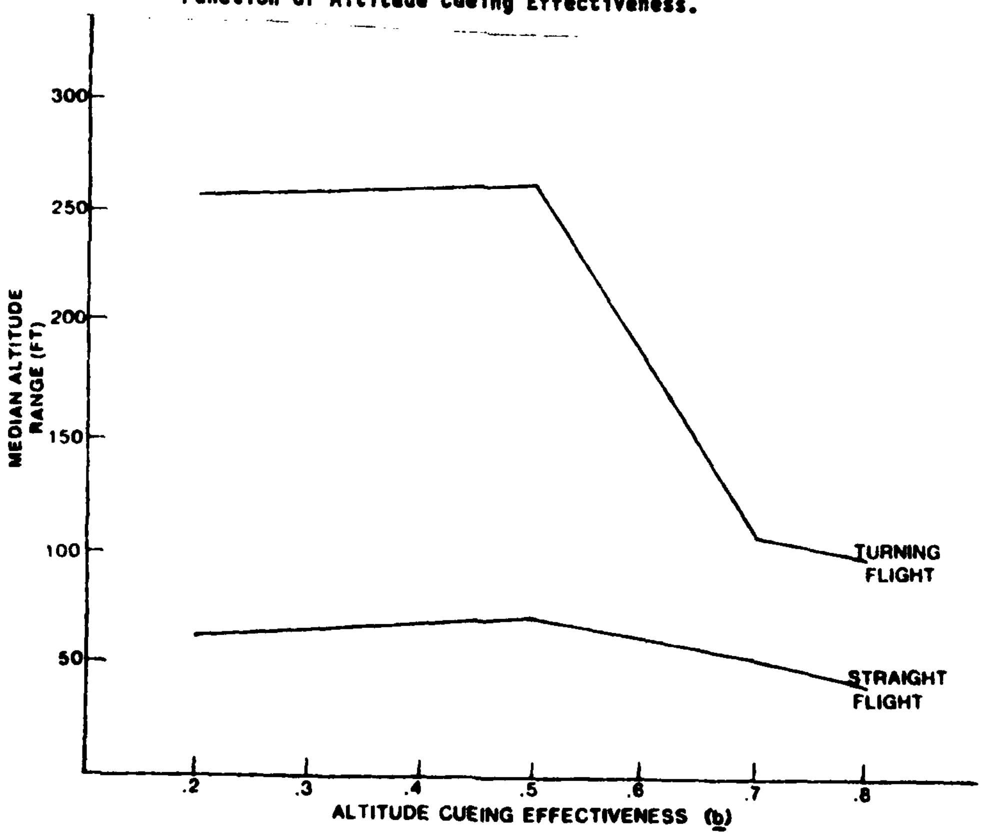

Figure 2. Median Altitude Range for Straight and Turning Flight as a Function of Altitude Cueing Effectiveness.

As was true for TA, AR was sensitive to both perceptual and task difficulty factors. The pattern of these effects, however, differs substantially for the two factors. The effect of task difficulty appears to be quantitatively different on TA than on AR. Target altitude increased by about the same amount for both straight and turning flight as altitude cueing effectiveness decreased. Altitude range, however, was relatively unaffected by the quality of the visual environment for straight flight but increased markedly for turning flight.

IV. COMPONENT PERFORMANCE ANALYSIS

Figures 1 and 2 show that for straight flight, TA is strongly affected by visual cue quality, while AR is relatively constant. At the same time, turning flight appears to interact with visual cue quality to markedly increase AR in the poor visual environments. In fact, the function relating TA to visual cue quality in both straight and turning flight is more like the AR function for turns than for straight flight. This suggests that the precision of the control performance, as measured by AR, is the determinant of TA in both turning and straight flight. Since turns had to be executed during the flight, the pilot chose a TA which permitted an adequate maneuvering envelope for both straight flight and turns. This implies that pilots select an appropriate altitude based on their ability to perceive and control altitude. What remains to be shown is how the perceptual and control task factors act individually and in concert to affect control precision. This analysis is accomplished by examining the performance components, S and CER.

Smoothness (S) is a measure of control input efficiency since it measures the proportion of inputs that alter the aircraft's direction of travel. Figure 3 shows that S is highly sensitive to altitude cue quality but insensitive to flight task difficulty. Changing the quality of visual

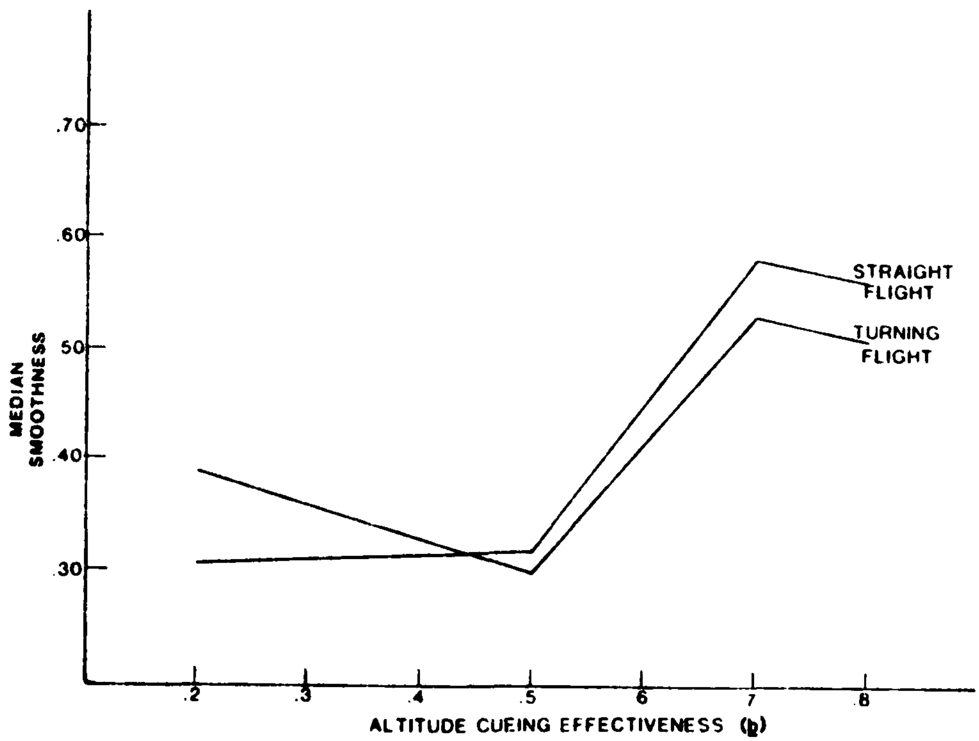

Figure 3. Median Smoothness for Straight and Turning Flight as a Function of Altitude Cueing Effectiveness.

information available to the pilot affected the proportion of critical and noncritical control inputs made. When cue quality was high, twice as many inputs were made to change the direction of travel than when cue quality was low.

The role of noncritical control inputs during flight is unclear. At least two logical explanations of these inputs exist. Since these inputs increased when the quality of the visual environment was poor, they may serve to give the pilot additional perceptual information needed for aircraft control. When altitude cues are good, only a small number of noncritical inputs is needed to provide flight control information, and the majority of inputs is made to effect flight control. When visual cues are poor, more noncritical inputs are needed, and so S declines. An alternative explanation of noncritical inputs is that they are successive approximations to the desired control solution. Unfortunately, the available data do not permit separation of these two possible explanations.

The second component performance variable, CER, measures the effectiveness of individual critical control inputs; that is, how quickly error accumulates following an error reducing input. Since CER measures the responsiveness of the man-machine system, it might be expected to be differentially sensitive to control task difficulty factors; Figure 4 shows this sensitivity. Critical Error Rate doubles from about 15 ft/sec in straight flight to about 30 ft/sec in turning flight. Yet CER does not vary systematically with altitude cue quality.

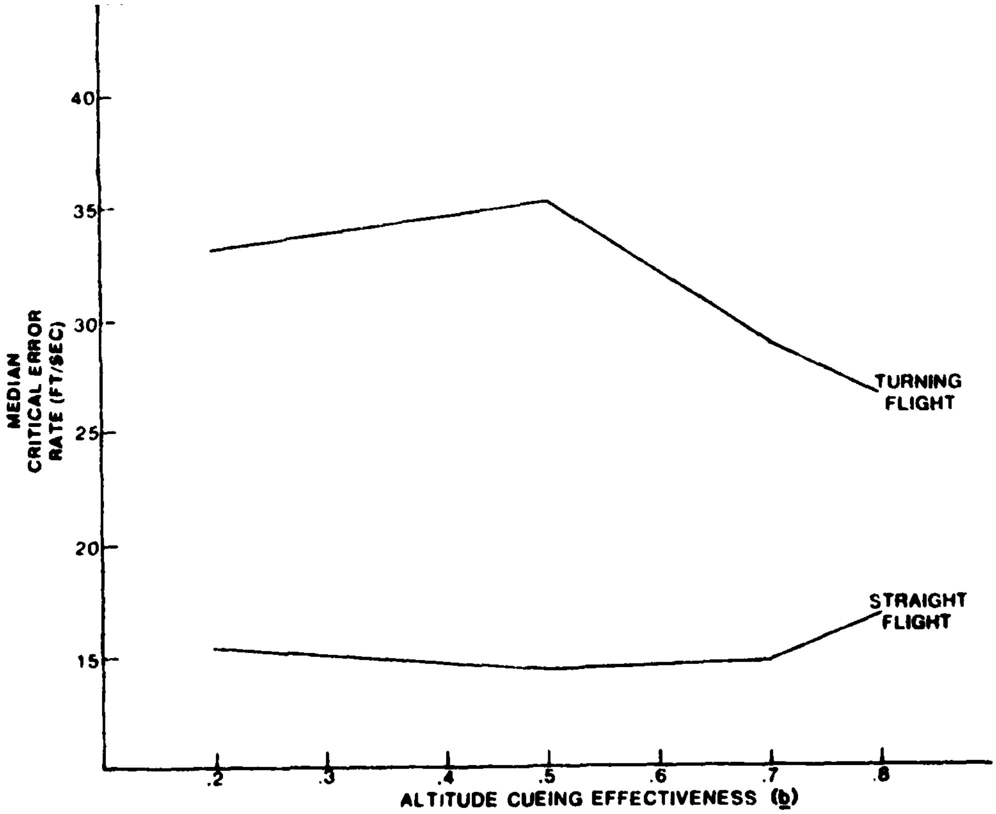

Figure 4. Median Smoothness for Straight and Turning Flight as a Function of Altitude Cueing Effectiveness.

Two components of control performance have now been identified: S, or input efficiency, and CER, or input effectiveness. Since these performance components show the differential sensitivity to task difficulty factors, they permit a determination of how increases in difficulty affect the control process. Increased perceptual task difficulty leads to a decrease in S because relatively fewer inputs are effective in changing the direction of travel. Increased control task difficulty, as reflected in turns, leads to an increase in CER since the inputs are less effective in altering the direction of flight.

Conceptually, the effects of variation in control efficiency (S) and input effectiveness (CER) can be related to overall control performance as reflected in AR. When input efficiency decreases, due to increased perceptual task difficulty, directional changes occur less frequently, and AR increases. Similarly, when inputs are less effective due to increased control task difficulty, the aircraft responds more slowly, and AR again increases. Therefore, AR is directly affected by both the quality of the visual environment and the difficulty of the flight control task.

V. DISCUSSION

The four performance measures described in this paper break down flight control performance into component processes. Two of these measures, TA and S, were primarily influenced by the altitude cueing effectiveness of the visual environment. The remaining two measures, AR and CER, were affected more by the difficulty of the flight control task than by the altitude cueing effectiveness of the visual scene. Taken together, these four measures describe flight control performance on the basis of both perceptual and task difficulty components.

In addition, the results of this investigation indicate that a performance measurement system requires an analysis of both overall flight performance and control inputs. Target altitude and AR represent wholistic measures based on the aircraft's position in space. Smoothness and CER reflect the specific control inputs made by the pilot during flight. Both types of measures are necessary for adequately understanding pilot control performance.

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