NASA Contractor Report 4073

The Effects of Display and Autopilot Functions on Pilot Workload for Single Pilot Instrument Flight Rule (SPIFR) Operations

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TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

LIST OF FIGURES (CONCLUDED)

LIST OF TABLES

SECTION I

INTRODUCTION

The conduct of single pilot instrument flight rules (SPIFR) operations is a demanding human operator task requiring highly efficient division of attention involving manual control, assimilation of information from a variety of sources, and the exercise of sound judgment. The current generation ATC system is basically configured to serve multimember crews and as noted in Ref. 1, "flying IFR alone is probably the toughest task in aviation." This study addresses the controls and displays needed during IFR conditions to help the single pilot avoid blunders, perform required cockpit functions, maintain the mental orientation to understand the flight situation, and to perform the flight tasks and subtasks with adequate precision.

The new electronic technologies are expected to have a dramatic impact on future controls and displays for SPIFR operations. These new technologies include VHSIC (very high speed integrated circuits), advanced RF circuits such as monolithic GaAs amplifiers, and integrated electro-optics such as fibre-optics and monolithic interface elements. These new technologies promise more functional utility and at the same time lower cost and higher reliability than the current electronics. However, their potential for reducing workload will only be realized if the interface with the pilot is well developed. The state of the art of this interface is not sufficiently mature so as to effectively take advantage of the recent quantum advances in electronic technology.

This report presents a first step in developing the criteria for pilot interaction with advanced controls and displays. The research program presented herein consisted of an analytical phase and two experimental phases. The analytical phase of the research consisted of a review of fundamental considerations for pilot workload taking into account existing data, and using that data to develop a divided attention SPIFR pilot workload model. The rationale behind developing such a model was based on the concept that it is necessary to identify and quantify the most important components of pilot workload as a starting point in the research. The pilot model was utilized to interpret and unify results of previous research and experiments as well as results of the experiments conducted herein.

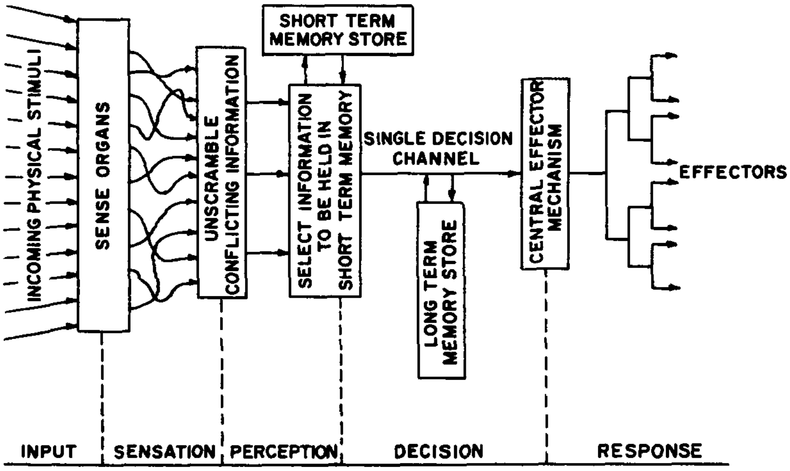
Two experiments were conducted. Experiment I consisted of a flight test program conducted at NASA Langley, which evaluated pilot workload in the presence of current and near-term displays and autopilot functions. Experiment II was conducted on a Flight Safety Intl. King Air simulator, and investigated the effects of co-pilot functions in the presence of very high SPIFR workload.

The fundamental considerations for pilot workload, including the development of a SPIFR workload model, is presented in Section II. Four subjective workload assessment scales and two objective measures were used in the experiments. These are discussed in Section III. The experimental results from flight test and simulation are presented in Section IV, and the conclusions of this research are given in Section V. A comprehensive review and interpretation of existing data related to SPIFR pilot workload is presented in Appendix A. Appendices B and C contain detailed descriptions of the scenarios used in Experiments I and II.

SECTION II

FUNDAMENTAL CONSIDERATIONS FOR SPIFR PILOT WORKLOAD

A divided attention workload model has been formulated to quantify the pilot behavior required for successful operation in the SPIFR environment. The first step in the development of the model was to identify the basic human operator functions and limitations that apply to the SPIFR task. A model defining these characteristics was adapted from Ref. 2 and is shown in Fig. 1. This model illustrates that the human pilot's primary limitation lies in the fact that he or she is basically a single channel processor; that is a human operator can only tend to one thing at a time. This effect tends to be magnified in a high workload situation.



- Simultaneous inputs are held in short-term memory
- The single decision channel is serial in nature allowing the human operator to attend to only one thing at a time
- Basic methodology is guided by long-term memory

Figure 1. Key Elements of Human Information Processing

As shown in Fig. 1 there are a large number of incoming physical stimuli which are perceived by the senses (sight, touch, sound, and kinesthesis feel) which, in some cases, may be conflicting. The function after "sensing" represents the human operators ability to unscramble conflicting signals as well as to pass only pertinent information to the "Short Term Memory." Examples of conflicting signals would be the classical discrepancy between the vestibular and visual cues which requires the pilot to ignore his instincts and believe the instruments. This function becomes quite refined during basic instrument training and is enhanced by a high quality display of aircraft attitude. Conflicting signals between the navigation displays can cause an enormous increase in workload while the pilot attempts to discern which information to reject. Examples of such conflicts are VOR receivers which do not agree, disagreement between a VOR crossbearing and the DME when identifying an intersection, and inappropriate autopilot responses to commands (wrong mode selected, poor autopilot performance, or malfunction). The addition of advanced displays, such as a moving map, may increase the chances of conflicts since more data is available; for example, the aircraft could appear to have varying degrees of course offset depending on the map scale selected.

Selected unscrambled information is placed in short-term memory to be utilized in serial fashion via the "Single Decision Channel." The methodology which guides the short-term memory and prioritizes information for use in the Single Decision Channel is established in the "Long-Term Memory."

The following observations can be made about short-term memory function.

- It is prone to errors which arise as a result of false hypotheses (see Ref. 2).
- All but one piece of incoming data (physical stimuli) are stored in short-term memory. Note that the data is "filtered" by the human operator to delete useless information.
- Much of the data in short-term memory is wiped out if an overridingly important piece of information is received (see Ref. 2).

- One objective of the displays and controls should be to reduce the requirements on short-term memory.

The following observations can be made about the long-term memory function.

- It sets priorities for action upon items in short-term memory.
- It sets the pattern and strategy for scanning behavior.
- Its efficiency is strongly associated with IFR proficiency.

Examples of incoming physical stimuli are

- Avionics and autopilot control settings
- Instrument readings
- ATC clearances
- Weather data
- Navigation information (approach plates, enroute charts, STARs, SIDS)
- Turbulence
- Malfunctions
- Vestibular (inner ear) cues
- Kinesthetic cues
- Engine and wind noise
- Control forces

The very general model describing human information processing has been evolved into a specialized divided attention SPIFR workload model by consideration of specific flight activities and piloting tasks.

A review of the SPIFR piloting tasks indicates that they can be broadly categorized as

- Navigation functions involving pilot interaction with the controls and displays, and mental orientation.

- Decision Making
- Copy and Interpret Clearances
- ATC Communications
- Accomplishment of Checklist Items -- Normal and Emergency
- Failure Detection
- Aircraft Systems Management
- Aircraft Control

The functions noted above have led to a more specific divided attention SPIFR workload model as shown in Fig. 2. This model illustrates that the human pilot's primary limitation lies in the fact that he or she is basically a single channel processor and must multiplex or "switch" between the specified tasks. Success or failure in a given task, therefore, depends very strongly on the pilot's ability to properly divide his attention according to the demands of the situation -- hence the need for continuous scanning of the controls and displays which must not only be rapid but efficient. Such efficient scanning is guided by long-term memory. The purpose of recurrent instrument training is to maintain the necessary ingredients in long-term memory for an efficient scan of the displays for a particular aircraft.

Two experiments were conducted to quantify the effects of the divided attention tasks in the Fig. 2 model in terms of overall pilot workload. Experiment I was accomplished in flight, and was designed to represent the highest possible workload in the presence of a fully operational aircraft. In these tests the experimental scenarios were formulated to provide variations in workload due to "Navigation," (Mental Orientation), and "Aircraft Control" tasks.

The second experiment was accomplished on a ground based simulator and was designed to maximize the impact of "Decision Making," "ATC Communications," "Emergency Checklists," and "Aircraft Systems Management" tasks, and to determine the relative contributions of these tasks to SPIFR pilot workload. Such insight was deemed to be valuable in

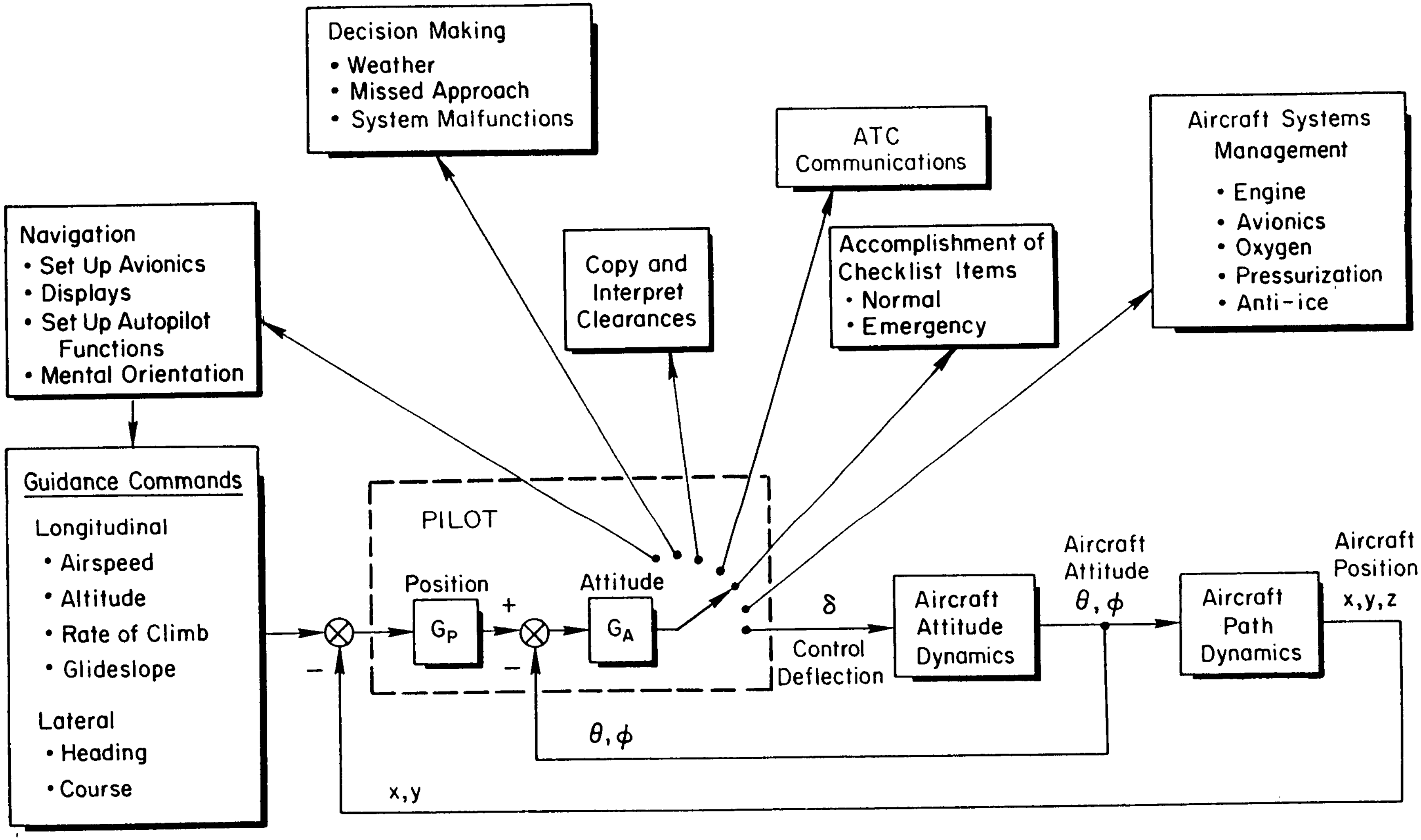


Figure 2. Divided Attention Pilot Workload Model for SPIFR Operation

determining the types of controls and displays that would be most effective for reducing SPIFR workload. Probably the best way to avoid excessive workload during instrument flight operations is to fly with a co-pilot, and to some ways of thinking, a fully rated co-pilot represents the ideal way to accomplish the divided attention tasks in Fig. 2. Flying IFR with a two-pilot crew is universally acknowledged to be significantly easier than flying single pilot. If the best way to avoid excessive workload is to fly with a co-pilot, we posed the question: Which of the activities in Fig. 2 are most important during IFR operations, and how does their presence or absence affect workload? To address this issue, in Experiment II, we treated an expert co-pilot as a component subsystem, and observed the effects of selective degradation in his accomplishment of the Fig. 2 tasks in terms of pilot performance and subjective workload rating scales.

SECTION III

WORKLOAD MEASUREMENT

Both qualitative and quantitative workload measures were used in the experiments. A battery of four subjective workload measurement scales were administered to the subject pilots upon completion of each IFR scenario. These were:

- The Multiple Scale Rating System (MSRS)
- A slightly modified version of the Cooper-Harper Handling Qualities scale (Ref. 3) (CH)
- A workload scale developed and evaluated in Refs. 4 and 5, termed the Modified Cooper-Harper Scale (MCH)
- A Subjective Workload Assessment Technique (SWAT) developed by the Air Force (Refs. 6 through 11)

A brief discussion of each of these scales follows.

A. MULTIPLE SCALE RATING SYSTEM (MSRS)

A multiple scale rating system (MSRS) for pilot workload was developed specifically for this experiment, and is given in Fig. 3. This rating system consists of five separate scales with the adjectives "Excellent," "Good," "Fair," and "Poor." These adjectives were found to be linear in terms of their semantic meanings to a large population of engineer and pilot subjects in Ref. 12. The purpose of the MSRS was to determine the specific components of workload that results in a given overall assessment. A new rating form was issued to the pilot for each rating segment in the experiment. The rationale behind each of the MSRS scales is discussed briefly below.

- Precision -- The evaluation pilot was asked to estimate the precision with which he was able to accomplish the segment of the scenario being rated in terms of pitch and roll attitude, lateral course deviation, and altitude deviations. The standard of performance was to minimize altitude excursions to less than

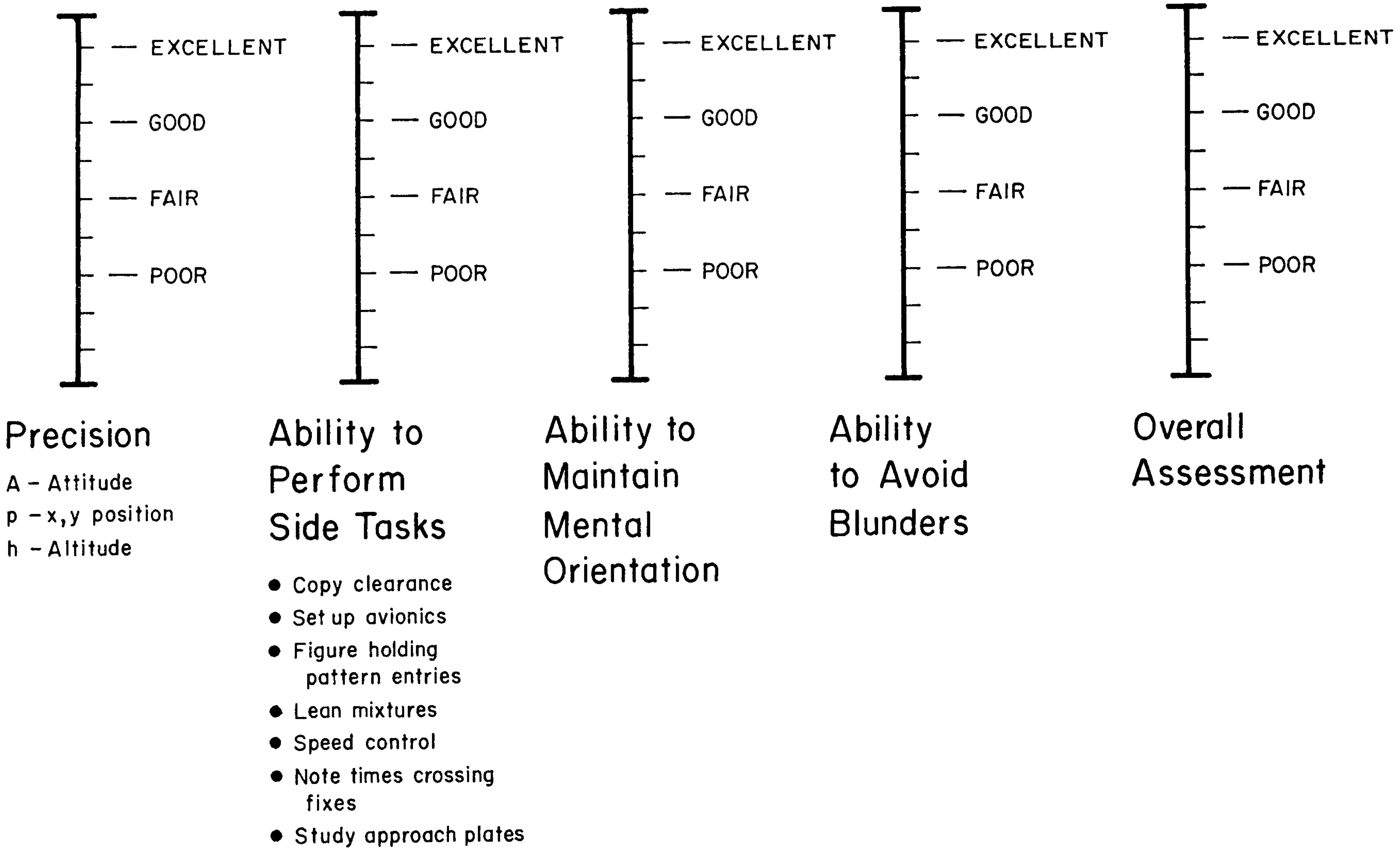


Figure 3. Multiple Scale Rating System (MSRS) For Pilot Workload

100 ft with the exception of minimum descent altitude or decision height, in which case no excursions below the reference altitude were accepted. The course deviation was to be kept within ± 1/3 of full scale, airspeed within ± 5 kt of the reference speed, and bank angle within ± 20 deg of the desired value. The rating was accomplished by simply making three marks on the scale and putting an "A," "P," or "H" to indicate whether it is attitude, position, or altitude that was being rated.

- Ability to perform side tasks -- A number of specific side tasks to be considered are listed below the scale. The pilot was instructed to also consider any additional side tasks such as the emergencies introduced in Experiment II.

- Ability to maintain mental orientation -- The evaluation pilot was asked to rate his ability to continuously maintain his orientation with respect to charted airports, navaids, airways, and intersections. The pilots were briefed that any tendency to turn the wrong way in a holding pattern should be considered as "Poor to Inadequate" on this scale.

- Ability to avoid blunders -- The pilot subjects were asked to identify deficiencies for each control display configuration and to estimate their ability to avoid blunders. In this context, it is entirely possible that a pilot could fly a "perfect mission" and still consider the ability to avoid blunders as poor. In fact, it is not uncommon to perform difficult single pilot IFR tasks, with good accuracy, knowing full well that if any additional tasks were added, or emergencies encountered, the excess workload capacity could exceed 100%. It is the tendency towards this particular phenomenon that we were asking the pilots to rate on this scale.

- Overall assessment -- Here we were asking the pilot's overall opinion of the workload associated with a given segment of a scenario for the control display configuration in question. This scale allowed us to weigh the importance of deficiencies noted on each of the other four scales. For example, if three of the four scales are rated "Good" and the fourth scale is rated "Poor" and the overall assessment is "Poor" it was our understanding that considerable weighting should be placed on the particular deficiency noted on the fourth scale.

B. COOPER-HARPER SCALE (CH)

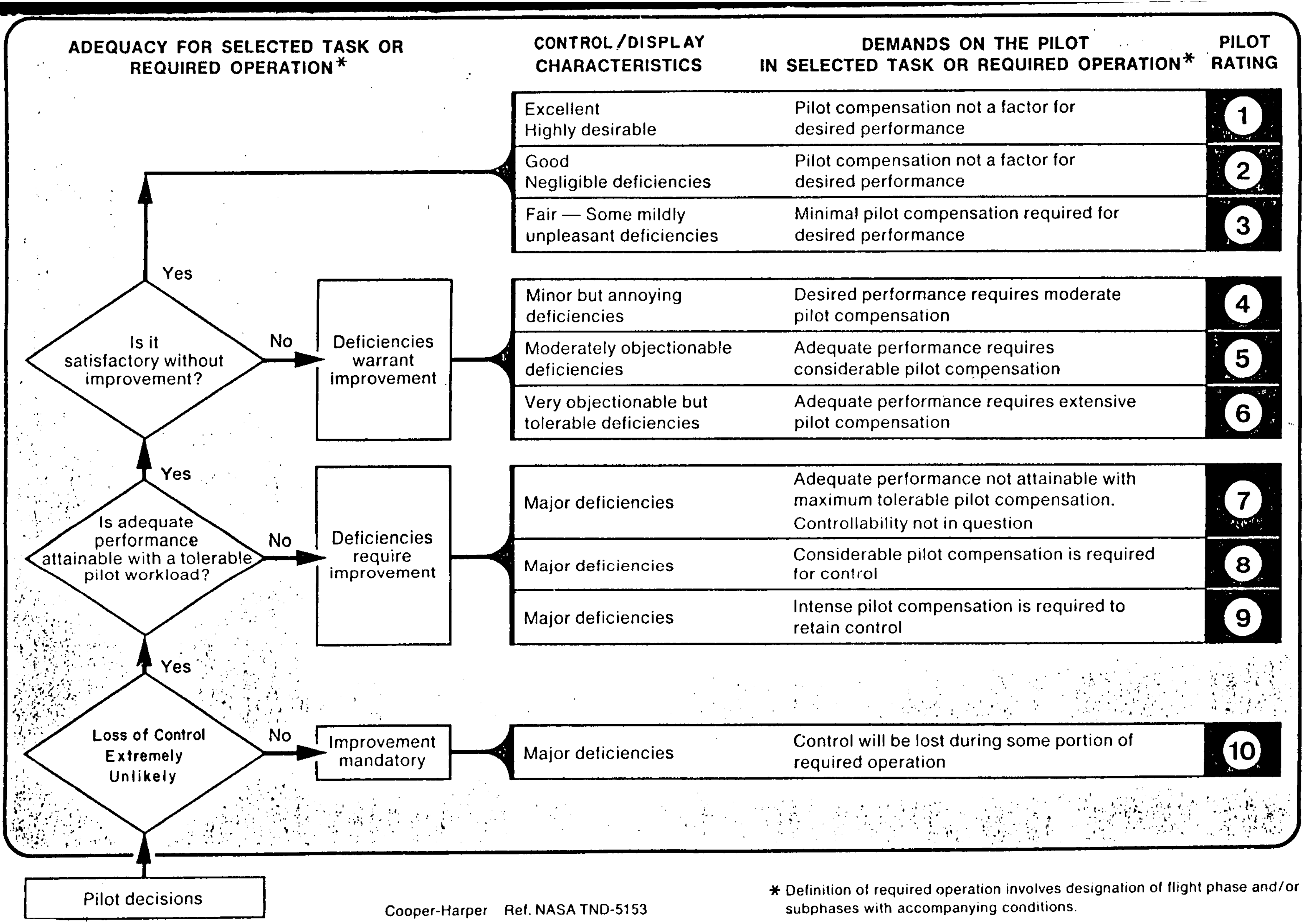
A slightly modified version of the well known Cooper-Harper (CH) scale for handling qualities (Ref. 3) was utilized to make an overall estimate of pilot workload. This scale is known to have meaningful adjectives which can be interpreted in terms of operational requirements. The scale is shown in Fig. 4 where it can be seen that the modifications consist of changing the name from Handling Qualities Rating Scale to Control/Display Rating Scale, revising the question in the lower left corner from, Is it controllable? to Loss of control extremely unlikely, and finally, changing the heading entitled Aircraft Characteristics to Control/Display Characteristics.

C. MODIFIED COOPER-HARPER SCALE (MCH)

This scale utilizes the decision tree format of the Cooper-Harper scale, and employs an identical structure. However, the semantics are entirely different; compare Figs. 4 and 5. The MCH scale was validated in three separate experiments in Ref. 4; a perceptual experiment, a mediational (cognitive) experiment, and a communications experiment. The MCH scale ratings demonstrated a monotonic increase with workload level in Refs. 4 and 5.

D. SUBJECTIVE WORKLOAD ASSESSMENT TECHNIQUE (SWAT)

The SWAT scale has undergone considerable development by the USAF, see for example Refs. 6 through 11. This scale consists of three components of workload; time, effort, and stress. The workload corresponding to each of these components is characterized by three statements, as shown in Fig. 6. As a result, there are 27 combinations of time, mental, and stress load to choose from to represent a particular workload situation. The SWAT procedure requires that each subject perform a sort of 27 cards, each of which contains statements that represents one of the possible combinations of workload. The subjects are asked to sort the cards so that the 27 combinations are rank-ordered to reflect the degree of subjective workload imposed by each. The results of eight



Cooper-Harper Ref. NASA TND-5153

* Definition of required operation involves designation of flight phase and/or subphases with accompanying conditions.

Figure 4. Cooper-Harper Scale (CH) for Control/Display Ratings

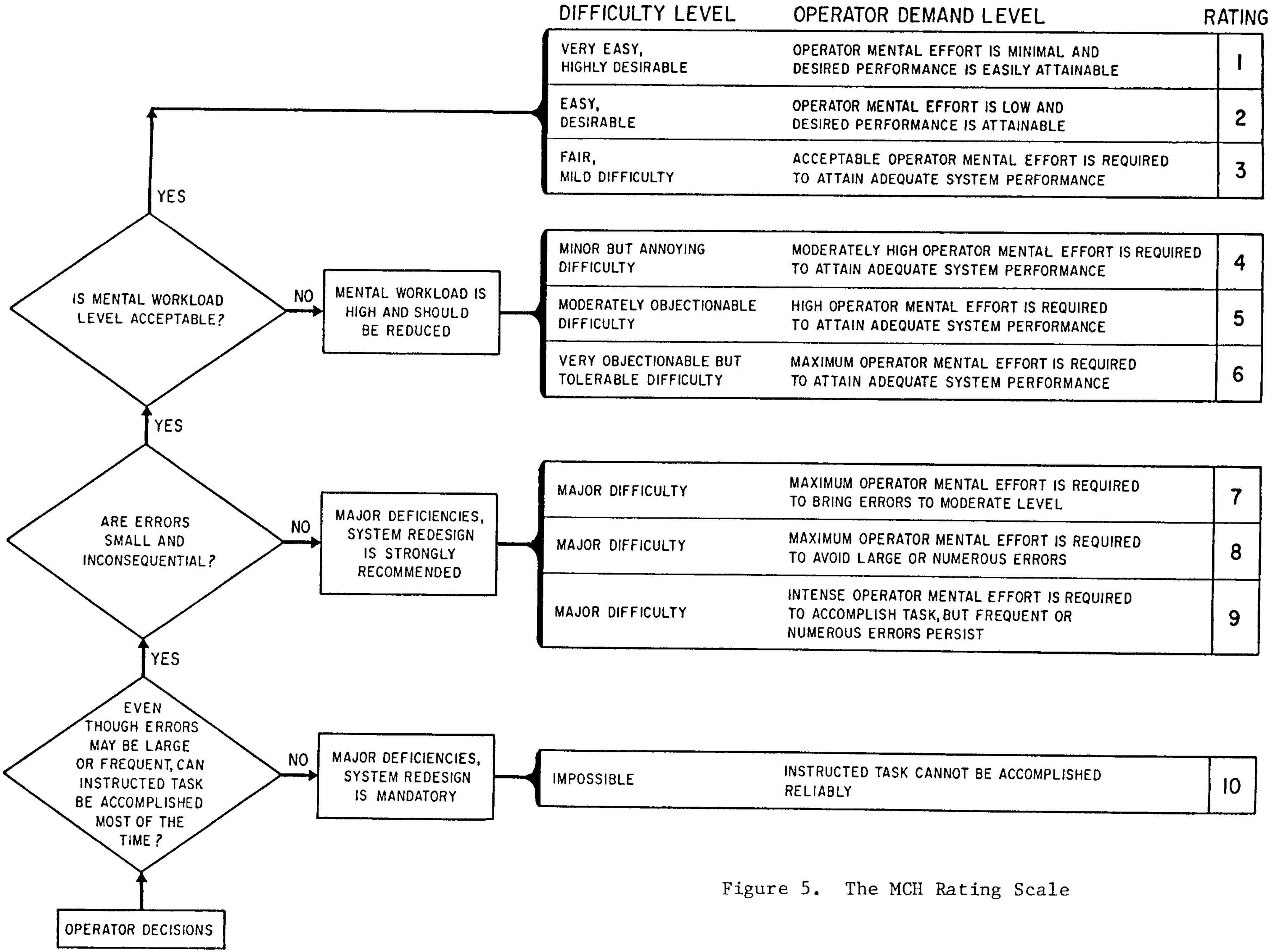


Figure 5. The MCH Rating Scale

I. Time Load

1. Often have spare time. Interruptions or overlap among activities occur infrequently or not at all.
2. Occasionally have spare time. Interruptions or overlap among activities occur frequently.
3. Almost never have spare time. Interruptions or overlap among activities are very frequent, or occur all the time.

II. Mental Effort Load

1. Very little conscious mental effort or concentration required. Activity is almost automatic, requiring little or no attention.
2. Moderate conscious mental effort or concentration required. Complexity of activity is moderately high due to uncertainty, unpredictability, or unfamiliarity. Considerable attention required.
3. Extensive mental effort and concentration are necessary. Very complex activity requiring total attention.

III. Stress Load

1. Little confusion, risk, frustration, or anxiety exists and can be easily accommodated.
2. Moderate stress due to confusion, frustration, or anxiety noticeably adds to workload. Significant compensation is required to maintain adequate performance.
3. High to very intense stress due to confusion, frustration, or anxiety. High to extreme determination and self-control required.

Figure 6. SWAT Scale

card sorts (4 NASA test pilots, and 4 engineers, 2 of which are pilots) indicated that there was significant agreement among subjects (also found in previous experiments, Ref. 8., for example). Therefore, the card sort data from these eight subjects was combined during the SWAT scaling procedure (accomplished by the USAF) to form one overall interval scale of workload with a range of 0 to 100. These results are given in Fig. 7, and are used as the basis for the SWAT data presented in Section IV.

The subjects used in the second experiment, discussed in Section IV, all performed the SWAT card sort, but the data was not utilized in the SWAT scaling procedure. These card sorts were performed to allow the subjects to become familiar with the SWAT statements, and to allow us to uncover any significant anomalies which might occur regarding subject attitudes related to time, mental and stress workload factors. None were observed.

SWAT RATING			WORKLOAD
TIME	MENTAL	STRESS	(0 TO 100)
1	1	1	0.0
1	1	2	23.6
1	1	3	47.5
1	2	1	14.9
1	2	2	38.5
1	2	3	62.4
1	3	1	34.1
1	3	2	57.7
1	3	3	81.6
2	1	1	5.1
2	1	2	28.7
2	1	3	52.6
2	2	1	20.0
2	2	2	43.6
2	2	3	67.5
2	3	1	39.2
2	3	2	62.8
2	3	3	86.7
3	1	1	18.4
3	1	2	41.9
3	1	3	65.9
3	2	1	33.2
3	2	2	56.8
3	2	3	80.8
3	3	1	52.5
3	3	2	76.0
3	3	3	100.0

Figure 7. SWAT Workload Results
(for 8 subjects)

SECTION IV

EXPERIMENTAL DETERMINATION OF SINGLE PILOT IFR WORKLOAD

Two experiments were conducted; the first to determine the effect of existing controls and displays on workload, and the second to investigate fundamental requirements for future cockpits. The first experiment (conducted in two phases) was accomplished at the NASA Langley Research Center using actual aircraft with different control/display combinations ranging from simple dual VOR to a moving map display. These tests involved several high workload scenarios, but did not include the effects of failures. The second experiment utilized a ground based training simulation of a current turboprop aircraft, which is representative of the most complex aircraft utilized for single pilot operations. Failures were simulated in this already high workload environment to maximize the necessity for divided attention operation. In some cases, a co-pilot was added whose allowable functions were systematically varied to determine which functions are of greatest value, and hence, should be artificially reproduced in the ideal SPIFR cockpit. The details and results of these experiments are discussed below.

A. EXPERIMENT I: EFFECT OF CONTROLS AND DISPLAYS ON PILOT WORKLOAD

1. Overview of Experiment I

The following overview is given to set the stage for the results presented in the following section (A.2), and additional details of the experiment are presented in Appendix B.

a. Purpose

Flight tests were conducted at the NASA Langley Research Center to evaluate pilot interaction with a variety of navigation controls and displays. The flights also took advantage of the availability of the NASA Langley Cessna 402B equipped with the Digital Advanced Avionics System (DAAS) research avionics system. The DAAS (Ref. 13) included a

CRT-based moving map display of area navigation information, and permitted evaluation of pilot interface with a sophisticated navigation display.

b. Equipment

Three aircraft and four control/display configurations were used for the flight tests. A Cessna 310 with a state-of-the-art VOR/DME based area navigation (RNAV) system represented the low to medium levels of navigation system capability. The cockpit included a horizontal situation indicator (HSI), a second VOR course deviation indicator (CDI), a remote magnetic indicator (RMI) with VOR and ADF bearing pointers, and dual DME displays. The navigation capability levels tested in this aircraft were dual VOR without DME, dual VOR and DME, and RNAV. For the lower levels of capability, certain displays, such as the RMI and DME, were covered. The second aircraft, the Cessna 402B, was equipped with the DAAS moving map display (see Ref. 13) and provided the highest level of navigation display tested. The third aircraft was a Beech Queen Air equipped with a typical executive aircraft instrument panel including an HSI, RMI, and dual DME. During the initial tests, the Cessna 310 was flown with a very simplified instrument panel with dual VOR and no HSI.

c. Scenarios

Realistic general aviation operation scenarios were used, with emphasis on the high workload terminal area phase of flight. Figures 8 through 10 show the details. Scenario A-1 consisted of departure from Langley to the Harcum 134 radial, BAZOO intersection, Norfolk. A holding pattern was entered at Norfolk, where pilot workload ratings (MSRS, CH, and SWAT) and comments were gathered. The second segment (Scenario A-2) consisted of flying to RIPPS intersection, where a back course approach to Patrick Henry (PHF) airport was initiated. The back course approach was flown at altitudes above the PHF airport traffic area, to reduce interference with other traffic and to permit the back course to be flown when the front course approach was in use. The scenario was completed after the approach at PHF and a second pilot rating form was completed.

Scenario A1 - LFI to hold at Norfolk VOR
Scenario A2 - Norfolk VOR to complete
PHF back course approach

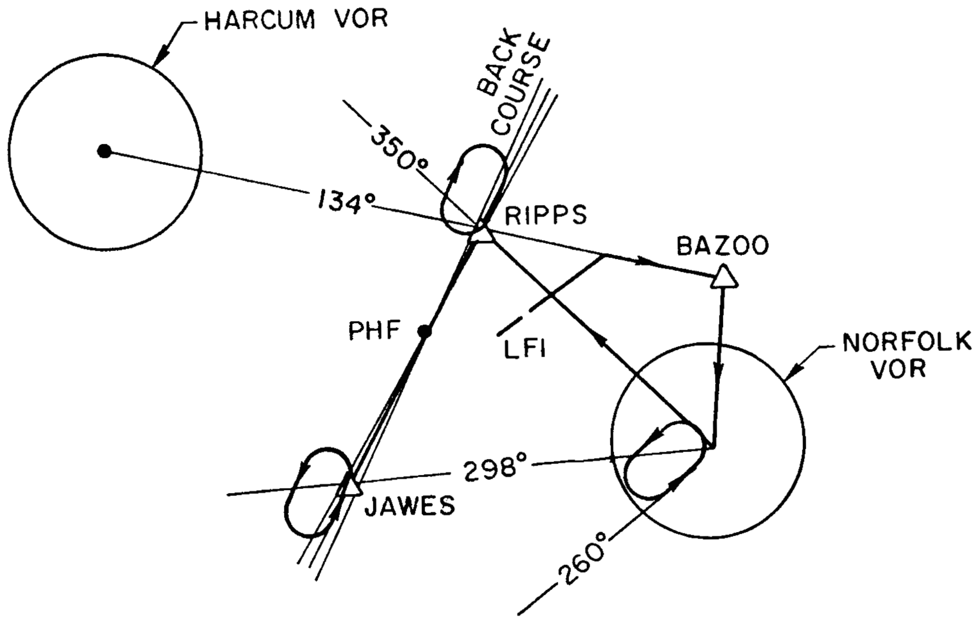
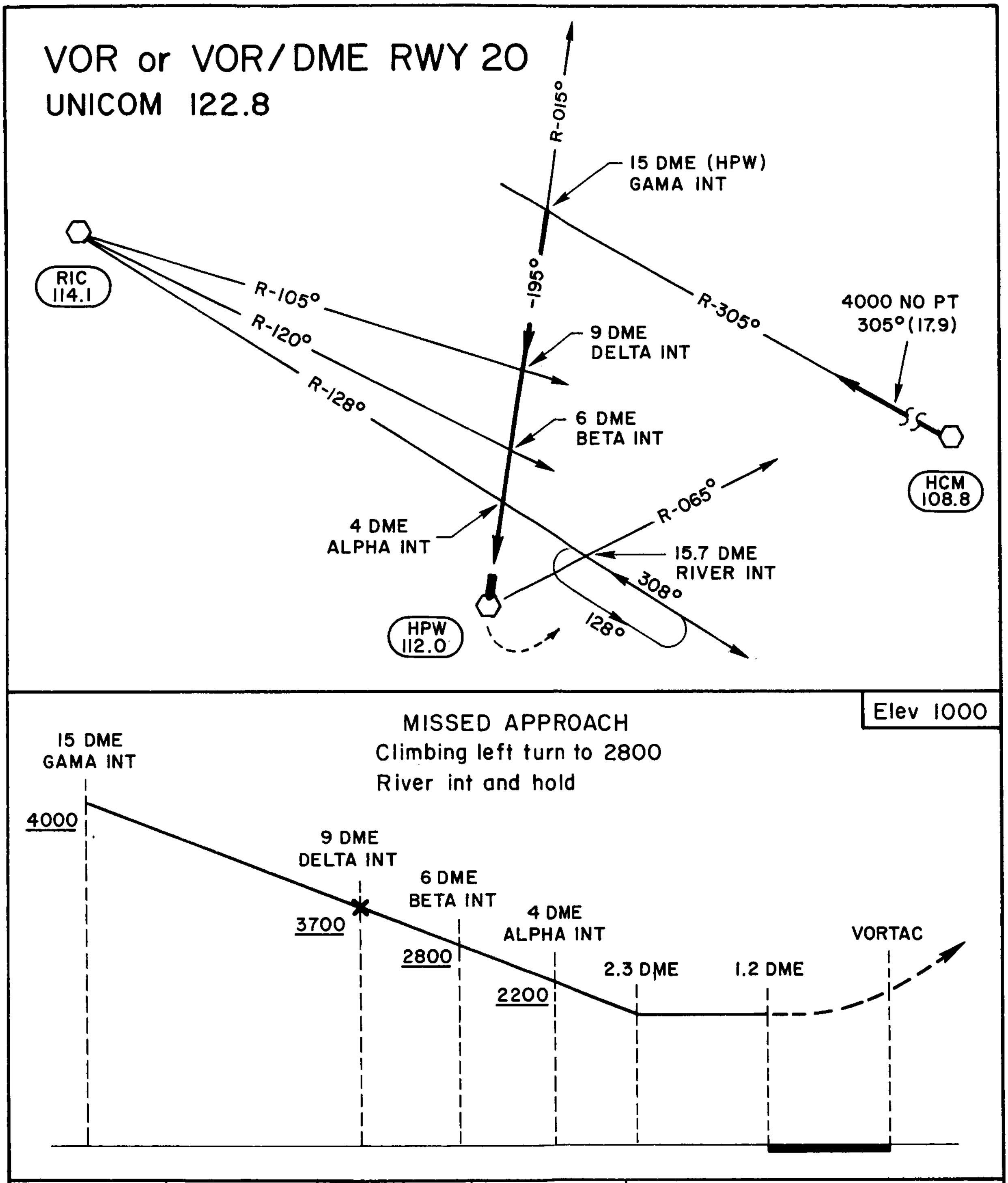


Figure 8. Scenarios A1 and A2

Scenario D1 consisted of a flight to Harcum VORTAC, and then an approach to a fictional airport at the Hopewell VORTAC (see Fig. 9). After the missed approach and holding pattern entry, a pilot rating form was completed. The Hopewell approach was then repeated with the DME turned off, and a second set of subjective pilot ratings was obtained gathered. In one of the data flights, the second approach was an ILS approach returning to Langley Air Force Base. Scenario D2 began the same as D1, except that after the first approach at Hopewell, an RNAV approach to the Gloucester, Virginia airport was flown (Fig. 10). The second pilot rating form was completed after the missed approach at Gloucester. Neither the Hopewell nor Gloucester approaches are FAA established or approved approaches, but were contrived for these flight tests, which were flown only under visual flight rules (VFR). Radar traffic advisories were utilized where available, but all approaches



CATEGORY	A	B	C	D
With DME	1700-1			
Without DME	1700-1 1/2			

FAF TO MAP 7.8 NM				
knots	90	100	110	120
min : sec	5:12	4:41	4:30	3:54

Figure 9. VOR/VOR and VOR/DME Approaches Used for Scenario D1

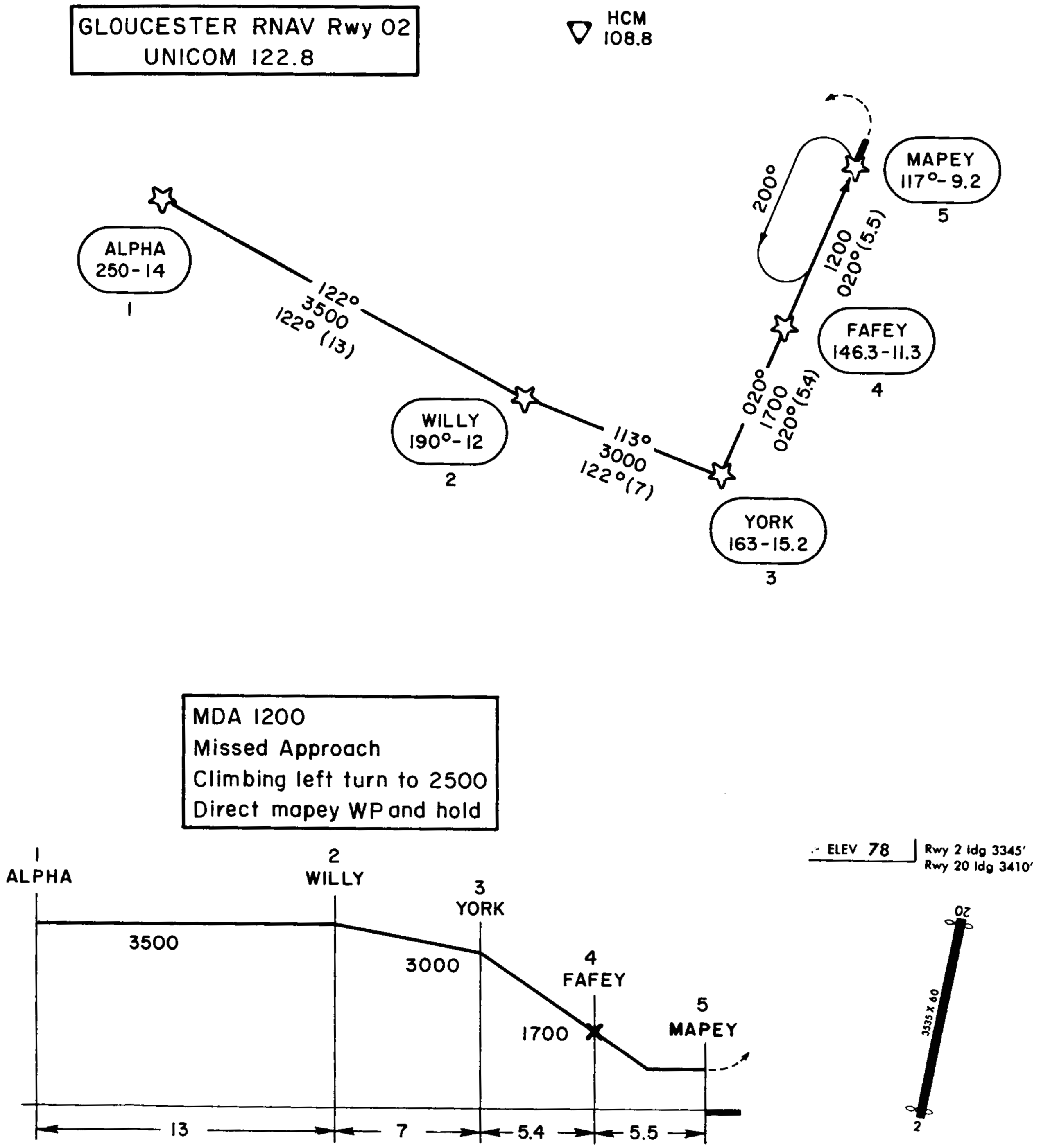


Figure 10. RNAV Approach Used for Scenario D2

were flown without the assistance of radar vectors to the final approach course.

The pilot ratings gathered included the subjective workload assessment technique (SWAT) rating, a Cooper-Harper rating (CH), and the multiple workload scale (MSRS). These subjective workload measures are described in detail in Section III.

In order to better determine differences in the pilot interface with the various displays, the overall pilot workload was intentionally increased by not allowing use of the aircraft autopilot and by requiring the pilot to wear an outside view restricting hood. An effort was also made to fly on days with atmospheric turbulence, but with little success.

A summary of the pilot ratings to be discussed below, are shown in Tables 1 and 2. The left column in Tables 1 and 2 are the rating scales discussed in Section III and the first five items are the elements of the MSRS scale (Fig. 3).

2. Results of Experiment I - Effect of Display Sophistication

a. Subjective Pilot Workload Rating Scale Results

The experimental results are summarized in Figs. 11 through 14 in terms of the subjective pilot workload rating scales discussed in Section III. The Multiple Scale Rating System (MSRS) results shown in Fig. 11 are based on an average over three pilots flying each of the scenarios noted below each display configuration in Figs. 11 through 14. These results indicate that the use of dual VOR without a DME is marginal in terms of pilot workload. That is, the variability is high, with some ratings in the "poor" category, and the average ratings fall in the "good to fair" range. Addition of DME shows improvement, but the variability is high enough to raise concern. The RNAV ratings indicate substantially less variability, even though the RNAV approach (Fig. 10) is identical in form to the VOR/DME approach in Fig. 9. This can be "explained" by plotting the pilot ratings only for approaches (see Fig. 12), wherein the ratings and rating variability are similar for

TABLE 1. PILOT RATING DATA -- CONVENTIONAL DISPLAYS

SCENARIO	A_1	A_2	A_1	A_2	D_1	D_1	D_2
DISPLAY	VOR/VOR	VOR/VOR	VOR/DME	VOR/DME	VOR/VOR	VOR/DME	RNAV
Precision							
P	70	60	60	60	60	60, 80R	80
W			70	71	70, 73R	91	91
Y			60	50	30	70, 70R	60
Sidetasks							
P	60	74	78	70	73	73, 75R	80
W			71	55	70, 90R	91	70
Y			65	60	50	70, 80R	70
Orientation							
P	75	78	78	80	80	80, 90R	80
W			71	73	70, 91R	91	73
Y			80	78	60	70, 80R	70
Blunders							
P	70	73	80	80	70	80, 85R	73
W			72	70	90, 90R	91	71
Y			70	50	31	70, 70R	80
Overall							
P	70	74	75	70	70	80, 80R	77
W			73	72	70, 90R	91	71
Y			60	60	40	70, 80R	70
SWAT							
P	0	0	20	20	35	20, 0R	0
W			0	41	25.2, 5.2R	25	20
Y			0	56	56	46, 0R	46
CH							
P	3	3	3	2-1/2	4	3-1/2, 3R	3
W			2	4	2, 2R	2	2
Y			5	5	6	4, 3R	4

*Note - R after rating denotes a repeat run.
P, W, and Y were the three pilot subjects.

TABLE 2. PILOT RATING DATA -- MOVING MAP DISPLAY

	A_1	A_2	D_1	D_2
Precision				
P	73	55	60	64
W	71	71		72
Y	70	70	70	80
Sidetasks				
P	74	75	60	80
W	71	95		70
Y	70	80	80	80
Orientation				
P	72	90	80	80
W	91	95		75
Y	80	90	90	80
Blunders				
P	72	86	70	70
W	71	74		75
Y	70	50	70	71
Overall				
P	72	86	70	72
W	75	75		74
Y	80	80	69	80
SWAT				
P	20	0	0	0
W	0	20		20
Y	21	21	0	0
CH				
P	2	2	3	3
W	2	2		2
Y	3	3	3	3

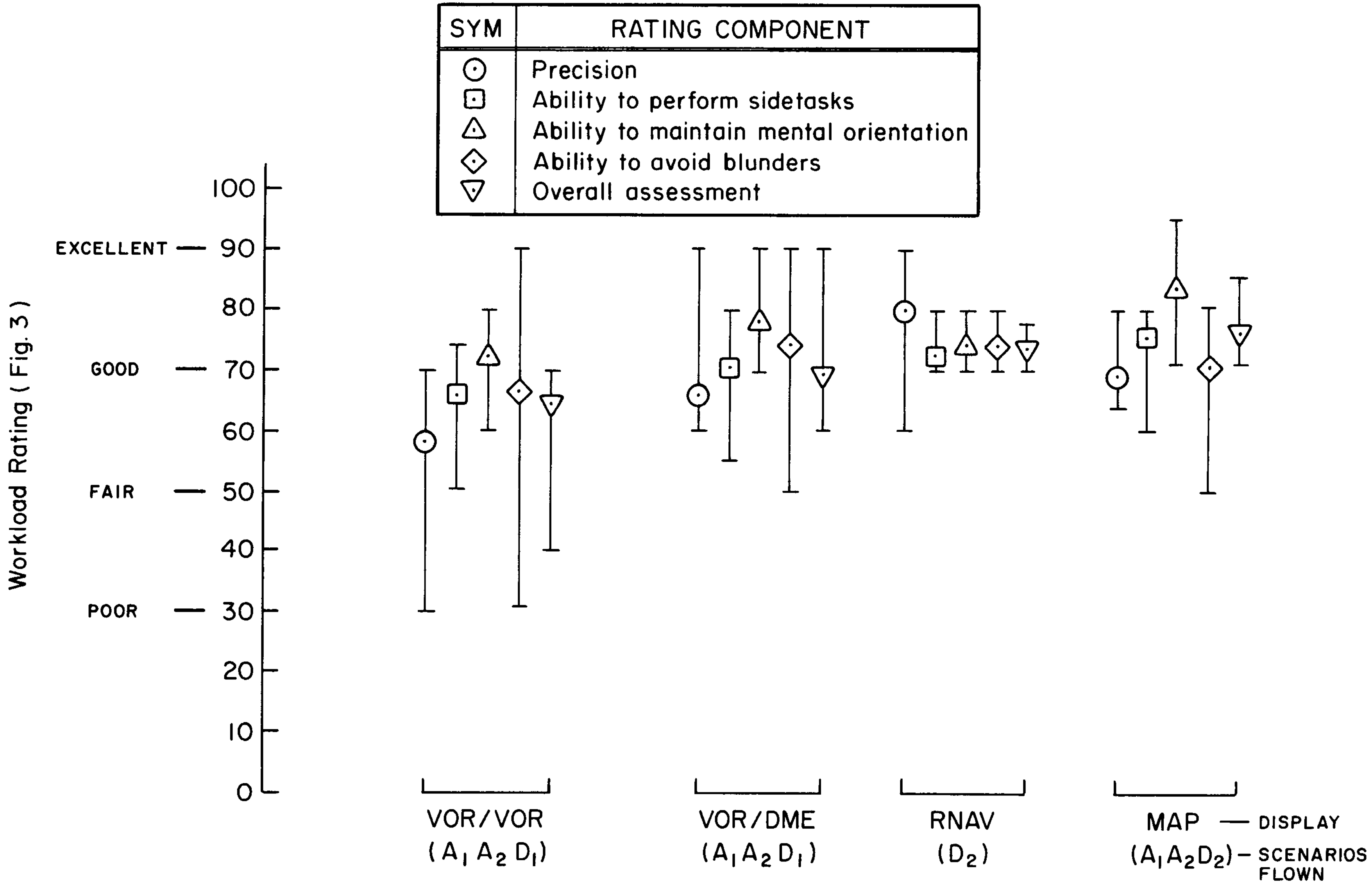


Figure 11. MSRS Results for Terminal Area Operations and Approaches

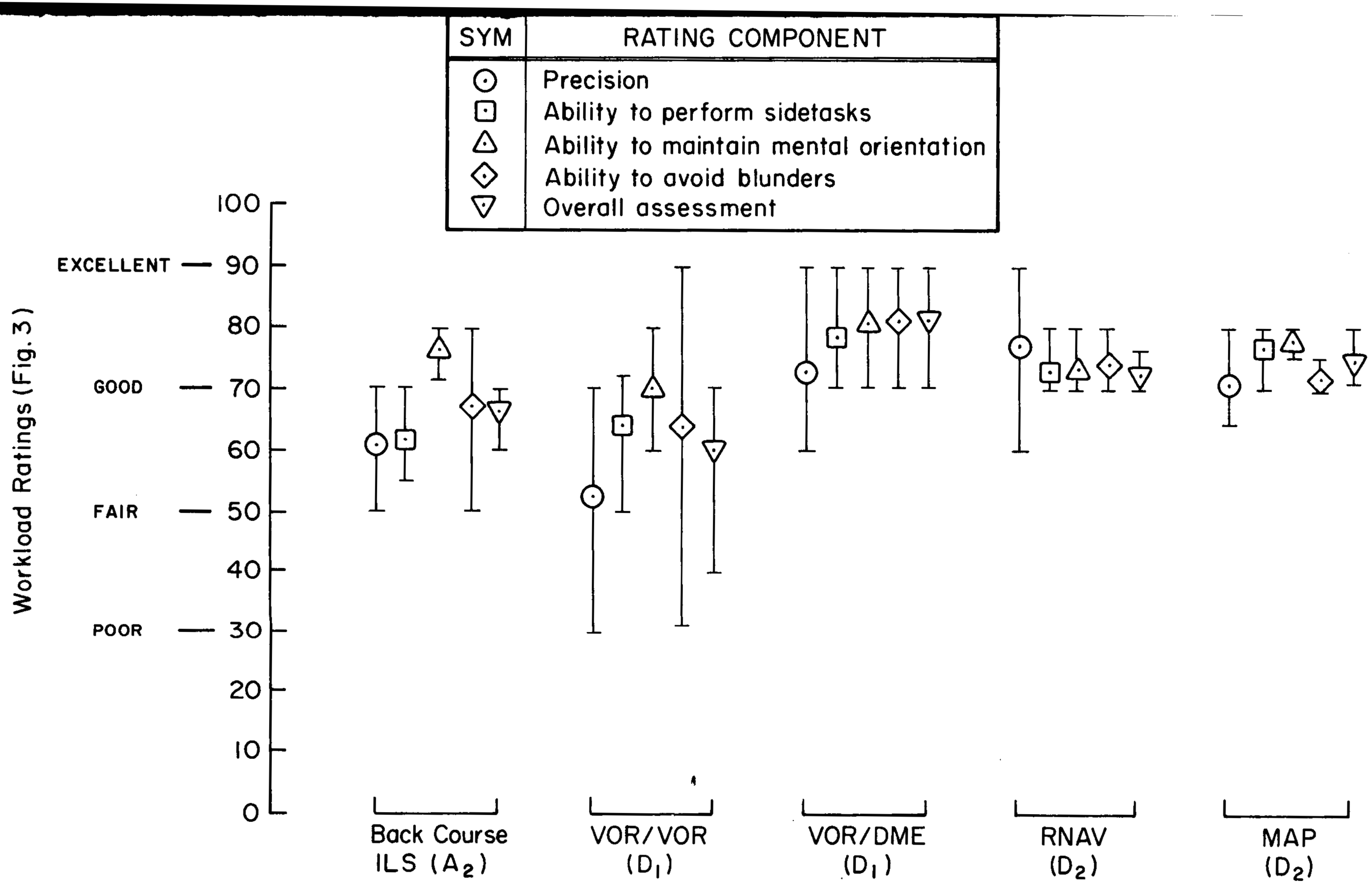


Figure 12. MSRS Results for Instrument Approaches Only

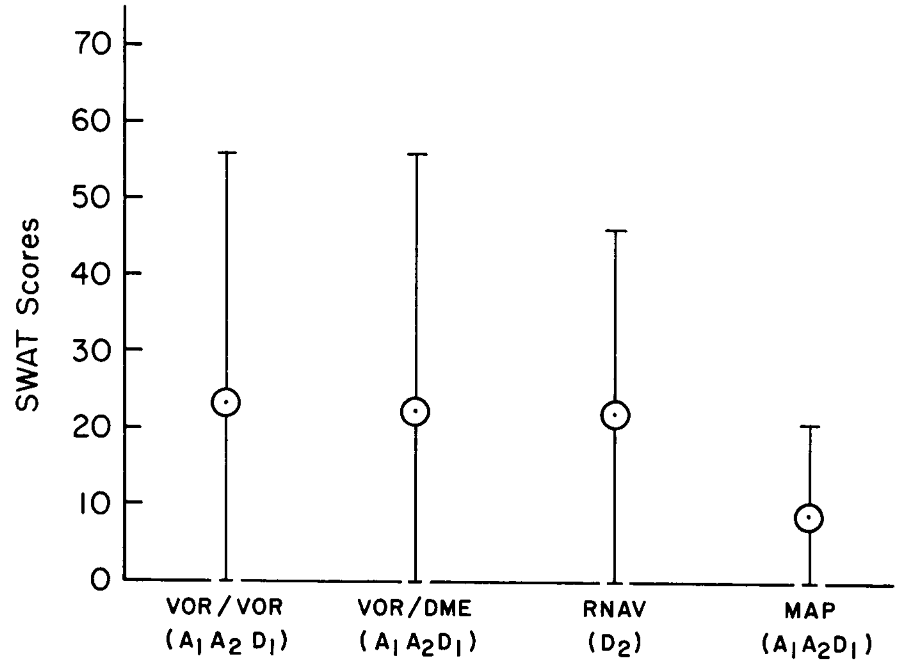


Figure 13. SWAT Scores

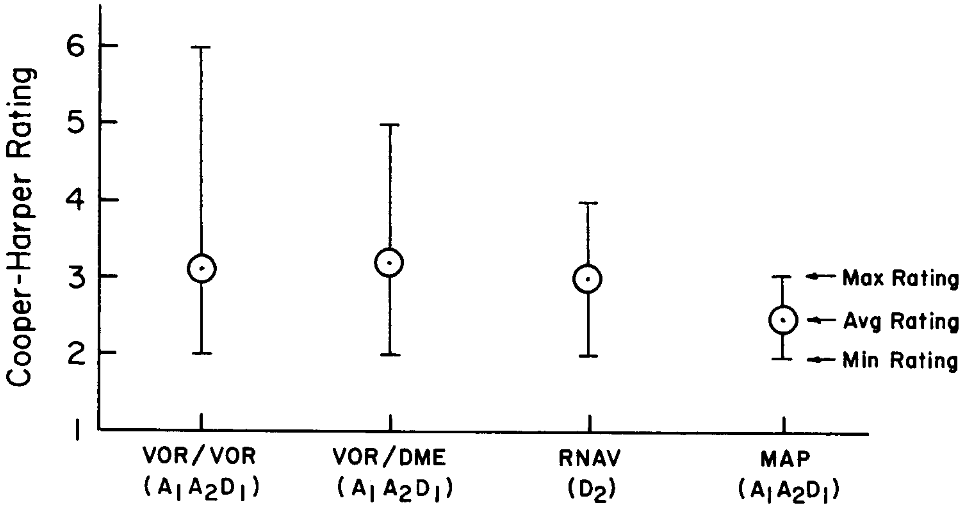


Figure 14. Cooper-Harper Pilot Ratings

VOR/DME and RNAV as one would expect. Apparently, the RNAV is slightly better than VOR/DME for terminal area navigation. The overall results for the moving map display indicate that it is about the same as VOR/DME and RNAV in terms of subjective pilot workload assessment on the MSRS scale. The fair rating given on the "ability to avoid blunders" (Fig. 11) is due to a tendency to tunnel in on the map, forgetting to control aircraft attitude. This result was also noted on a previous study which compared an HSI to a moving map display (Ref. 14).

The moving map display showed less variability and a slightly improved average score in terms of the SWAT and Cooper-Harper ratings in Figs. 13 and 14. The average ratings indicate that all of the tested displays were about the same in terms of these metrics, and that all were acceptable. However, the more sophisticated displays showed considerably more consistency (lower variability) which is a key consideration for minimizing pilot errors.

In the following subsection, we review the pilot errors that occurred, and the pilots' ability to detect such errors before they became critical to the safety of the flight.

b. Pilot Errors and Error Detection

During the course of the experiment, many opportunities for navigation system input errors by the pilot were present. Most of the errors that actually occurred in these flights involved either entering incorrect data for a waypoint, or placing the navigation system in a mode different than the mode intended. As an example of the first error, while preparing for the approach at Hopewell, the pilot entered the data for waypoint GAMA (Fig. 9). He correctly entered the radial and distance information, but inadvertently entered the radio frequency for Harcum VORTAC rather than the Hopewell VORTAC. An example of a navigation mode selection error occurred when the pilot was flying toward an RNAV waypoint, but the navigation system (KNS 80) had been placed in the VOR mode. This had the effect of guiding the aircraft to the VORTAC rather than to the desired waypoint.

In previous studies, this type of input error has been associated with high pilot workload. In these flights, however, the same type of errors were observed during periods of very low workload. In particular, one of the waypoint entry errors was made during low workload enroute cruise, and moments later the pilot made an unsolicited comment about having very low workload. Such errors are characteristic of the linear operator, and are a well known phenomenon amongst air traffic controllers. That is, there is a tendency for errors to occur during periods of light traffic. The phenomenon is discussed in further detail in Ref. 15.

A few errors appeared to be associated with using an RNAV system to fly VOR approaches. An RNAV approach chart shows, next to each waypoint, the correct station frequency, radial, and distance for that waypoint. The chart for a VOR approach does not use that format for the various points in the approach. For example, the Hopewell approach chart shows the GAMA waypoint on the Hopewell 015 degree radial at 15 miles, but the pilot must scan the chart to assemble that information. Since the final approach course of 195° was depicted near waypoint GAMA, that number could, and in fact was, inadvertently entered as the radial that GAMA resides on. This suggests that using an RNAV system to define waypoints on a VOR or VOR/DME approach results in a risk of mislocating waypoints or of defining a waypoint with reference to a navigation facility that is not approved for the approach.

The pilots tended to quickly detect and correct input errors during these flights. Most errors were detected when instrument indications did not agree with pilot expectations. The pilots appeared to be cross-checking instrument indications against both expected indications (based on aircraft position), and for agreement with other navigation instrument indications. An example of the first cross-check occurred during the error described above, where the pilot defined waypoint GAMA referenced to Harcum VORTAC rather than Hopewell VORTAC. While flying between Harcum and GAMA on the Harcum 305 radial, the pilot activated the GAMA waypoint. The course deviation needle would normally have remained centered, but showed a full scale error due to the waypoint mislocation. This alerted the pilot to recheck the data, and the error was quickly corrected.

This method of error detection has numerous implications. One is that less experienced pilots, who might be following instrument indications without a good mental picture of the aircraft location, may not have detected many of the errors. Another implication is that when the aircraft situation, or instrument approach design, is such that an input error does not cause an obvious change in instrument indications, the error may not be detected. Two examples of this occurred during the flights. In one case, the aircraft was flying toward an RNAV waypoint. The waypoint was located approximately on a line between the aircraft and the navigation facility that defined the waypoint. The navigation system should have been in the RNAV mode, but had inadvertently been placed in the VOR mode. This had the effect of moving the waypoint farther from the airplane, toward the VORTAC. Because the aircraft and the waypoint were both on a VORTAC radial, this error did not affect the displayed course deviation. The pilot eventually noticed that the wrong mode was selected, but the aircraft had already flown 4 miles past the waypoint. In the second case, the aircraft was flying from one VORTAC towards a second VORTAC, on a route that leads to an ILS localizer intercept. Radials from the second VORTAC were used to identify fixes on the ILS approach. The pilot intercepted the localizer with the navigation receiver still tuned to the station behind the aircraft, with the pilot believing that the station in front of the aircraft had been selected. Since the aircraft was flying on a line between the VORTAC stations, the CDI behaved as expected prior to localizer intercept. The error was detected after intercept when the CDI needle did not move in the expected direction.

c. Pilot Comments

Many of the pilot comments focused on the relative advantages between using VOR/VOR, VOR/DME, and moving map display of aircraft position. The VOR/VOR navigation mode was generally the most difficult. The pilots indicated that they missed the DME when it was removed.

Reasons cited were that VOR/DME provides a point in space while VOR/VOR only gives you lines of position, and that DME helps solve timing problems on approach. One pilot stated that with VOR/VOR, judging distances is much more difficult and the pilot must be more aware of time/distance relationships. Another stated that with VOR/VOR, the pilot must "think and tune too much" during flight. When the VOR/DME mode was used, comments indicated that the DME cut the workload during the approach.

Comments on the moving map display were very favorable. Pilots commented that holding patterns were very easy with the map. When each pilot filled out rating forms in flight, they were relieved of piloting duties for several minutes by the safety pilot, usually in a holding pattern. One pilot indicated that after completing a rating form, it was much easier to assess the navigational situation and "get back in the loop" when the map display was used than when the conventional instruments were used. Enroute, the comments indicated that good positional awareness could be achieved from the map, and that a great deal of precision was not needed. Other comments indicated that overall workload could be lowest with the map, if the interface with avionics were simpler than it was with this research system. A few comments indicated greater difficulty in holding wind correction angles with the map than with the HSI. This may be due to details in the format of the map tested. Other comments indicate that the map is a very compelling display, and that there is a tendency to drop other, essential instruments from the pilot's scan. The need for pilots to adapt to the map was brought out by a comment that even though workload was lower with the map than with the "round dial" instruments, the pilot felt more comfortable with the round dial instruments. To put the contribution of a map display in the perspective of reducing overall pilot workload, one comment stated that if he were to improve a basic avionics suite, he would add a wing leveler autopilot before adding a moving map display. Numerous comments were received to indicate that the need to continuously fly the aircraft was a major contributor to the workload. The effects of adding autopilot functions are discussed in subsection IV.A.3 below.

d. Summary of the Effect of Display Sophistication

The pilots performed well with all navigation modes tested, but the results indicate that the navigation task is more comfortable and less error prone when HSI/DME/RMI information is presented, compared to elementary VOR/VOR data. A moving map displayed further enhanced positional awareness. The pilots frequently detected errors in avionics setup when instrument indications conflicted with expectations. Fewer errors were caught by routine verification of avionics settings. The results suggest that these errors in navigation avionics setup will be made during both low and high workload conditions. Pilot comments also suggest that a large reduction in workload could be achieved through the use of a simple autopilot.

e. Practical Considerations For the Design of Conventional Displays

Experiment I was conducted at NASA Langley in two phases. The previous results refer to the second phase wherein a modern state-of-the-art instrument panel was installed in the Cessna 310 aircraft. The displays used during the first phase were older and had some specific deficiencies, as well as advantages, which led to several interesting observations. The pilots indicated that the simplicity of some displays was especially desirable. In particular, the pilots liked the following items on the early Cesna 310 instrument panel (see Apppendix B).

- The navigation frequencies appeared on the VOR instrument faces.
- The frequency control knobs were on the instruments. Therefore they were faster to tune than the more sophisticated system where the frequency selection for all navigation and communication was centralized in a remote location.
- Both course deviation indicators were close to the basic T and were easy to include in the instrument scan.

Specific pilot/system interface characteristics on the Beech Queenair panel (See Appendix B) that proved undesirable for SPIFR operations during the Phase 1 flight test experiments are summarized below.

- The use of the HSI and RMI combination allowed the pilot to put the output of NAV1 or NAV2 on the HSI or to put NAV2, or the ADF output on the RMI needles. Such flexibility may be highly valuable in multi pilot situation. However, in a single pilot IFR environment, the loss of simplicity with such a system tended to outweigh the advantages accrued by the flexibility of routing navigation signals to various displays.
- Centralized Keyboard selection of communications and navigation frequencies was considered to be slow and attention demanding.
- Communication frequency displays, which were located next to the navigation frequencies on the central panel, required visual selection and time to read, monitor, and check.
- The length of the light bar on the electronic course deviation indicator (ECDI) was not as easy to interpret as a mechanical needle.
- The digital readout of course on the Electronic Course Deviation Indicator (ECDI) was not considered to be nearly as good as the 360 deg analog omni bearing selector. Slew switches used to select headings and courses were found to be extremely undesirable, and in fact, the slew switch on this particular HSI made it less desirable than the basic CDIs on the Cessna 310.

f. Pilot Interface With Controls and Displays

During the course of Experiment I, it became apparent that the operation and interpretation of "sophisticated" controls and displays was an overridingly important component of pilot workload. This point was especially reinforced during a general debriefing held after completion of the flight test experiments wherein the pilots indicated that simplicity was especially desirable in the SPIFR environment.

Figure 15 represents an intuitive interpretation of the general results obtained in this control/display experiment. Curve A in Fig. 15 represents the fact that the workload due to mental orientation and side task performance generally decreases with increasing control/display sophistication. However, the workload associated with pilot operation and interpretation of the controls and displays increases rapidly when the interface with the pilot becomes complex. This is represented by Curve B in Fig. 15. The total workload can (and did in some cases) actually increase with more sophisticated controls and displays. This is especially critical in the single pilot environment where a co-pilot is not available to operate the more complicated control/display configurations. Hence, the assertion that the primary challenge facing designers of controls and displays for aircraft being used in the single pilot IFR environment is to improve pilot interface characteristics so that Curve B in Fig. 15 represents a negligible component of the overall pilot workload. The current state of the art in electronics is such that it has outpaced, by a considerable margin, the ability to present the information to the pilot in a simple way. The message is clear; the pilot in a single pilot IFR environment does not have time to be a computer programmer.

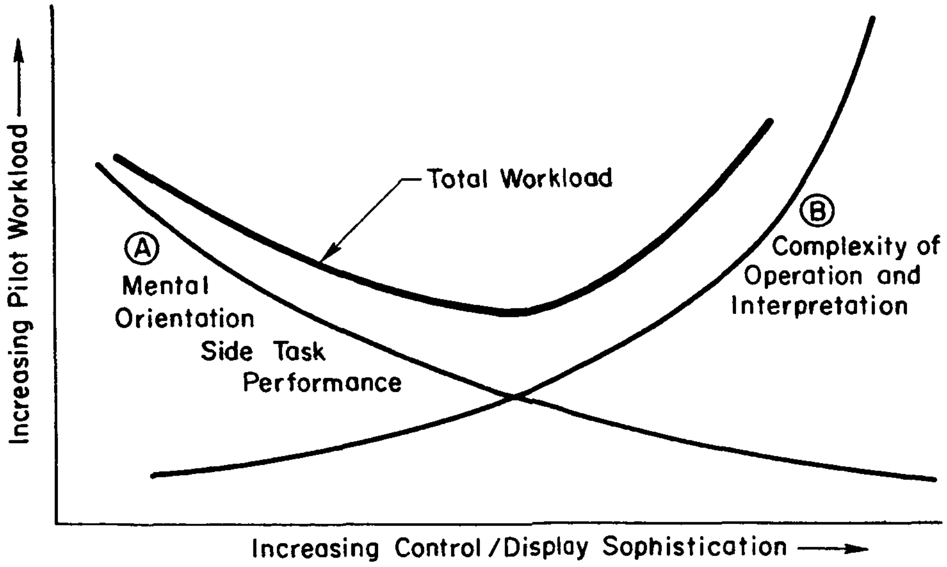


Figure 15. Illustration of the Tradeoff Between Mental Orientation and Side Task Performance and System Complexity

3. Results of Experiment I -- Effect of Autopilot Sophistication

The autopilot experiments were conducted during the Phase 1 flight testing discussed at the end of the previous section, and as a result, the autopilot evaluations were conducted in the presence of a somewhat degraded display format, i.e., the new Cessna 310 panel (Appendix B) was not available. However, the addition of an autopilot was found to more than compensate for this degradation. The general improvement in the Cooper-Harper pilot ratings with increasing autopilot sophistication is shown in Fig. 16 for 2 different display configurations. In general, increasing the autopilot sophistication resulted in an improved rating for each of the workload components as shown in Fig. 17.* One notable exception was "blunder avoidance" which was actually degraded in some cases as shown in Fig. 17. The tendency towards pilot error when using an autopilot did not seem particularly related to any specific display combination. For example, the Figs. 17 and 18 control/display configurations were identical with the exception that the pilot was allowed to use the DME and RMI in Fig. 18. It seems highly unlikely that the addition of a DME or RMI display would induce errors. In fact, the errors that occurred were more related to manipulation and interpretation of the autopilot controls. Some of these blunders are summarized as follows.

- Altitude Hold -- The pilot engaged the altitude hold mode when reaching the minimum descent altitude on a back course approach. However, he became absorbed in timing the approach, checking localizer deviation, and other cockpit duties and did not add power. As a result the autopilot attempted to hold altitude using pitch attitude resulting in a loss in airspeed. The pilot noticed the error as the airspeed passed through

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*The form of the multiple scale rating system (MSRS) was revised during the Phase 1 and Phase 2 flight tests. The primary differences between the Fig. 3 scale and that used in Phase 1 are, 1) the increments have been changed from 5 to 10 and, 2) the best ratings were changed from low numbers to high numbers. The basic results in terms of the adjectives "excellent, good, and fair" are felt to be unchanged.

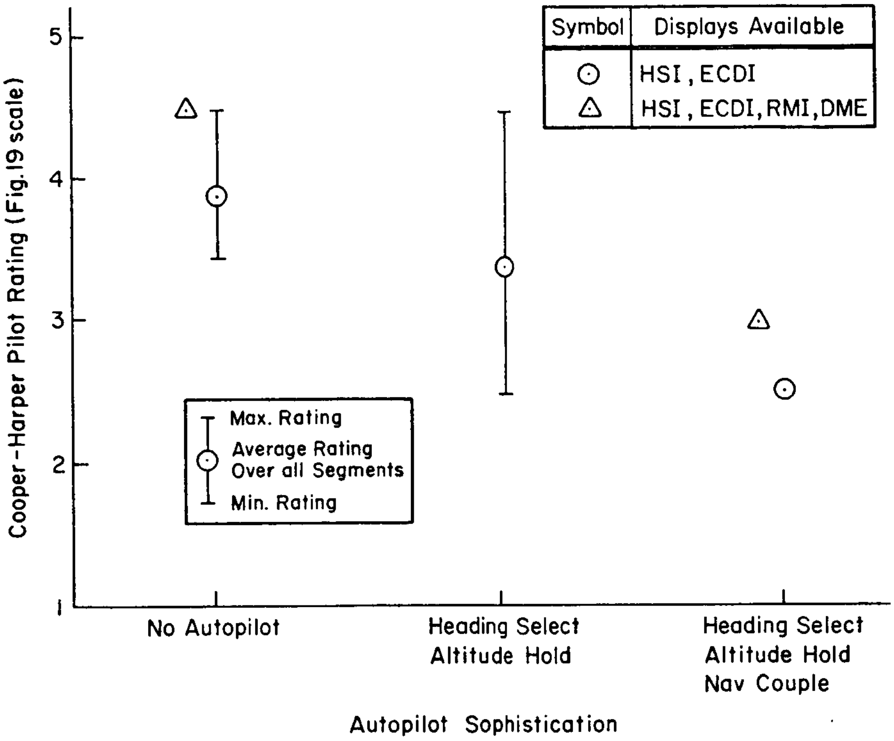


Figure 16. Effect of Increasing Autopilot Sophistication on Cooper-Harper Scale Rating

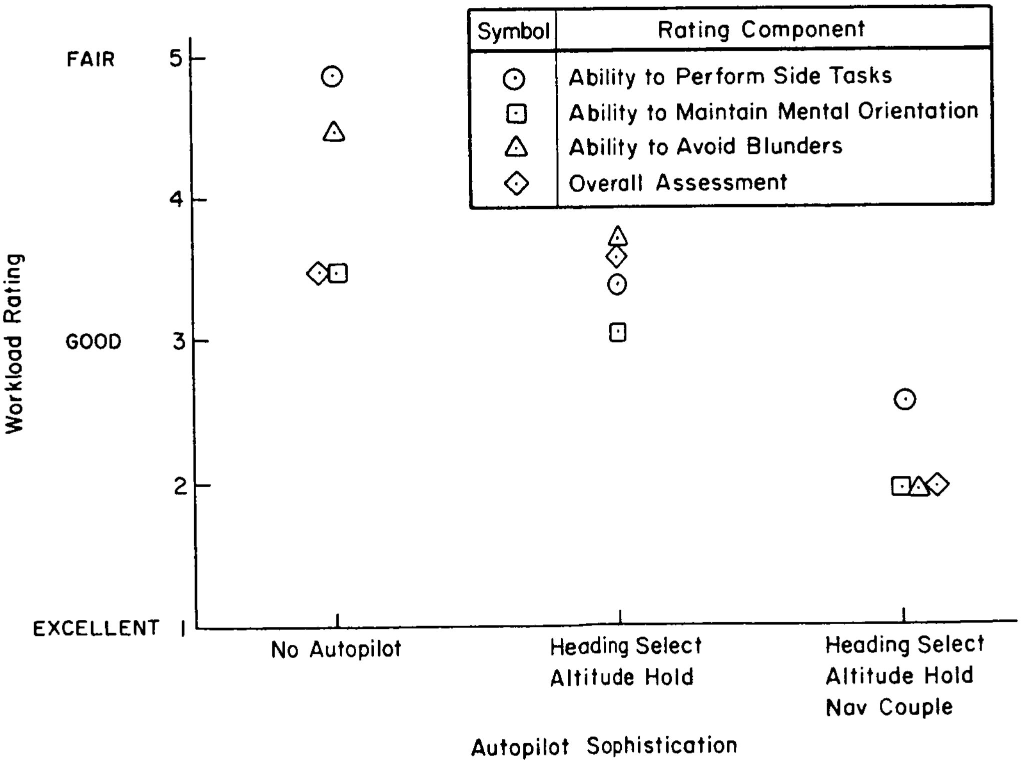


Figure 17. Effect of Autopilot Sophistication on Individual Components of Pilot Workload -- Displays Were HSI and ECDI

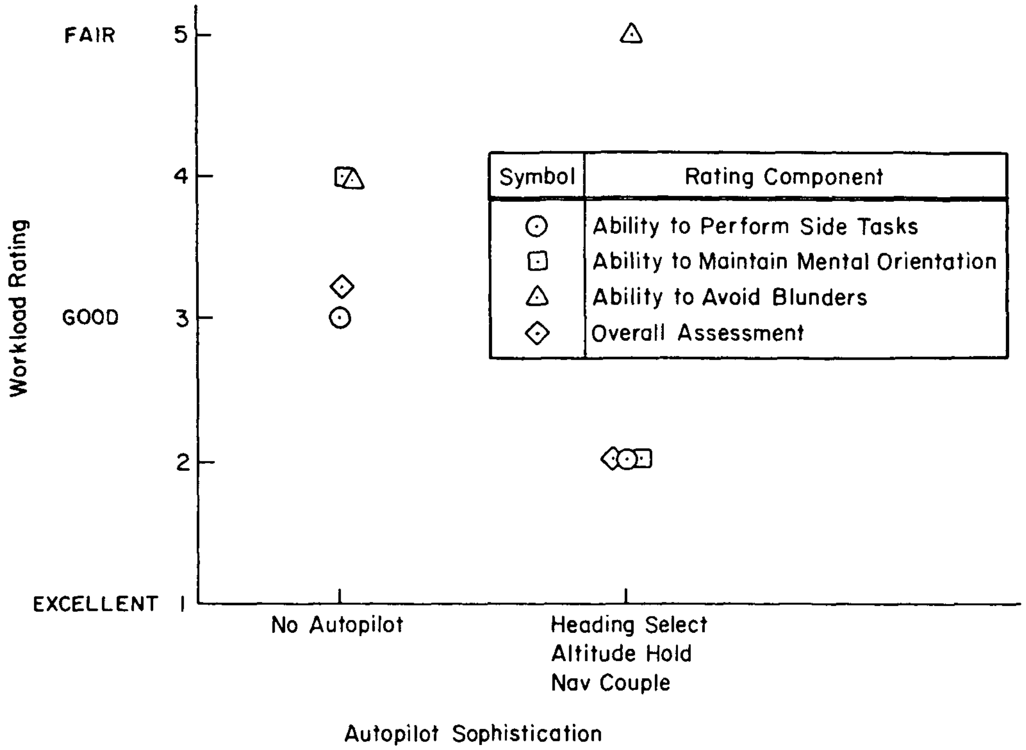


Figure 18. Effect of Autopilot Sophistication on Individual Components of Pilot Workload -- Displays Were HSI, ECDI, DME, RMI

70 kts (80 mph) and immediately added the required power. It is also important to note that the blunders noted here, and other places in this report, were made by experienced test pilots who were familiar with the aircraft being flown. They should not be attributed to either poor pilot training or lack of experience.

- The pilot flew through the Bazoo intersection (where he was supposed to turn; see Fig. 8) while manipulating the autopilot controls. It should be noted that the autopilot controls were located low on the center console requiring large head movements which were especially difficult when wearing an instrument hood. This is a common location for autopilot controls. By the time the pilot realized that he had missed the intersection, the error was sufficiently large so that he was unable to intercept the specified inbound radial and flew direct to the Norfolk VOR.
- There were numerous times when the pilots tried to change heading via the heading bug while the autopilot was in the navigation-coupled mode.

This tended to result in momentary confusion and led to other blunders such as errors in altitude, missed clearances, etc.

- One HSI display had a button on it which caused the course bar on the HSI to automatically slew so that it pointed to the station (an auto-RMI mode). On one occasion the pilot accidentally pushed this button while the autopilot was in the NAV coupled mode resulting in an abrupt uncommanded turn. This was found to be disconcerting as it required the pilot to "fight the autopilot for control of the aircraft."

Figure 19 compares the average workload ratings across all the display configurations tested with the autopilot off, and with a full autopilot (heading select, altitude hold, and NAV couple). This figure verifies the suspected trend. That is, the autopilot is effective in reducing all aspects of workload, except for the tendency toward blunders. The autopilot is seen to be particularly effective in improving the ability of the pilot to perform side tasks. In addition, the pilot's overall assessment of workload is considerably improved with the addition of the autopilot.

Pilot errors take a different form with and without an autopilot. Without the autopilot the errors tend to be associated with not having sufficient excess mental workload capacity to fly the airplane and perform the associated side tasks. Typical blunders were: turning the wrong way on a back course, erroneously copying clearances, inability to figure out whether the aircraft had crossed the localizer or not (pilot unable to spend the time required to interpret the needle deflection), excessive bank angle excursions during periods of unattended operation, excessive altitude excursions (common) and, finally, having problems finding time to perform the necessary mental calculations such as reciprocal headings, holding pattern entries, etc. These problems were considerably compounded if any turbulence existed. With the autopilot on, the blunders tended to be more associated with operation of the autopilot itself.

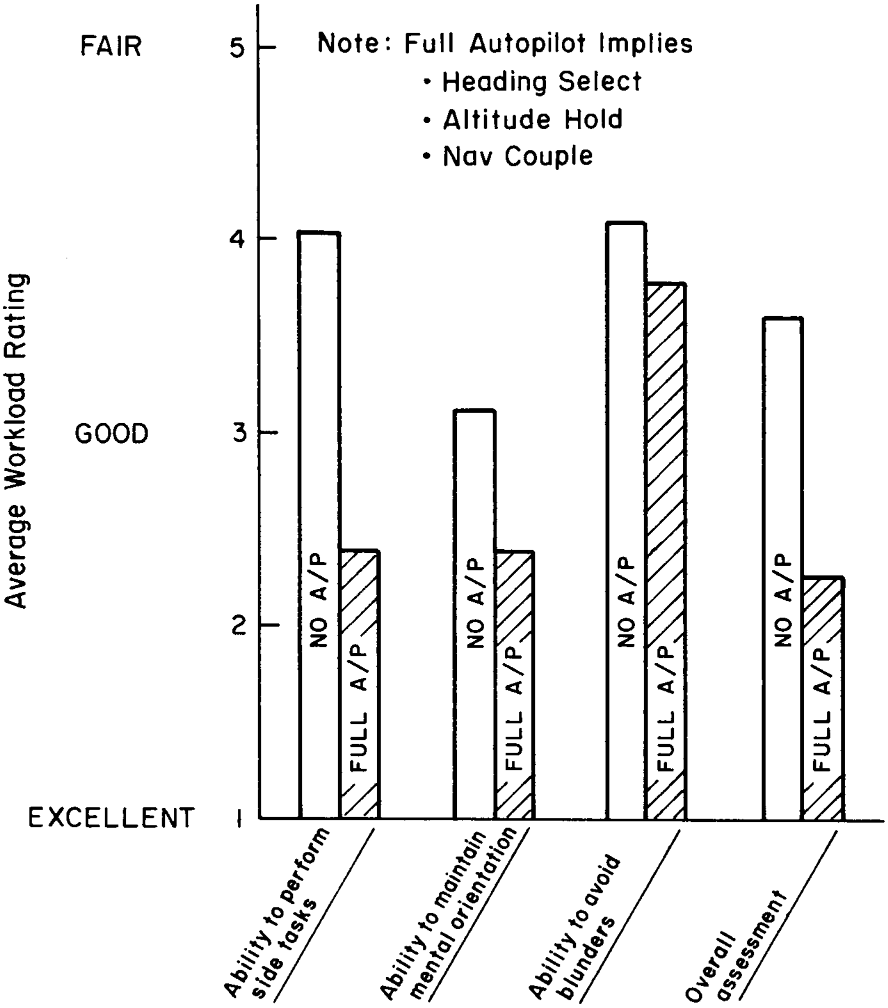


Figure 19. Comparison of Average Workload Ratings Across All Displays With and Without Autopilot

B. EXPERIMENT II: ANALYSIS OF CO-PILOT FUNCTIONS AND THEIR EFFECTIVENESS FOR REDUCING WORKLOAD

1. Overview of Experiment II

The results of Experiment I indicated that current general aviation displays and autopilots are quite acceptable for single pilot IFR operations in a high workload terminal area environment. These results must be considered in the context that:

- There was no significant turbulence.

- The pilots were highly trained NASA test pilots.
- There were no avionics or systems anomalies or failures.
- The test aircraft were of moderate complexity (light twins).

In Experiment II, a much higher workload environment was created by adding turbulence, systems, engine, and avionics failures, and a highly complex turboprop aircraft (Beech Super King Air). The subject pilots were all well trained, having recently completed recurrency training at Flight Safety Intl. The tests were conducted on the Beech King Air training simulator at Flight Safety's Long Beach, CA facility. An experienced instructor operated the simulator, performed ATC functions, and initiated systems failures as required by scripted scenarios. Five scenarios were developed which involved revised clearances, weather problems, systems and engine failures, icing conditions, and moderate turbulence. The scenarios are given in Appendix C.

The Experiment II tests were conducted in two phases. The first phase was to determine the workload level of each scenario with and without a competent co-pilot. In the second phase, we systematically removed certain co-pilot functions in an effort to determine a ranking which could be employed to estimate the value of automated functions for the SPIFR cockpit.

2. Phase 1 — Co-pilot Present or Not Present

The Multiple-Scale-Rating-System results for this phase of the experiment are shown in Fig. 20. These scores are averaged across all five scenarios, and represent two subject pilots, although not all combinations were flown by both pilots. To put these results in context, consider the divided attention tasks and environmental conditions included in the scenarios.

- Turbulence and severe icing.
- Engine failure on takeoff, or enroute.

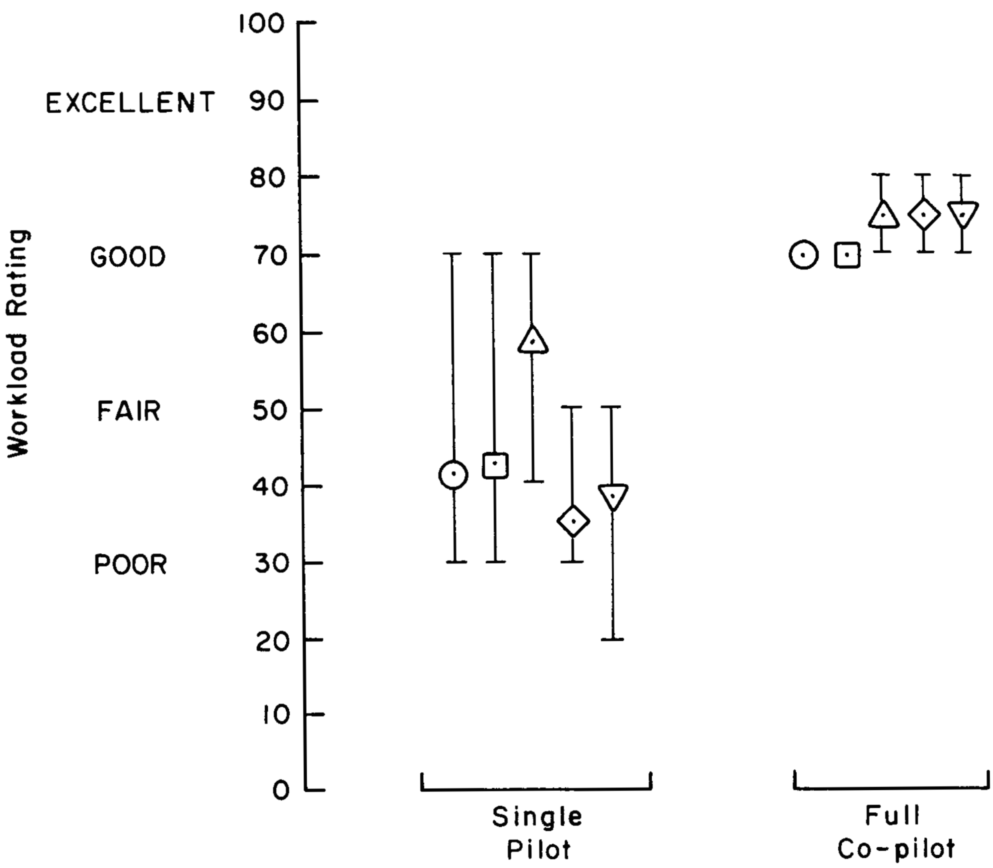
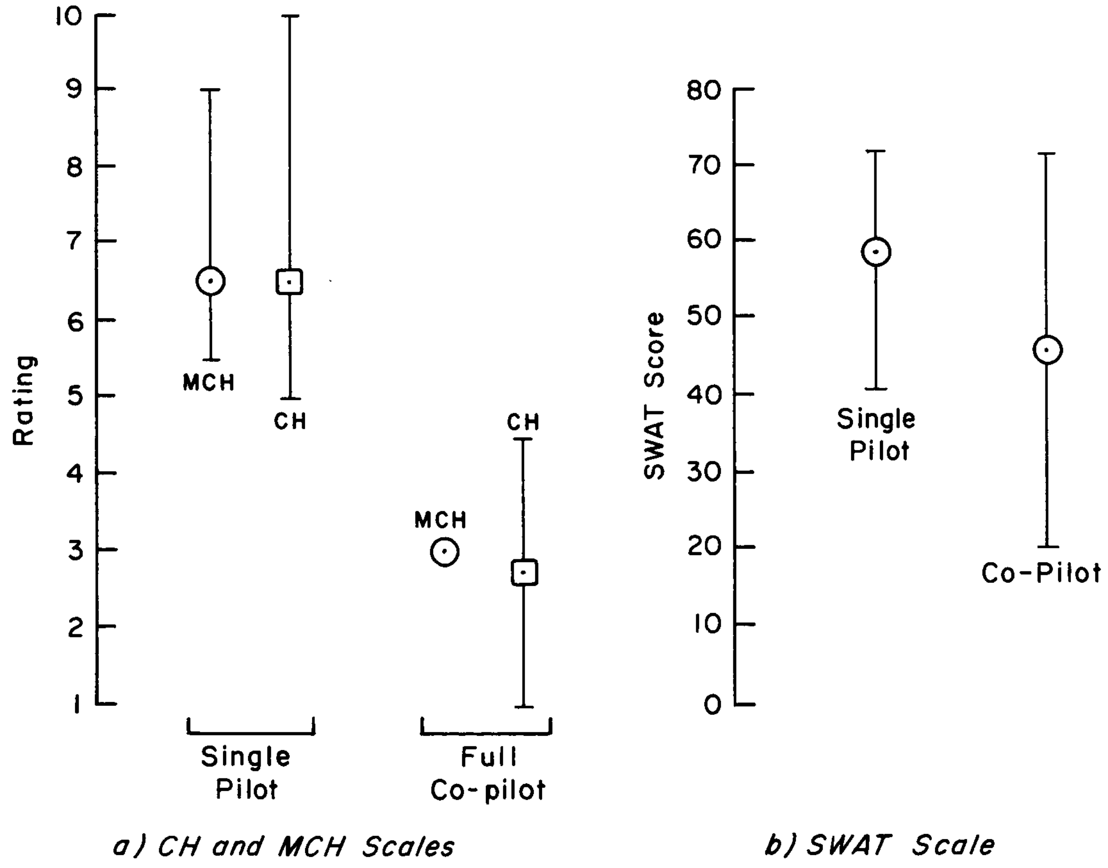


Figure 20. Single Pilot vs. Co-pilot in Presence of Failures, Turbulence, and Icing -- MSRS Workload Scale

- Problems requiring mandatory shutdown of an engine (chip light or oil low pressure) followed sometime later by failure of the operating engine, requiring that the first engine be restarted.
- Inverter failure which slowly caused the HSI heading to read erroneously.
- Landing gear failure requiring manual operation.
- Poor weather requiring selection of an alternate based on several marginal alternatives.
- Revised clearances.

These failures represent the highest divided attention workload environment that could possibly be expected, with the exception that the situation was not life threatening in the simulator. The MSRS ratings of "good" in Fig. 20 indicate that operations with a competent co-pilot are safe as can be expected under such severe conditions. Not suprisingly, the ratings are "fair-to-poor" without a co-pilot. The Cooper-Harper (CH) and Modified Cooper-Harper (MCH) ratings exhibit the same trend as shown in Fig. 21a. The SWAT trends are less pronounced (Fig. 21b). This is consistent with the Experiment I results where the SWAT scale exhibited a rather poor sensitivity to workload.

Procedures and timing were sufficiently variable that a pilot could fly the same scenario several times while still retaining much of its original novelty. Futhermore, care was taken to fly a given scenario first with a co-pilot, then single pilot so that any learning effects would not be attributed to the co-pilot.



a) CH and MCH Scales *b) SWAT Scale*

Figure 21. Subjective Workload Assessment Scores With and Without a Co-pilot -- Average Across All Scenarios

A four axis autopilot was always available, and was used nearly full time by all of the test subjects. However, in some situations, the autopilot mode selection interface was clumsy and too slow, and the pilot temporarily disengaged the autopilot. This usually occurred in a holding pattern.

Phase 2. Systematic Variation of Co-pilot Functions

Each of the pilots in Phase 1 were asked to list the functions performed by the co-pilot that were helpful in reducing divided attention workload. The functions common to all scenarios, and which were felt to be most significant, were as follows.

A. Communications

B. Navigation

C. Normal and emergency checklist items and altitude calls

D. Copy and readback of clearance

All of the subject pilots felt that active control of the aircraft should be retained by the pilot-in-command, a result that should be taken in the context that the autopilot was essentially always engaged.

The objective of the remainder of the test was to determine the ranking and relative importance of each of these functions. While it would be desirable to have a sample size of three or four pilots, there were insufficient resources to utilize more than one pilot for this phase.

In addition to the subjective workload measures (Section III), observed pilot errors (OPER) were noted and logged by the experimentor, and a reaction time experiment was added to the test in an attempt to incorporate a quantitative workload measure. A green light was installed on the left side of the glare shield, and the pilot subject was instructed to turn off this light each time it came on with a button mounted on the control yoke. The observer/experimenter manually injected reaction time "probes" by triggering a microcomputer at designated high workload points in the scenario. Each scenario carried from 10 to 20 reaction time probes, depending upon the speed at which it was accomplished and procedural choices left to the pilot's discretion.

Following completion of the scenario, the pilot was debriefed and asked to fill out a rating scale battery consisting of MSRS, CH, MCH, and SWAT (see Section III). Peak, mean, and a series of multiple regression analyses were performed.

3. Results

a. Equivalence of Workload Scenarios

A regression analysis was conducted to test for differences in difficulty among the 5 scenarios used. An analysis of variance (ANOVA) for this regression across all subjective workload scales indicated that the five scenarios did not differ significantly from one another. This allowed treatment of the five scenarios as equivalent in further analyses, and verifies the experimental procedure.

b. Ranking of Co-pilot Function

A regression analysis was performed to rank the various co-pilot functions in order of their effect on overall workload. The co-pilot function was treated as a dependent variable, and was regressed against all of the workload measures with the rank order rotated to maximize the F ratio of the ANOVA. This resulted in a large F ratio (F = 84.7) which indicates that the different functions of the co-pilot had a strong effect on workload across virtually every rating scale. The results of the above noted A through D co-pilot functions, as well as the limits of no co-pilot, and a fully capable co-pilot were ranked as follows from lowest to highest workload.

1. fully capable co-pilot
2. remove function D - copy and/or read back clearances
3. remove function B - navigation

4. remove function C - normal and emergency check-list items and altitude calls

5. co-pilot absent

6. remove function A - communications

As expected, a fully capable co-pilot has the most favorable effect on reduction of workload. There is really no plausible explanation for the fact that a co-pilot without communications capability (he was allowed to talk to the pilot) was rated worse than no co-pilot at all, and this is considered a statistical artifact (probably due to the small sample size of one). It might be conjectured, however, that having a co-pilot that won't communicate with ATC is sufficiently frustrating so as to make the workload higher than it would be with no co-pilot.

The above ranking also derives from taking the average of all the workload ratings (MSRS, MCH, CH, SWAT)* and plotting that vs. co-pilot function as shown in Fig. 22. These results indicated that the six chosen co-pilot functional states represent an approximately linear function of workload. More pilot subjects would be required to determine whether this result is an experimental anomaly, or actually represents a valid finding. Of greater interest however, was the finding that copying clearances and navigation functions played a relatively minor role, and that communications with ATC was the predominant role of the co-pilot in reducing workload. These results imply that the pursuit of data uplinks would have a significant payoff in terms of workload reduction in the SPIFR cockpit. Support for this important result can be found in Ref. 16, which is summarized in Appendix A, Section H. Indeed, the experimental results shown in Fig. A-9 indicate that a large reduction in workload occurred (equivalent to adding a co-pilot), when an automated data link was included in the SPIFR cockpit. In addition, the results of a questionnaire in Ref. 15

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*The MSRS was inverted for this calculation so 10 was the highest workload and 1 the lowest. This was done for consistency with the CH and MCH scales.

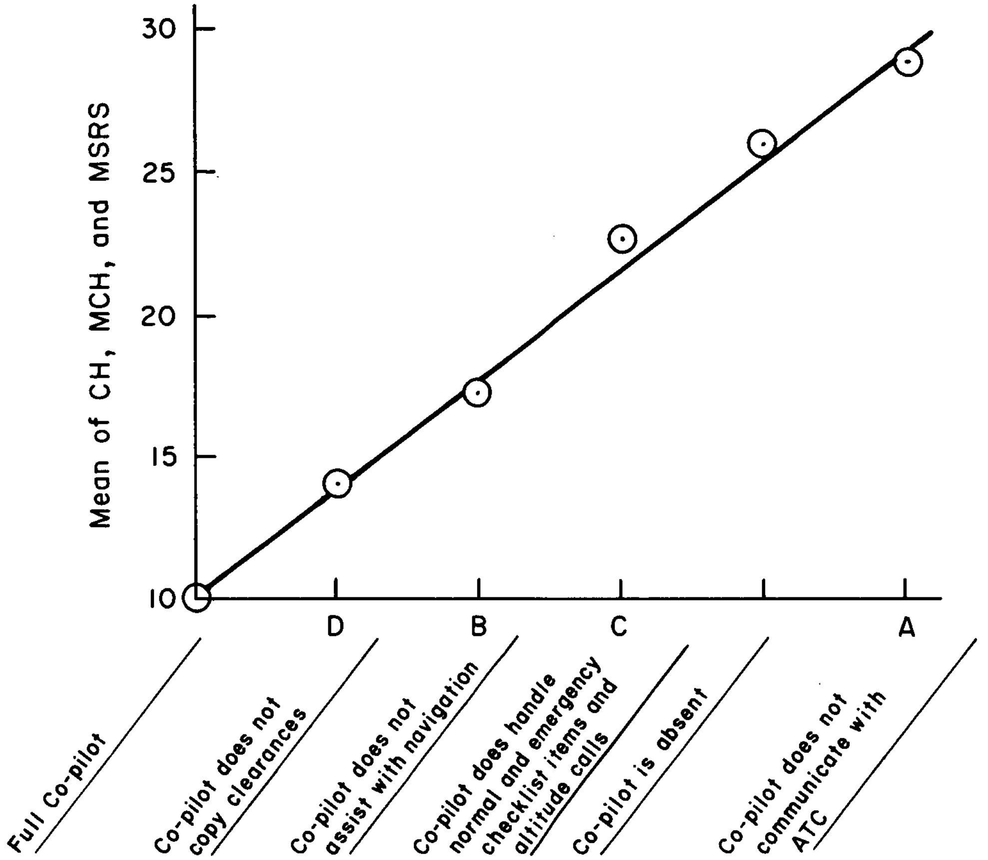


Figure 22. Co-pilot Functions vs. Workload

indicated that the primary value of a co-pilot is to handle "radio work" (communications).

c. <u>Multiple Scale Rating Sustem (MSRS) Results</u>

Of the five MSRS dimensions of workload, the "ability to avoid blunders" (scale number four) showed the strongest correlation with co-pilot function (R = 0.79) as can be seen from a comparison of the data with the regression line in Fig. 23. Similarly, the data points representing MSRS scale number 1 (precision) shows the poorest correlation with co-pilot function (R = 0.63). This result is consistent with the small workload increment attributed to navigation as a co-pilot function (see Fig. 22).

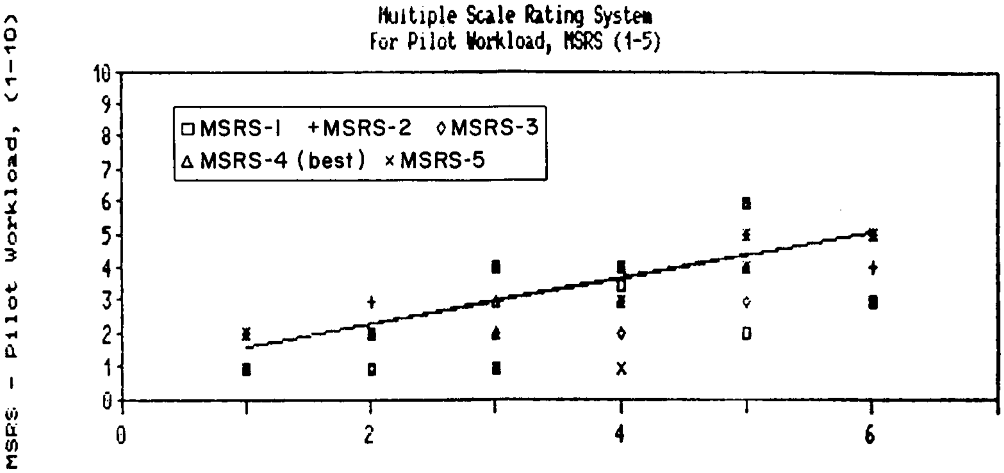


Figure 23. MSRS Regression With Co-pilot Function

d. Cooper-Harper (CH), Modified Cooper-Harper (MCH), SWAT, and Observer Pilot Error Rating Results

The CH, MCH, and OPER regression lines, and raw data points, are plotted in Fig. 24, and the three components of SWAT are plotted separately in Fig. 25. Clearly the most robust of these scales was the MCH (R = 0.85), while the CH correlated somewhat less at 0.66 with co-pilot function.

The only element of the SWAT to show a significant correlation with co-pilot function was the Mental Effort dimension (Fig. 25) which is consistent with the dominant role played by checklists and communications functions (Fig. 22). As with Phase 1 of this simulation, and the Experiment I flight tests, the SWAT scale exhibits a lack of sensitivity to workload relative to the other subjective workload scales.

The observer pilot error ratings (OPER) showed a reasonably good correlation (R = 0.74) with co-pilot functions. This is reasonably consistent with the MSRS scale number four (ability to avoid blunders) which showed a correlation of 0.79, indicating that the pilot's assessment of error avoidance agrees reasonably well with his performance.

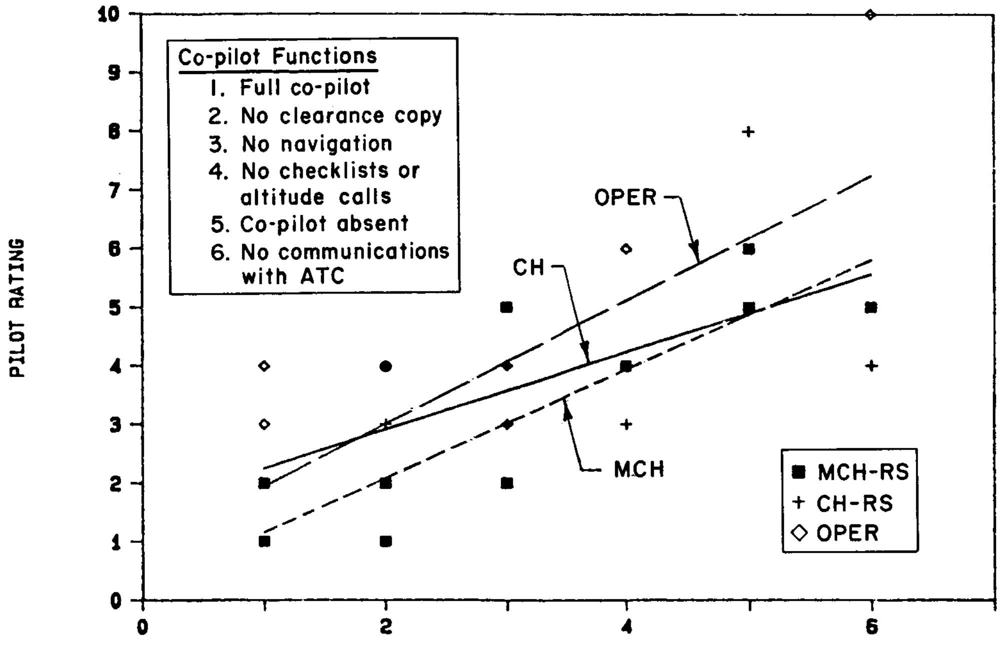


Figure 24. Co-Pilot Function vs. Rating Scales

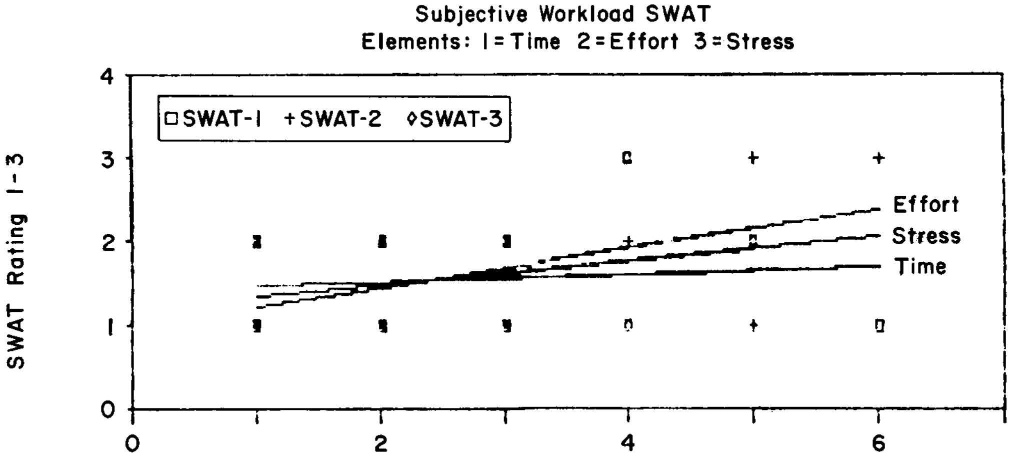


Figure 25. Swat Regression With Co-Pilot Function

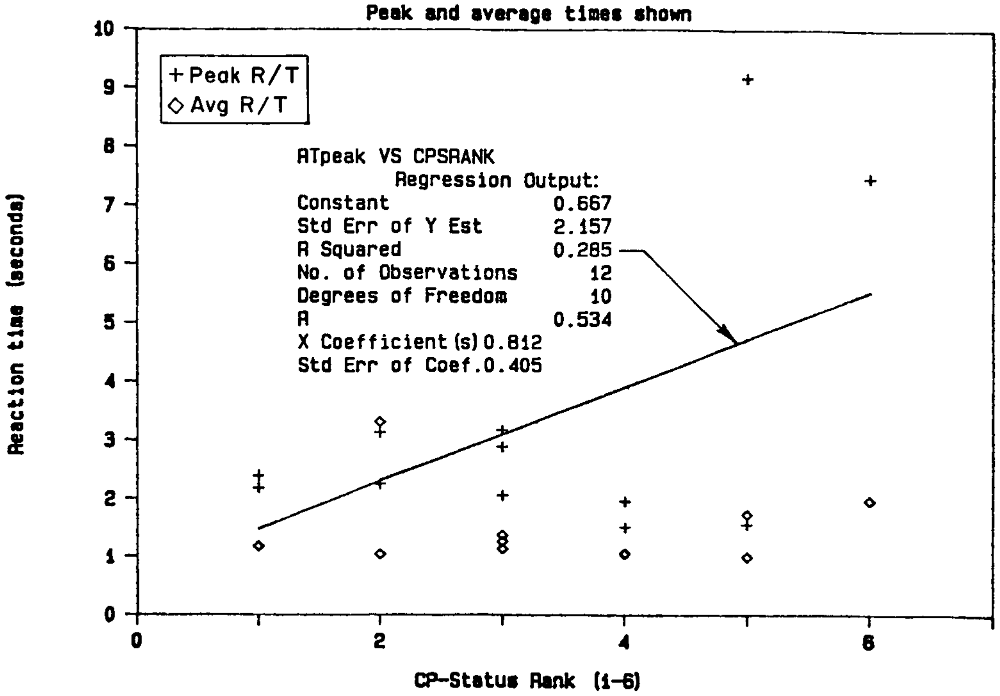


Figure 26. Co-pilot Function vs. Reaction Time

e. Reaction Time Results

The reaction time results are shown in Fig. 26 and are seen to be highly variable. The peak reaction time exhibits better performance (R = 0.534) than the average, although neither is very impressive as a workload metric. This is consistent with the results of Ref. 17, wherein similar techniques to quantify "spare mental capacity" did not show sensitivity to increasing workload.

SECTION V

CONCLUSIONS

A. ANALYTICAL DIVIDED ATTENTION PILOT MODEL

- The highly stressed human operator can only tend to one item at a time in a divided attention task environment.
- Short-term memory tends to be wiped out by an overridingly important piece of information.

B. FLIGHT TEST EXPERIMENTS WITHOUT FAILURES -- EXPERIMENT I

- Dual VOR without DME or RNAV is marginal (high workload) for SPIFR operations.
- Adding DME helps and RNAV is better.
- A moving map display aids in mental orientation, but has inherent deficiencies as a stand alone replacement for an HSI.
- Slewing controls were not satisfactory in this experiment.
- Centralized navigation frequency selection was less favorable than distributed information (on the face of the navigation display).
- Autopilot functions were highly effective for reducing pilot workload in the SPIFR environment.
- Pilot blunders occurred at the same rate with and without an autopilot, although the nature of the errors was different.

C. SIMULATION EXPERIMENT INCLUDING THE EFFECTS OF FAILURES -- EXPERIMENT II

- Extremely high workload situations were adequately handled with a competent co-pilot.
- The importance of co-pilot functions, from most to least, were,
    1. communications with ATC.
    2. accomplishment of normal and emergency checklists, and altitude calls.
    3. navigation.
    4. copying and reading back clearances.

- The Multiple Scale Rating System and Modified Cooper-Harper subjective workload scales correlated best with variations in co-pilot function.

- The Subjective Workload Assessment Technique (SWAT) was relatively insensitive to variations in workload in this study.

REFERENCES

1. Larson, George C., "Single-Pilot IFR: Threat or Menace?," Business and Commercial Aviation, June 1981.

2. Hurst, Ronald, ed., Pilot Error: A Professional Study of Contributory Factors, London, Crosby Lockwood Staples, 1976.

3. Cooper, George E., and Robert P. Harper, Jr., The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities, NASA TN D-5153, Apr. 1969.

4. Wierwille, Walter W., and John G. Casali, "A Validated Rating Scale for Global Mental Workload Measurement Applications," Proceedings of the Human Factors Society - 27th Annual Meeting, 1983, pp. 129-133.

5. Casali, John G., and Walter W. Wierwille, "A Comparison of Rating Scale, Secondary-Task, Physiological, and Primary-Task Workload Estimation Techniques in a Simulated Flight Task Emphasizing Communications Load," Human Factors, 1983.

6. Reid, Gary B., F. Thomas Eggemeier, and Thomas E. Nygren, "An Individual Differences Approach to Swat Scale Development," Proceedings of the Human Factors Society - 26th Annual Meeting, 1982, pp. 639.

7. Eggemeier, F. Thomas, Mark S. Crabtree, Gary B. Reid, et al., "Subjective Workload Assessment in a Memory Update Task," Proceedings of the Human Factor Society - 26th Annual Meeting, 1982, pp. 643.

8. Eggemeier, F. Thomas, and Michael A. Stadler, "Subject Workload Assessment in a Spatial Memory Task," Proceedings of the Human Factors Society - 28th Annual Meeting, Oct. 1984.

9. Eggemeier, F. Thomas, Brian E. Melville, and Mark S. Crabtree, "The Effect of Interviewing Task Performance on Subjective Workload Ratings," Proceedings of the Human Factors Society - 28th Annual Meeting, Oct. 1984.

10. Courtright, John F., and Gil Kuperman, "Use of Swat in USAF System T & E," Proceedings of the Human Factors Society - 28th Annual Meeting, 1984, pp. 700.

11. Eggemeier, F. Thomas, Jennifer Zingg McGhee, and Gary B. Reid, "The Effects of Variations in Task Loading on Subjective Workload Rating Scales," Proceedings of the IEEE National Aerospace and Electronics Conference, Dayton, Ohio, 1983, pp. 1099-1105.

12. McDonnell, John D., Pilot Rating Techniques for the Estimation and Evaluation of Handling Qualities, AFFDL-TR-68-76, Dec. 1968.

13. Bailey, A.J. et al.: *Demonstration Advanced Avionics System (DAAS) Functional Description*, NASA CR-166282, Jan. 1982.

14. Clement, Warren F., *Investigation of the Use of an Electronic Multifunction Display and an Electromechanical Horizontal Situation Indicator for Guidance and Control of Powered-Lift Short-Haul Aircraft*, NASA CR-137922, Aug. 1976.

15. Reason, James, and Klara Mycielska, *Absent-Minded? The Psychology of Mental Lapses and Everyday Errors*, Prentice Hall, Englewood Cliffs, N.J., 1982

16. Parker, James F., Jr., Jack W. Duffy, and Diane G. Christensen, *A Flight Investigation of Simulated Data-Link Communications During Single-Pilot IFR Flight. Vol. I - Experimental Design and Initial Tests*, NASA CR-3461, Aug. 1981.

17. Wierwille, Walter W., and Sidney A. Connor, "Evaluation of 20 Workload Measures Using a Psychomotor Task in a Moving-Base Aircraft Simulator," *Human Factors Society*, 1983.

18. Bergeron, Hugh P., "General Aviation Single Pilot IFR Autopilot Study." 1980 Aircraft Safety Operating Problems. NASA CP-2170, Part 1, 1981, pp. 201-217.

19. Johannsen, G., W. B. Rouse, and K. Hillmann, *Studies of Planning Behavior of Aircraft Pilots in Normal, Abnormal, and Emergency Situations*, Forschunginstitut fur Anthropotechnik, Bericht Nr. 53, Dec. 1981.

20. Barber, Marvin R., Charles K. Jones, Thomas R. Sisk, and Fred W. Haise, *An Evalution of the Handling Qualities of Seven General-Aviation Aircraft*, NASA TN D-3726, Nov. 1966.

21. Loschke, Paul C., Marvin R. Barber, Einar K. Enevoldson, and Thomas C. McMurtry, *Flight Evaluation of Advanced Control Systems and Displays on a General Aviation Airplane*, NASA TN D-7703, June 1974.

22. Roskam, J., "Flight Test Results of a Separate Surface Wing-Leveling System," SAE Paper 740369, Apr. 1974.

23. Jenks, Gerald E., "Development of a Separate Surface Stability Augmented Attitude Command Control System on a Beech Model 99," presented at SAE Aerospace Control and Guidance Systems Committee, Utah, Mar. 1976.

24. Adams, James J., *Simulator Study of Conventional General Aviation Instrument Displays in Path-Following Tasks with Emphasis on Pilot-Induced Oscillations*, NASA TP 1776, Dec. 1980.

25. Adams, James J., *Simulator Study of a Pictorial Display for General Aviation Instrument Flight*, NASA TP 1963, Mar. 1982.

26. Adams, James J., Flight-Test Verification of a Pictorial Display for General Aviation Instrument Approach, NASA TM-83305, 1982.

27. Talbot, Peter D., and Glen W. Stinnett, Jr., Landing Approach Evaluation of an Integrated CRT Display for General Aviation Aircraft, NASA TM X-3096, July 1974.

28. Pennington, Jack E., Single Pilot Scanning Behavior in Simulated Instrument Flight, NASA TM-80178, Oct. 1979.

29. Eckhart, Franklin F., G. Warren Hall, and Paul A. Martino, Flight Evaluation of a Stability Augmentation System for Light Airplanes, Rept. Nos. FAA-ADS-83 and IH-2154-F-1, Nov. 1966.

30. Driscoll, Norman R., Effects of Simple Stability Augmentation System on the Performance of Non-Instrument-Qualified Light-Aircraft Pilots During Instrument Flight, NASA TN D-3970, May 1967.

31. Walchi, R., and D. Eldredge, Flight Evaluation f a Pilot-Assist Stability Augmentation System for Light Aircraft, Federal Aviation Administration , FAA-DS-70-14, May 1970.

32. Hoh. Roger H., David G. Mitchell, Irving L. Ashkenas, et al., Proposed MIL Standard and Handbook -- Flying Qualities of Air Vehicles. Vol. II: Proposed MIL Handbook, AFWAL-TR-82-3081(II), Nov. 1982. (Available from DTIC as AD A123-726.)

APPENDIX A

REVIEW AND INTERPRETATION OF EXISTING DATA

A large amount of experimental, analytical, and human factors data related to the single pilot IFR problem was reviewed. Specific interpretations of some of the more significant results are discussed in this appendix.

A. CONVENTIONAL AUTOPILOT

The effect of increased autopilot sophistication for workload relief was studied in a comprehensive pilot simulation program at the NASA Langley Research Center. The simulation included a visual attachment which allowed the pilot subjects to land or execute a missed approach depending on where the ceiling was set by the researcher. This element of realism is felt to have added considerable credibility to the Ref. 18 results. These results are summarized in Figs. A-1 and A-2. The side tasks noted in Fig. A-1 consisted of solving simple time, speed, and distance problems on an E6B type navigation computer. The implicit assumption made was that the number of side task problems that could be completed was a measure of the workload of the primary task. That is, a pilot operating in a low workload environment would have time to complete a greater number of side tasks than when operating in a very high workload environment. This is consistent with the Fig. 2 pilot workload model where the side task problems are intended to replace many of the pilot functions that cannot be easily simulated, i.e., decision making, ATC communications, failure detection, and aircraft systems management. The unknown factor in this approach is the lack of compelling cues to attend to a specific function. For example, a pilot is strongly motivated to read back an ATC clearance even if it interrupts some other task which in fact may be more important. Nonetheless, the solution of math problems as a side task is a well known tool for workload assessment and is felt to provide valuable insight.

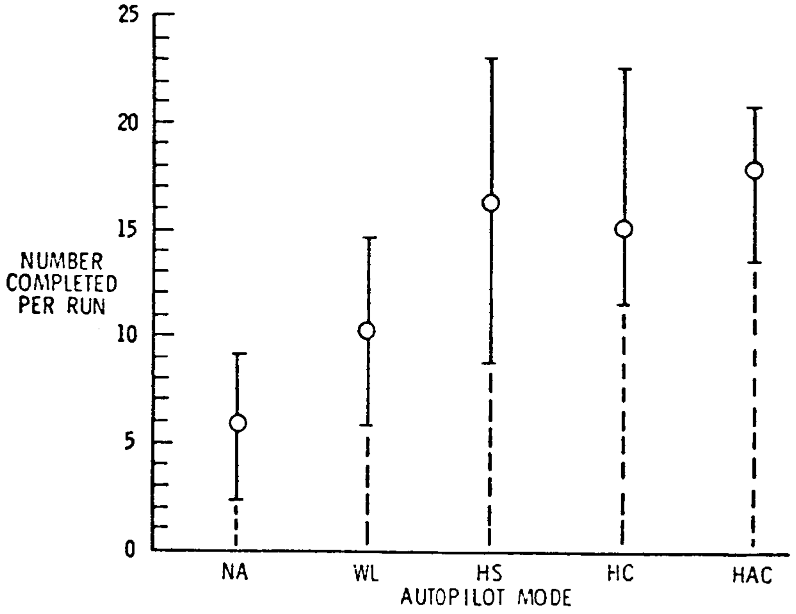


Figure A-1. Average Number of Side Tasks Performed For All Approaches and All Pilots

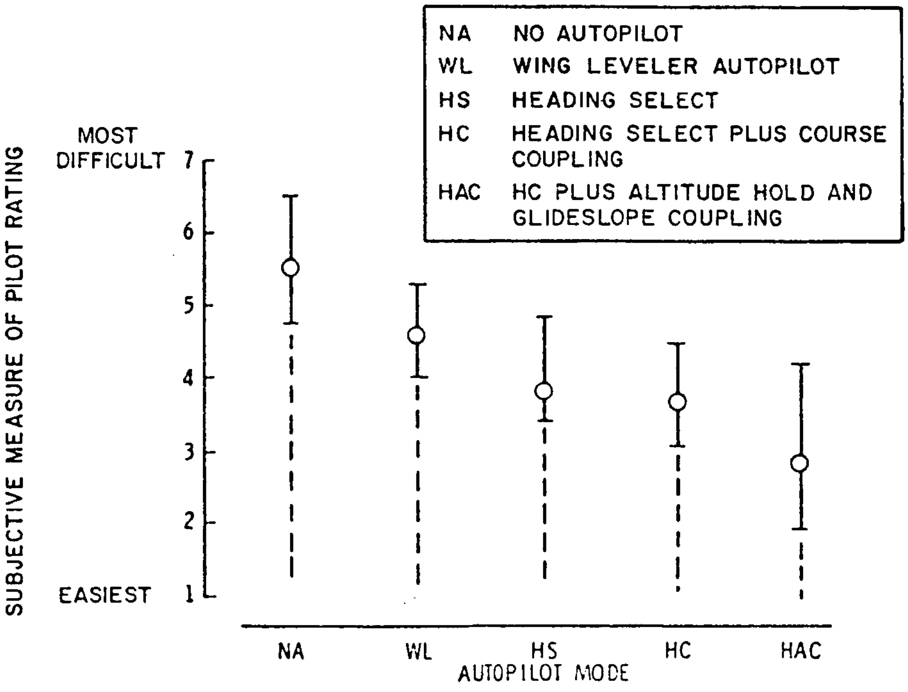


Figure A-2. Workload Ratings

The experimental results shown in Fig. A-1 indicate that the addition of a wing leveler and a heading select mode allowed the pilot to complete a significantly greater number of side task problems. However, further autopilot sophistication had a negligible effect on workload, at least in terms of completing side tasks.

The pilot subjects in the Ref. A-1 experiment were also asked to make subjective ratings of their workload on a scale of 1 to 7 with 1 designated as the easiest and 7 as the most difficult (see Fig. A-2). The use of this subjective workload scale produced similar results to that noted in Fig. A-1; that is, the addition of a wing leveler and heading select mode showed significant reductions in pilot workload. The addition of course coupling is seen to result in no significant change in the pilots subjective assessment of workload. Unlike the Fig. A-1 side task results, altitude hold did produce a noticeable improvement in the pilot's assessment of workload. This result probably indicates that the pilots spent more of their time on functions other than the problem solving side task when the altitude hold mode was being utilized.

The lack of substantial subjective workload rating reduction with increasing autopilot sophistication is counter-intuitive and appears to be primarily associated with the tendency for the pilots to make more frequent errors when operating in the autopilot mode. The instrument approach tasks used in this experiment required considerable pilot interaction with the autopilot controls as he or she progressed through the various segments of the approach. In some cases the pilot blunders could be directly associated with inappropriate operation of these controls, i.e., such as trying to select a new heading when operating in the course coupled mode, etc. In other cases the pilots appeared to become so absorbed in operating the autopilot that they became mentally disoriented and in one case actually let down on the outbound course of an NDB approach (see Ref. 18 for details). The apparent lack of mental orientation when operating with a sophisticated autopilot was particularly puzzling in view of the fact that little or no time is required to maintain control of the aircraft. Based on the Fig. 2 workload model it would seem that the autopilot would allow additional time to be spent on mental orientation. This, in fact, appears to be the case for the more basic functions (i.e., aircraft control) in terms of the Figs. A-1 and A-2 metrics but does not explain the apparent lack of mental orientation when operating in the more sophisticated autopilot modes. The results of the experimental testing conducted in the present research suggest that the interface between the pilot and the controls and displays plays an overridingly important part in pilot workload. That is, having sophisticated autopilot modes may actually increase the tendency towards blunders if the interface with the pilot is not very carefully worked out.

One other possible explanation for the tendency for increased pilot blunders with sophisticated autopilots is offered in Ref. 19 which studies the planning behavior of pilots in normal, abnormal, and emergency situations. The Ref. 19 experiment utilized a fixed base simulator representing a corporate jet aircraft (the HFB-320). In that study it was found that the availability of an autopilot resulted in decreased planning during scenarios where clearance changes were required due to abnormal situations such as snow on the runway, etc. The revised clearance usually resulted in a transition to a holding pattern which was executed for 3 complete cycles before the approach was made. The low level of planning observed with an active autopilot may indicate a sense of complacency among pilots when executing "standard procedures" in the autopilot mode. It is not clear at this time whether complacency (see for example, Ref. 15) or control/display problems are primarily responsible for the apparent inability of autopilots to decrease the tendency towards blunders.

B. ADVANCED AUTOPILOT

Subsequent to the Ref. 18 autopilot study, a complementary research program was initiated at NASA Langley to investigate the concept of an automatic terminal approach system (ATAS). The primary objective of this research was to determine if increased automation would reduce the tendency toward blunders noted in the conventional autopilot study of

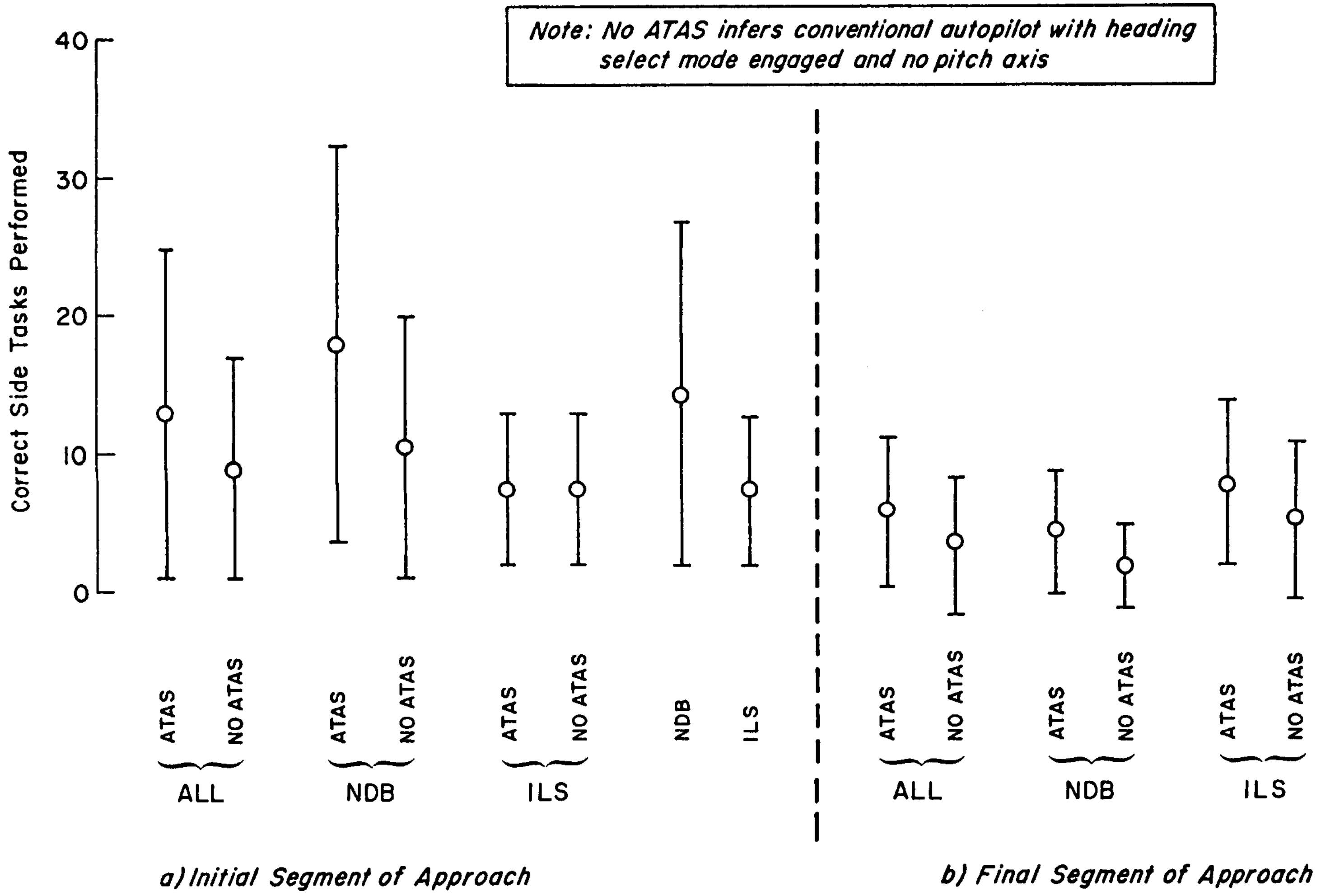
Ref. 4. In essence, ATAS performed the pilot interactive functions automatically, removing the necessity for mode switching, setting heading and course bugs, and navigation frequencies. The ATAS stored all instrument approach data and used the data to automatically fly the approach by tuning the navigation radios and controlling the autopilot.

The ATAS was evaluated on the same NASA Langley general aviation research simulator as used in the Ref. 18 autopilot study and used many of the same pilot subjects as well. These results are shown in Fig. A-3 where the ATAS is compared to a conventional autopilot in the heading select mode. The initial and final portion of the approaches were plotted separately to investigate the effect of the different nature of these tasks (maneuvering and tracking vs. pure tracking respectively). As would be expected, the pilots were able to perform a greater number of sidetasks when relieved of the necessity for setting up autopilot functions throughout the approach. However, pilot commentary and performance indicated that while the concept of a fully automatic approach seemed valid, interface problems between the pilot and ATAS resulted in a substantial number of blunders. General suggestions to improve the interface were noted during the study and are summarized below.

- More prompting to advise the pilot of system status as well as actions required.
- Improve ATAS/autopilot hardware interface.
- Consolidate ATAS and autopilot controls.
- Display aircraft position with respect to airport continuously.

One comment made by a subject pilot summarizes the situation, "ATAS works fine once everything is in automatic, but the transition from all off to full automatic is awkward." Other commentary which support this general conclusion were

- "The ATAS does not seem 'friendly,' needs more prompting."
- "Would like to have one button that will set up everything in automatic."



Note: No ATAS infers conventional autopilot with heading select mode engaged and no pitch axis

a) Initial Segment of Approach

b) Final Segment of Approach

Figure A-3. Number of Correct Side Tasks Performed -- ATAS

C. STABILITY AUGMENTATION

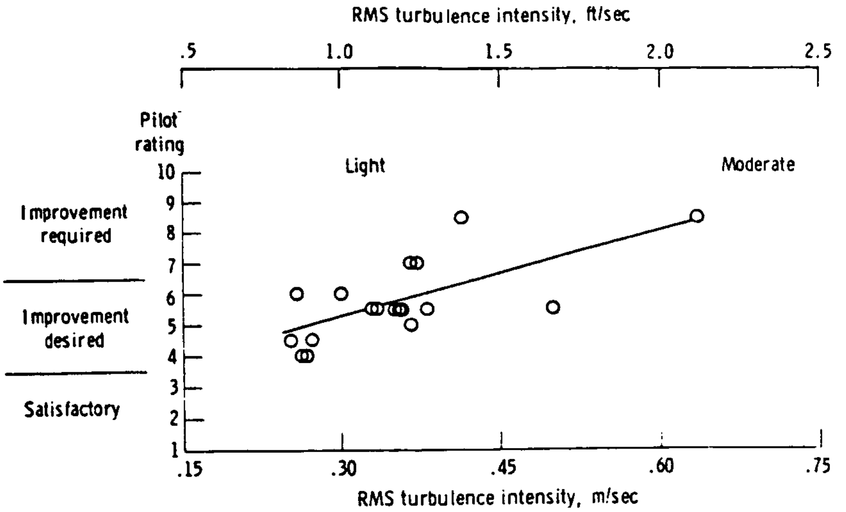
Stability augmentation is utilized when it is desired to modify the basic aircraft response to control inputs and/or turbulence. The primary difference between a stability augmentor and an autopilot is that the stability augmentor moves the aerodynamic controls to modify the aircraft response without any apparent motion of the cockpit controls. The autopilot, of course, moves the cockpit controls and aerodynamic controls simultaneously. Hence, with an autopilot it is necessary to fly the aircraft through the autopilot controls (heading and course select knobs, etc.) whereas in the case of a stability augmentor, it is possible to fly the aircraft through the normal controls while enjoying the benefits of improved stability (see Ref. 6 for a more detailed discussion of this). Pilot comments obtained during the flight test portion of this control/display research indicated that this would be a desirable feature in that the standard aircraft controls are felt to be more "friendly" than knobs and buttons.

An evaluation of the handling qualities of seven general aviation aircraft was conducted at the NASA Dryden Flight Research Center (see Ref. 20). In this study, several qualified test pilots evaluated the handling qualities of general aviation aircraft in VFR and simulated IFR conditions with various levels of atmospheric disturbances. The conclusions of these pilots were that the handling qualities of these aircraft as a class were good to acceptable for instrument flight in smooth air, but fell into the acceptable to unsatisfactory range when operating in moderate levels of turbulence. It would therefore be expected that the use of stability augmentation to improve light aircraft handling qualities and turbulence would be beneficial for reducing single pilot IFR workload.

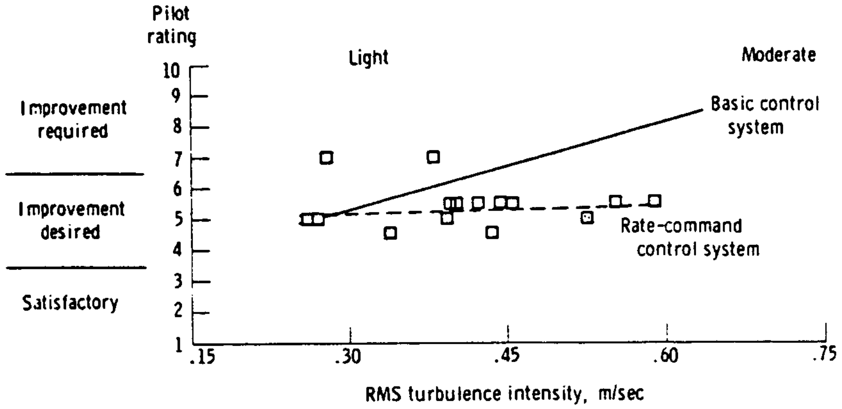
An experimental flight test program was conducted at the NASA Dryden Flight Research Center to determine the level of handling qualities improvement that could be achieved with stability augmentation and a flight director display in varying levels of turbulence (see Ref. 21). Several pilots participated in the program which utilized a light twin engine aircraft. The effect of stability augmentation was evaluated using the standard Cooper-Harper pilot rating scale with the results shown in Fig. A-4. Figure A-4a indicates that the handling qualities of the unaugmented aircraft degrade rapidly with increasing turbulence intensity. The use of stability augmentation to achieve a rate command control system in the pitch and roll axes is illustrated in Fig. A-4b where it seen that the undesirable effects of turbulence are essentially eliminated. In Fig. A-4c the effect of using an attitude command control system produced satisfactory flying qualities in all levels of turbulence. This result was somewhat counter-intuitive in that pitch attitude stabilization eliminates the ability of the aircraft to weathercock into vertical gusts and therefore results in greater normal acceleration response to a given vertical gust. However, the data clearly shows that the pilots preferred the attitude command control system. One possible explanation is that the pitching motions associated with weathercocking into the vertical gusts was more objectionable to the pilot than the larger vertical accelerations that occur if such weathercocking is eliminated. Put another way, it appears that the attitude excursions in turbulence are more objectionable than normal acceleration responses.

The effect of a flight director display on the unaugmented aircraft is shown in Fig. A-5a. Considering that the task was an ILS approach, it is not suprising that the flight director display resulted in a considerable improvement in the pilot ratings. However, the use of attitude augmentation in combination with the flight director display improved the pilots opinion even further, to the point where in significant levels of turbulence they give almost perfect ratings (Fig. A-5b).

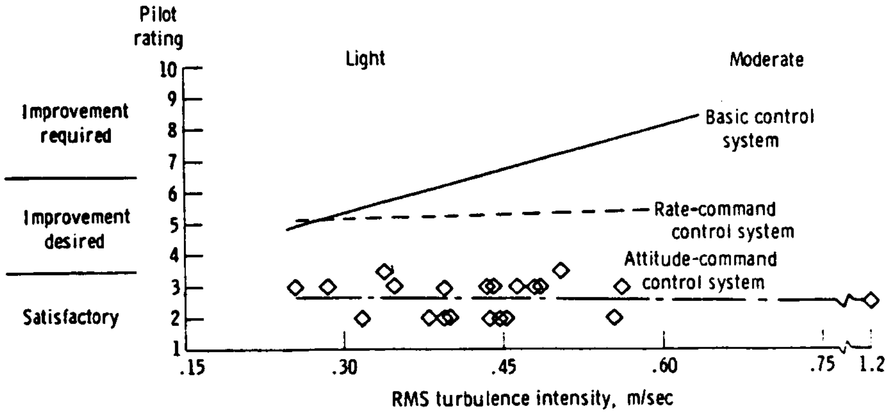
The degrading effects of turbulence on pilot workload are well explained by the Fig. 2 model. Without augmentation, the aircraft pitch and roll attitudes are continuously upset requiring the pilot to spend the large majority of available time controlling the aircraft. If we accept the basic hypothesis that the pilot can only tend to one item at a time, the other SPIFR functions cannot be accomplished (i.e., the



a) Pilot Ratings of Handling Qualities for ILS Approach Task With Basic Control System

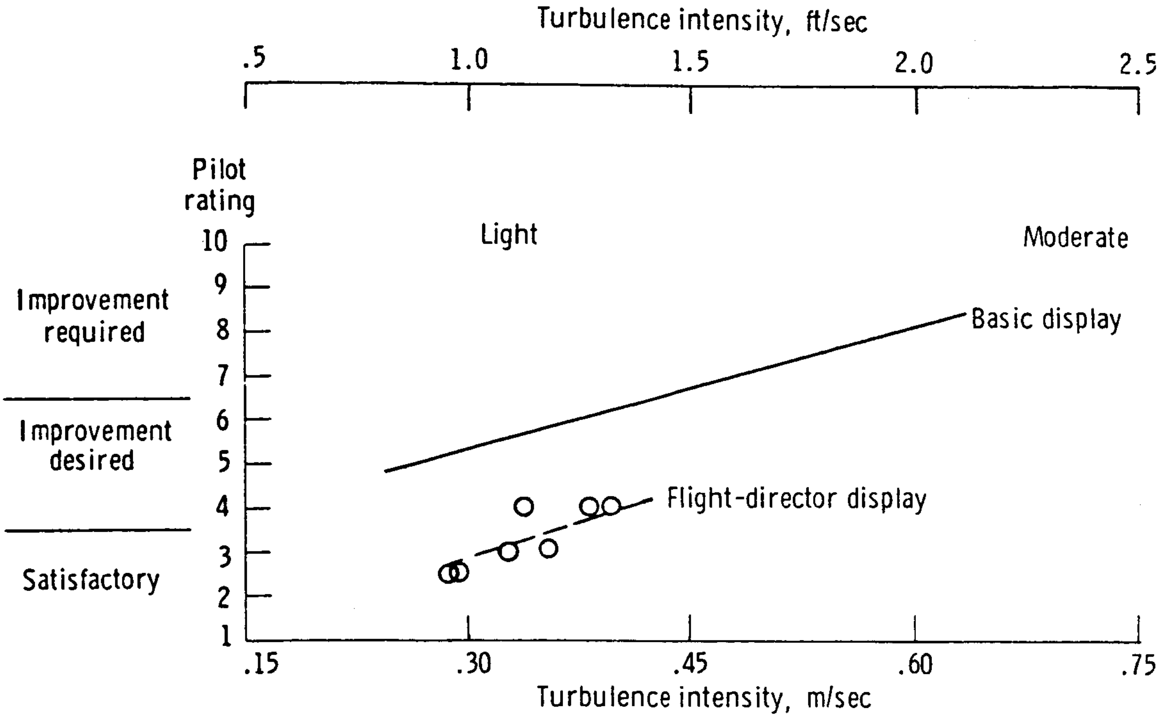


b) Pilot Ratings of Handling Qualities for ILS Approach Task With Basic and Rate-Command Control Systems

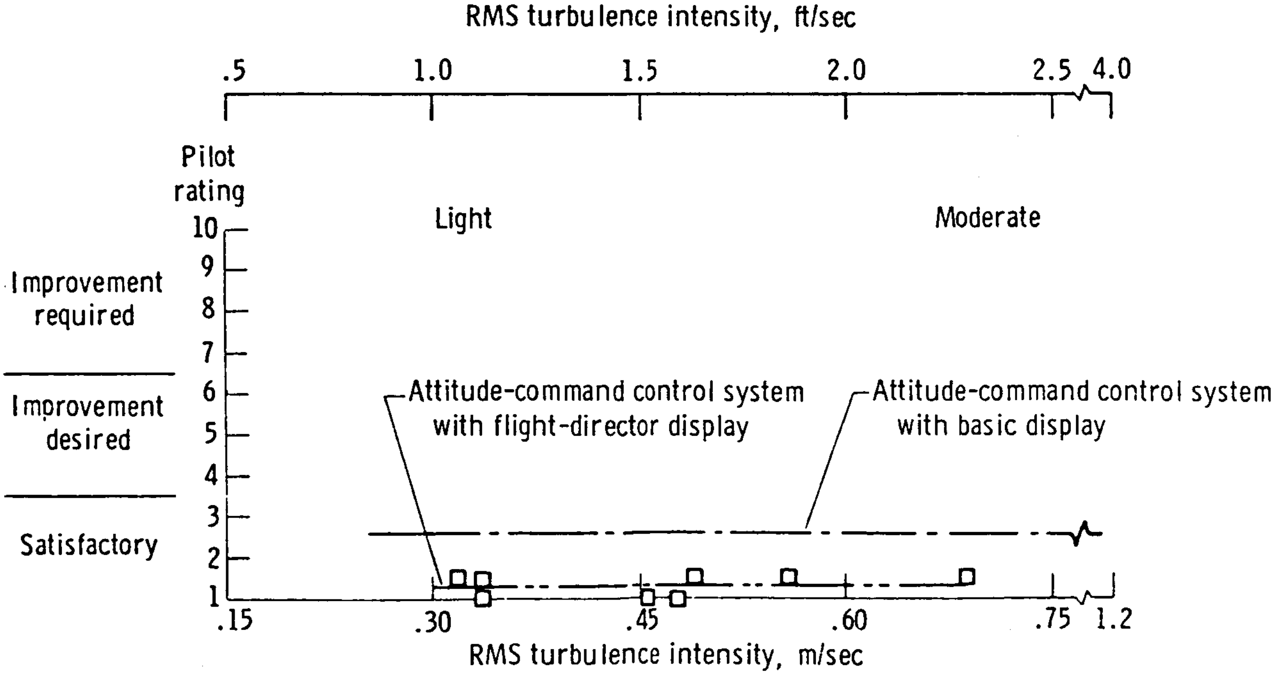


c) Pilot Ratings of Handling Qualities for ILS Approach Task With Basic, Rate-Command, and Attitude-Command Control Systems

Figure A-4. Effect of Augmentation on Cooper-Harper Pilot Ratings (Taken from Ref. 7)



a) Pilot Ratings of Handling Qualities for ILS Approach Task With Basic Control System With Basic Display and Flight-Director Display



b) Pilot Ratings of Handling Qualities for ILS Approach Task With Attitude-Command Control System With Basic Display and Flight-Director Display

Figure A-5. Effect of Flight Director Display on Cooper-Harper Pilot Ratings (Taken from Ref. 7) "switch" is nearly always on δ). The use of attitude augmentation frees the pilot from the aircraft control task thereby allowing time for the other SPIFR functions.

The implementation of a stability augmentation system on a general aviation airplane would be somewhat impractical utilizing conventional techniques, i.e., a series servo. The irreversible nature of such a servo dictates a fully powered flight control system; clearly out of range economically for general aviation airplanes flown with a single pilot. A possible alternative to the series servo is discussed in Refs. 22 and 23 and consists of a separate control surface dedicated solely to the stability augmentation system. The neutral to slightly unstable nature of the lateral axis of conventional airplanes makes this axis particularly amenable to augmentation; recall that a wing leveler reduced workload significantly (see Figs. A-1 and A-2). However, the roll control power of most general aviation aircraft is already marginal, and the reduction in lateral control surface area on existing aircraft would almost certainly result in unacceptable handling qualities. One solution might be to incorporate roll control spoilers in addition to a small aileron which would be used to complement the spoilers as well as to provide separate surface augmentation.

In summary the Ref. 21 flight test program has proven that the use of stability augmentation essentially eliminates the degrading effects of turbulence on light aircraft flying qualities, especially in instrument conditions.

D. COMPARISON OF HSI, RMI, AND CDI DISPLAYS

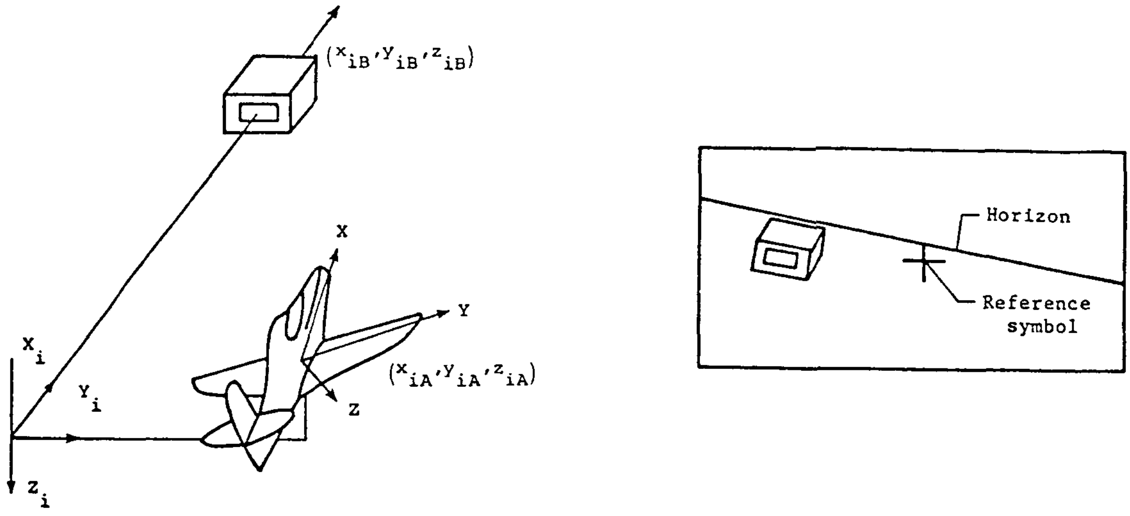
A piloted simulation study comparing three displays commonly utilized for navigation in SPIFR operations was accomplished on the NASA Langley general aviation simulator. The results of the study (Ref. 24) showed that the HSI provided the most accurate lateral path following, at moderate range from the VOR followed by the CDI with the RMI ranking third. These results were not surprising in that the HSI combines heading and course offset on one display. The pictorial nature of the display obviates not only the need for scanning two displays, but also the mental calculations required to compute appropriate headings.

The RMI is basically designed to supplement an HSI by providing the pilot with crossbearing information. Its advantage over a CDI in this role, is that it does not saturate, and hence provides continuous information of aircraft position with respect to a selected VOR or nondirectional beacom (NDB). The tradeoff is one of display sensitivity. For example, if the aircraft is 10 deg off course, a CDI would indicate full scale deflection, whereas the RMI needle only shows 10 deg out of 360 deg on a 3 in. diameter display. Hence, the RMI is specifically unsuited for tracking, a fact which is verified by the Ref. 11 piloted simulation results.

E. FOLLOW-ME BOX DISPLAY

NASA Langley has been experimenting with a unique CRT display for general aviation utilizing piloted simulation (Ref. 25) as well as an in-flight evaluation (Ref. 26). The display replaces the mechanical attitude gyro with a computer drawn "box" displayed on a CRT (see Fig. A-6). The pilot task is to fly through the tunnel located at the end of the "follow-me box." If the sides or top of the box are visible the aircraft is off course and/or off altitude. During enroute segments the box is located at fixed points whereas during an instrument approach it slides down the final approach course at some fixed range ahead of the aircraft until it reaches the missed approach point at which time it becomes fixed. Advantages noted with this display in Refs. 25 and 26 are summarized below.

- The geometry of the display is such that computed lead information is available to the pilot. Therefore, it is easy to track without separate reference to heading as is required with conventional general aviation displays.
- The 3-D perspective gives some idea of the approach angle being flown to the waypoint.
- It is possible to track straight or curved paths.
- The pilot remains oriented with respect to the desired course, even for large offsets where most conventional displays saturate.



a) Typical Flight Situation

b) Display for Typical Flight Situation

Figure A-6. Follow-Me Box Display Concept (Taken From Ref. 11)

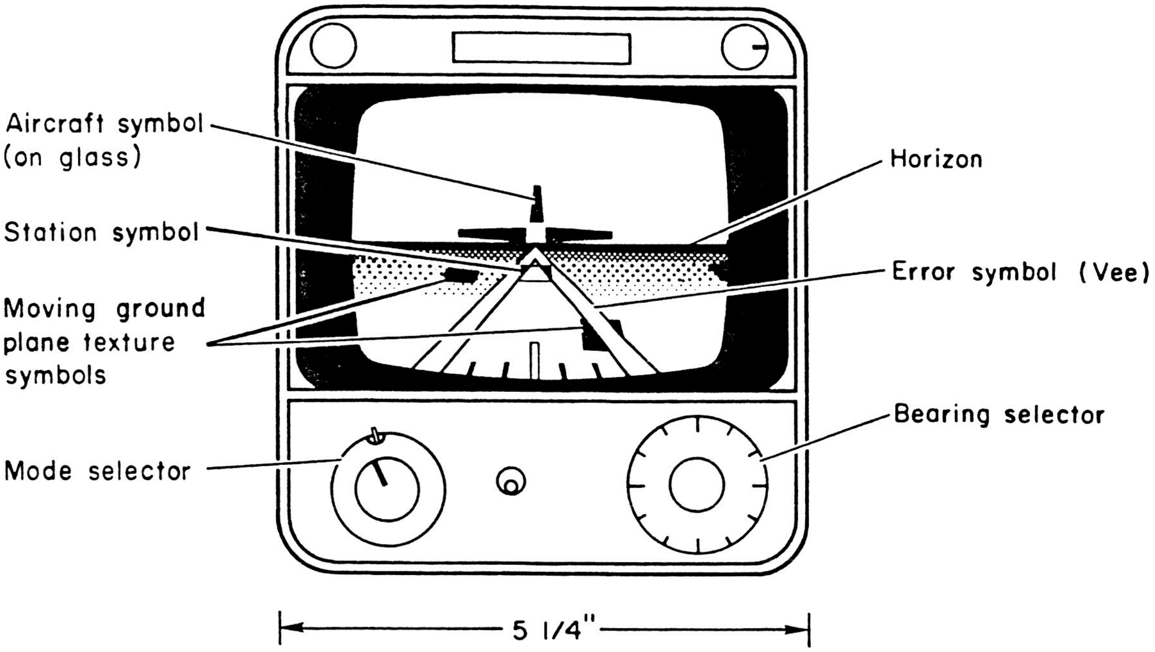
- The second box gives good cues to prepare for the direction to turn for the next waypoint.
- Measured tracking precision was good.

Some disadvantages of the display noted in Refs. 25 and 26 were:

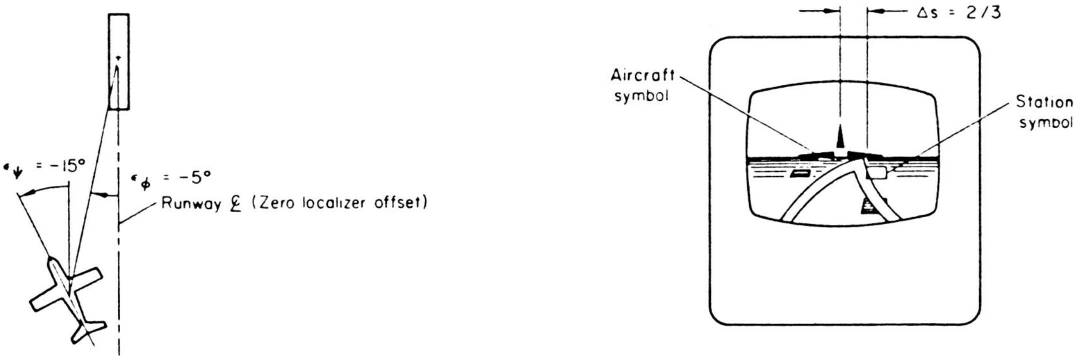
- The absence of roll and pitch angle indices on the CRT may make it unsatisfactory for general use in its present form.
- The CRT used for the display is too small.
- The follow-me-box is too small at long distances making it impossible to perceive sufficient detail to determine lateral and vertical offsets from course and altitude, i.e., can not determine box orientation at long range.
- Cluttering is a problem around the center of the screen whenever the box is fairly small.

F. INTEGRATED CRT DISPLAY

The idea of using CRT Displays to replace the conventional attitude gyro plus flight director was pursued quite vigorously during the early 1970s. Perhaps the most successful of these was was the "pathway in the sky" display shown in Fig. A-7. This display which was developed by



a) Display Features and Controls



(a) Aircraft situation.

(b) Display.

b) Display and Aircraft Situation for Localizer Error and Heading Error

Figure A-7. Integrated CRT Display Device (Kaiser Model FP-50)

Kaiser and was evaluated in a Learjet at the NASA Ames Research Center. The results of this evaluation are given in Ref. 27. During each test series, the pilots first made a minimum of 2 visual approaches and 3 conventional (raw data) ILS approaches. The remaining approaches were then made with the CRT Display. Three research pilots participated in the program. Interestingly, the display was most beneficial to the pilot who had the least experience in the Learjet although improved tracking was noted with the CRT Display for all 3 pilots. In fact, the statistical data (shown in Fig. A-8) indicated that tracking with the CRT Display resulted in similar performance as tracking in VFR conditions. The worst performance was obtained using the conventional raw-data ILS display. This result is not surprising inasmuch as the CRT Display provided the pilot with lead information wherein raw data ILS tracking requires the pilot to scan several displays in order to generate the necessary lead required for a stable tracking solution. A better evaluation of the CRT Display would have been to compare it with a flight director.

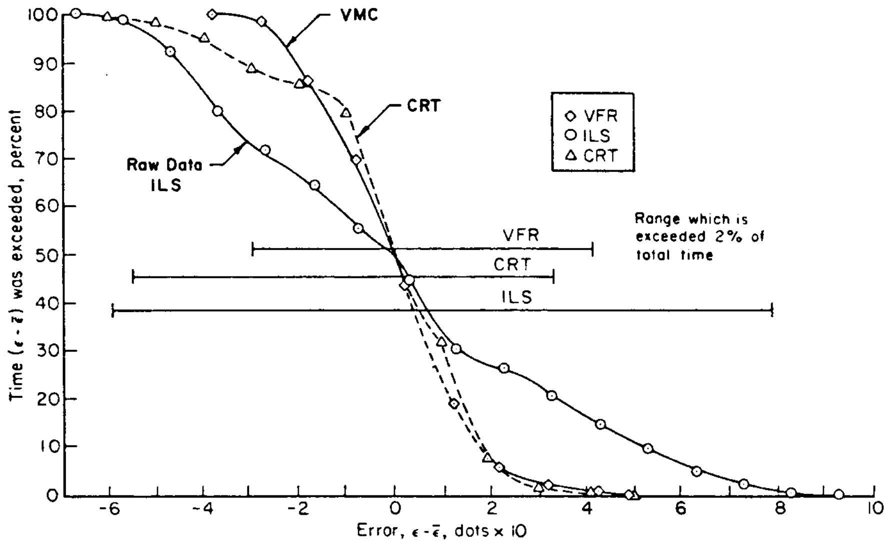


Figure A-8. Comparison of Localizer Cumulative Error Distributions

G. PILOT INSTRUMENT SCANNING BEHAVIOR

A piloted simulation study of instrument scanning behavior was accomplished at the NASA Langley Research Center and is reported in Ref. 28. An occulometer was utilized in this experiment to obtain quantitative information of the pilots scanning behavior during 9 different IFR flight maneuvers. The results of the study indicated that the pilot spent between 70 and 80 percent of their time looking at the artificial horizon and the directional gyro during all of the maneuvers tested. This supports the assumption that the pilot spends most of his time on basic aircraft attitude control. It therefore seems reasonable to expect that the use of an autopilot or stability augmentation would lead to the greatest payoff in terms of IMC workload reduction. It is important to keep this aspect of the problem in perspective when making the appropriate interpretations of the results of the Ref. 18 autopilot study showing a tendency towards blunders. That is, one should not assume that increased blunders are a fundamental aspect of autopilots but rather that these blunders are more attributable to the particular pilot interface with the autopilot system.

The results of the Ref. 28 study indicated that the pilot spent between 55 and 65 percent of their time looking at the artificial horizon (attitude indicator). This is probably attributable to the fact that airplanes are either neutrally stable or unstable in the lateral axis (spiral mode) and hence require continuous attention to maintain a selected bank angle or wings level flight. Hence, the addition of a simple wing leveler is suggested as an appropriate way to significantly reduce pilot workload in IMC conditions with a minimum cost.

The fact that the pilots spent between 15 and 30 percent of their time on the directional gryo would indicate that the next most important function would be a heading select or heading hold autopilot mode. This has been verified in the simulation program reported in the Ref. 18 where the greatest pilot workload reductions were seen to occur for the wing leveler and heading select modes. The use of integrated displays which incorporate lead information also minimize the need for scanning heading information while tracking. However, such a display does not allow the pilot to "switch his attention" to other IFR functions and therefore is probably less effective than the wing leveler or heading hold autopilot.

One of the basic problems confronting a non-instrument rated pilot who finds himself in conditions of low visibility is his lack of awareness of the necessity of continuously controlling aircraft attitude through the use of the artificial horizon. Experience has shown that simply telling a pilot that attitude control is the one single most overriding consideration in aircraft control and IMC conditions is not sufficient. A considerable amount of training is required to make this fact part of the pilots reality to the point that he would use it in an emergency situation. Since it is not possible to force such training on the pilot population, an alternative solution would be to educate pilots as to the extremely beneficial safety implications of having a wing leveler autopilot, or even better, an augmentor. The safety advantages of such an autopilot have been demonstrated in several inflight research programs conducted by both the FAA and NASA (see Refs. 29, 30, and 31). Each of these programs demonstrated that non-instrument rated pilots were able to, in most cases, safely accomplish a reasonably complex instrument flying task with the assistance of a simple wing leveler autopilot. These same pilots were prone to getting lost as a minimum, with total loss of aircraft control occurring in some cases, without the assistance of the wing leveler.

H. DATA LINK COMMUNICATIONS

A flight investigation of simulated data uplink communications during single pilot IFR flight was accomplished by Biotechnology Incorporated under contract to NASA Langley Research Center and is reported in Ref. 16. A light twin engine aircraft was used, and the evaluations took place in an actual high density air traffic control environment. On runs where the data link was tested the information was uplinked to a flight data console (FDC) which consisted of numeric display of ATC command data as well as reference data information. A keyboard was available to allow the pilot to enter information when the uplinking capability was not activitated. The flight data console was operated in 2 modes. In mode 1 the system presented stored flight data items as entered by the pilot. In this mode the flight data console (FDC) served as a memory aid and in essence took the place of paper and pencil on a knee pad. When operating in mode 2, the flight data console received command information from air traffic control and presented it on the displays. This included instructions for changes in heading, changes in altitude, new frequencies, updated altimeter setting, and displays which indicated "clear for approach" and "clear to land" instructions. In actual operation, the ATC instructions were received by the console operator in the rear seat of the aircraft. He entered the information in such a way that the pilot would perceive that is was actually coming directly from ATC. A message alert light was located at the top of the display to alert the pilot to the fact that he is being issued a clearance or revised clearance.

Each of the 8 subject pilots were given 4 flights. These are summarized as follows.

- Flight A -- In this flight the subject pilot flew with an instrument rated co-pilot and was free to use the co-pilot in any way he desired. The only restriction was that the co-pilot could not actually fly the aircraft. Flight with a fully qualified instrument rated co-pilot was considered optimum in terms of reducing workload and making the flight as proficient and safe as possible. Therefore, this flight was intended to provide a baseline against which other flights might be compared.

- Flight B -- Here the pilot was alone in the sense that the safety pilot did not participate. Subject pilot used the flight data console as a data storage system (memory aid) to assist during each instrument approach.

- Flight C -- This is the customary single pilot instrument flight wherein the safety pilot did not participate.

- Flight D -- In this flight all approaches were flown using air traffic control information provided through the flight data console.

Each of the 4 flights lasted for approximately 1-1/2 hrs and included 4 instrument approaches: an ILS approach, an NDB approach, a VOR approach, and an ASR approach.

When asked to rate their perception of workload for each of the 4 flights immediately following each flight, the ratings all fell about midway between light and very heavy; that is, the pilots were unable to distinguish a change in workload for any of the 4 flights. However, when asked to look back over the 4 flights after completing the entire experiment, the pilots rated Flight A and Flight D as having a much lower workload than Flights B and C (see Fig. A-9). While the authors of Ref. 16 were unable to explain why the pilots could not perceive a change in workload immediately after each run it is clear that in looking back over the experiment the subject pilots overall perception was that the data uplink provided a substantial reduction in workload.

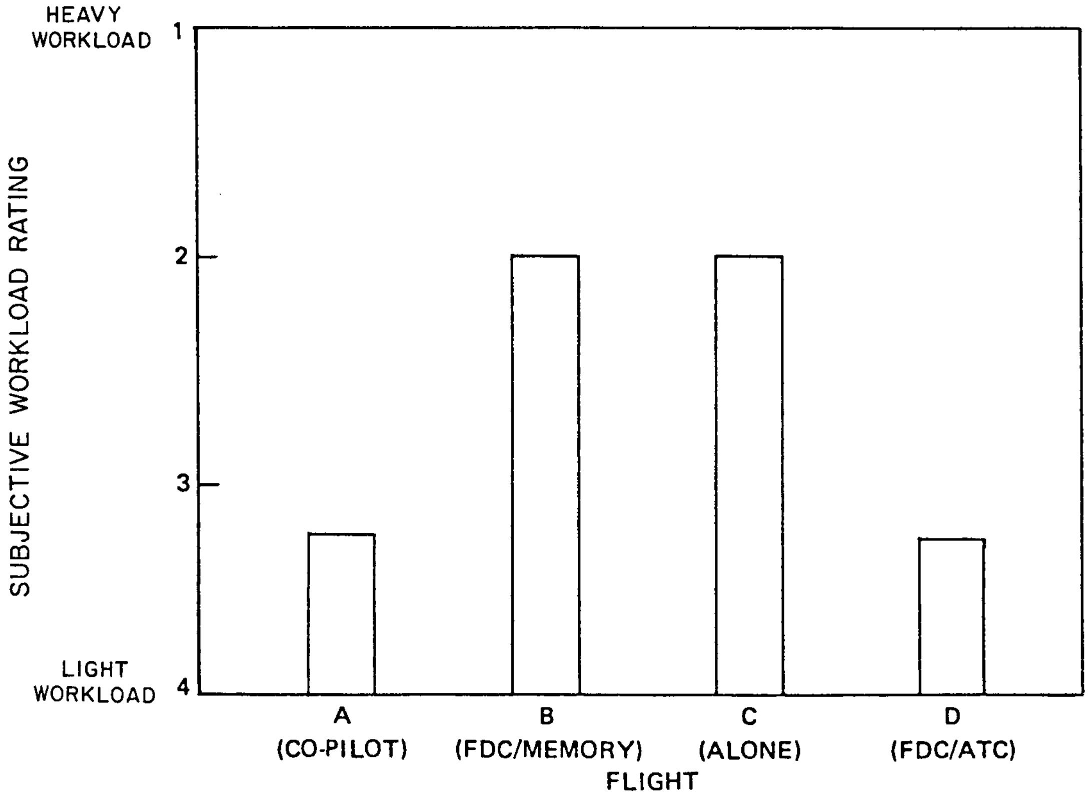


Figure A-9. Average Workload Rankings Obtained Following Completion of All Flights (1 = Heavy, 4 = Very Light) (Taken From Ref. 17)

In addition to participating in the flight experiment, each of the subject pilots were asked to complete a questionnaire. Results of that questionnaire indicated that the primary value of a co-pilot is to handle radio work (communications). On this basis we would certainly expect a reduction in workload with a data uplink capability for the single pilot IFR task.

Positive comments noted by the subject pilots regarding the data uplink capability were as follows.

- There is no confusion as to who the instruction from the ground is for.
- You can hardly miss a call.
- No misunderstanding or forgetting numbers.
- No fumbling with pencil, knee board, mike, or volume control.
- The uplink capability was very easy to use and provided much workload relief.
- Pilots liked the quiet of the radio-free environment.

There were also some negative comments regarding data uplink capability as simulated in Ref. 16. These were as follows.

- Position of the flight data console was poor requiring the pilots to move their heads to read it, thus, detracting from the instrument scan.
- The flight data console was difficult to read in daylight.
- The security of voice communication was missing. This was felt to be a significant factor. One pilot indicated that he would be most comfortable with the use of the data uplink capability in conjunction with a radio.
- The pilots were not able to question ATC.
- The data uplink tends to force greater reliance on ATC than the pilots were ready to give.

A problem not mentioned in Ref. 16 but that is felt to be significant, is the value of hearing clearances given to other aircraft that are also operating in the ATC environment. An alert instrument pilot can usually detect a pattern based on the instructions given to other aircraft. Once this pattern is understood clearances tend to make a lot more sense thereby requiring less interpretation and minimizing the element of surprise.

The results of the Ref. 16 study indicate that data uplink when used in conjunction with the communications radio could significantly reduce pilot workload. This is consistent with the findings of Experiment II in the present research.

I. AIRCRAFT CONTROLS

The vast majority of general aviation airplanes utilize the wheel or yoke controller. The primary disadvantage of this controller is that it uses up valuable panel space which could otherwise be utilized for instrumentation. One proposed solution to this has been the Brolley controller which consists of 2 handles which eminate from the instrument panel and are interconnected. With this controller the pilot can fly with either hand as in the conventional wheel controller without the disadvantage of blanking panel space directly in front of the pilots eye. This controller was investigated in the terminal configured vehicle (TCV) program being conducted at the NASA Langley Research Center. Another alternative would be the center stick which is popular in military fighter aircraft, but seems to meet with considerable resistance in the general aviation community. Considering the necessity to sell airplanes it is unlikely that any manufacturer would risk utilizing a center stick controller. It is therefore deemed impractical at this time.

The sidearm controller represents an attractive alternative to the standard yoke or Brolley controller in that it is conveniently located in the cockpit. Sidearm controllers are presently being used in Rutan's Vari Eze and Long Ez aircraft as well as the military F-16 and the Space Shuttle. While the viability of the sidearm controller is generally well established, discussions with engineering test pilots who have participated in sidearm controller research programs indicate that a considerable amount of work needs to be done in this area. Probably the best source of data on sidearm controllers is the proposed military Flying Quality Standard and Handbook (Ref. 32). Section III.2.9.4 of Ref. 32 contains a considerable amount of flight test data generated at the U.S. Air Force Test Pilot School utilizing the variable stability T-33 aircraft configured with a sidearm controller. The following discussion is based on considerations from Ref. 32.

Some guidance for designing sidearm controllers may be gained from Fig. A-10 which indicates the effect of stick force gradient with normal acceleration and deflection. The pilot ratings denoted as "CH" refer to the Cooper-Harper rating scale which is discussed in some detail in Ref. 32. However, a broad interpretation of that scale is that pilot ratings from 1 to 3-1/2 are considered to be "satisfactory" and from 3-1/2 to 6-1/2 indicates "improvement is desired," and pilot ratings worse than 6-1/2 indicated that "improvement is necessary." Referring to Fig. A-10 it can be seen that the pilots preferred increased control stick motion with decreased control force gradients and decreased control stick motion with increased control force gradients. Control configurations 13, 14, and 15 of Fig. A-10 yield the best results both in pilot ratings and comments. Pilots indicated that control motions were noticably large but not uncomfortable. These configurations were on the edge of the test matrix, thus, the extent of this favorable region was not determined and additional testing is required. It should be noted that the maneuvers used to generate these pilot ratings and comments consisted of 2 g bank-to-bank turns as well as wind-up turns. Such maneuvering is, of course, not normally accomplished in general aviation aircraft and hence the data in Fig. A-10 should be considered more as background information than specific design guidance. Additional data on sidearm controllers is given in Ref. 32.

In general, it would seem that the use of a sidearm controller presents a most attractive alternative to the current standard wheel or yolk controller in that it frees up the maximum amount of panel space

Longitudinal Control Force/Response Gradient (lb/g)	1.1	1.4	2.0	5.0
Very Light (3.0)	13 No pitch bobble tendency but imprecise positioning. Avg of CH 3.7	9 Pitch and lateral are both too sensitive. Avg of CH 4.4	5 Pitch and lateral both a little too sensitive. Avg of CH 5.1	1 Pitch extremely sensitive. Lateral fair. Avg of CH 6.7
Light (4.0)	14 Pitch and lateral steady and responsive. Motion noticeably large. Avg of CH 2.9	10 Pitch a little sensitive. Lateral bobble. Avg of CH 4.3	6 Slight pitch bobble. Better at higher g's. Lateral sluggish (cont. harmony). Avg of CH 4.5	2 Pitch too sensitive. Lateral wandering and sensitive. Avg of CH 6.0
Medium (5.0)	15 Motion noticeably large. No pitch bobble, slightly sluggish. Avg of CH 3.3	11 Very slight pitch bobble tendency, but good. Large lateral corrections difficult Forces high & bobble Avg of CH 4.4	7 Pitch steady once on tgt. Lateral forces high (cont. harmony) Avg of CH 3.85	3 Pitch a little sensitive. Lateral slow to respond. Avg of CH 5.0
Heavy (8.6)	16 A/C very sluggish and forces uncomfortable. Avg of CH 5.0	12 A/C sluggish but stable. Forces heavy. Avg of CH 4.5	8 Pitch steady but forces too heavy. Lateral forces to heavy. Tiring. Avg of CH 4.3	4 Pitch very stable at higher g's, but forces tiring. Avg of CH 4.1

Control Force/Deflection Gradient (lb/deg)

Figure A-10. Pilot Comments and Ratings for Variations in Sidearm Controller Force Gradient Characteristics (Taken from Ref. 18) and takes advantage of an area of the cockpit that is currently not utilized. However, specific research regarding desirable characteristics for sidearm controllers in general aviation airplanes is required. In particular, the small motions inherent to a sidearm controller will result in very large control forces due to the lack of mechanical advantage. This is overcome in the F-16 and Space Shuttle by the use of a fully irreversible fly-by-wire flight control system. In the case of the Vari Eze and Long Ez the control forces are relatively low because of the small size of these aircraft. However, when one considers that the elevator hinge moment increases as the cube of the elevator cord, it can be seen that the control forces will grow rapidly as the size of the aircraft is increased. Even moderate sized 4-place general aviation aircraft will probably produce excessive control forces for a typical sidearm controller. This problem must be resolved before the sidearm controller can become a viable alternative for general aviation aircraft.

APPENDIX B

SCENARIOS AND DISPLAY CONFIGURATION USED IN EXPERIMENT I

A. SCENARIOS USED IN EXPERIMENT I

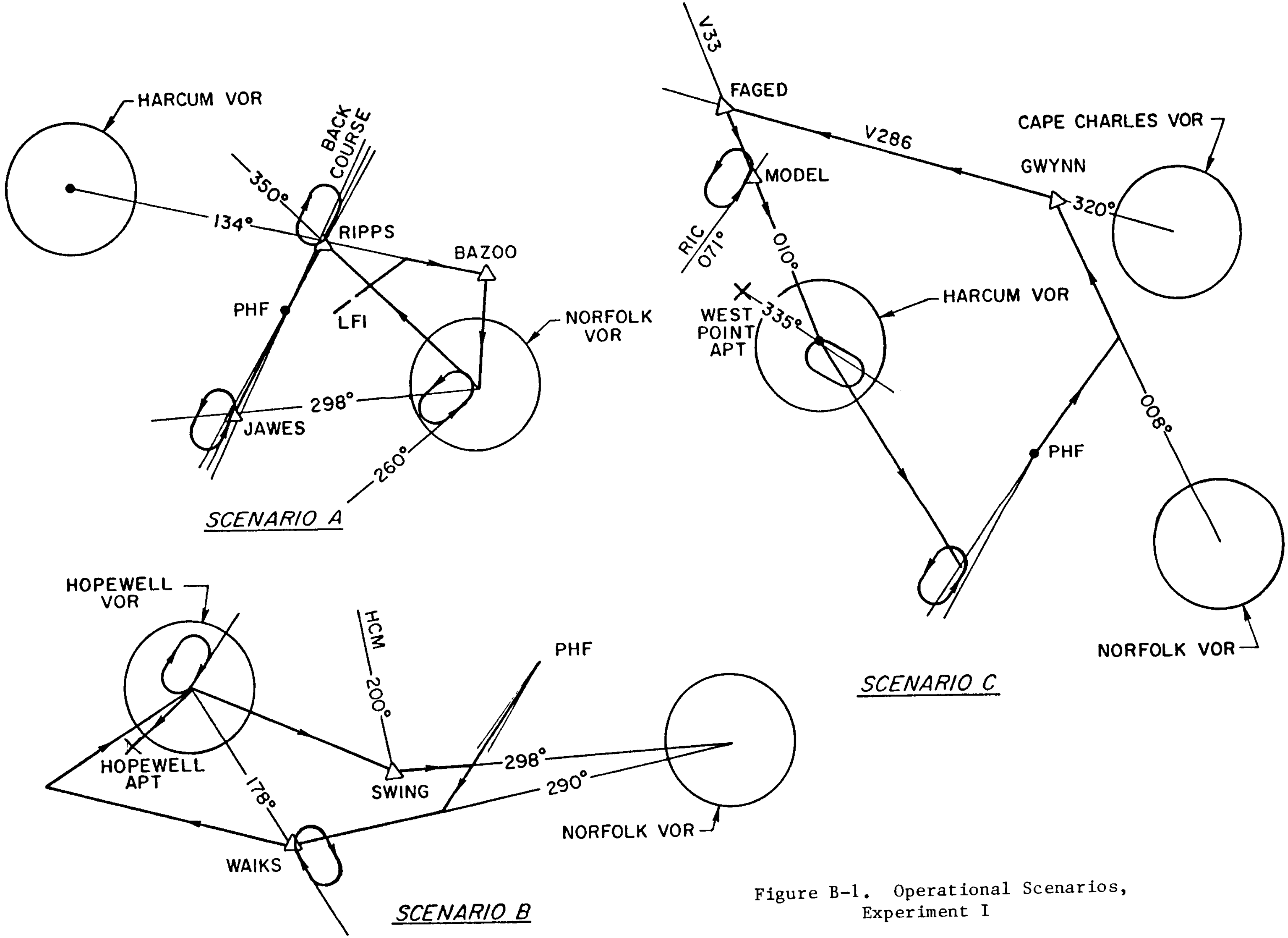
Three scenarios were developed to create a high workload environment in as realistic manner as possible. The routings and associated holding patterns and approaches are shown in Fig. B-1. The scenarios were designed to be as equivalent as possible in terms of workload requirements. Each of the three scenarios consist of four basic segments. These are as follows:

1) Departure via navigation along airways, VOR radials, and intersections to a holding fix and copying an approach clearance in the holding pattern.
2) Fly the clearance (copied above) to the final approach fix, execute a procedure turn, and the published approach procedure.
3) Execute the published missed approach procedure.
4) Return to Langley or Patrick Henry Airport via radar vectors for an ILS approach.

In the interest of run to run consistency the experiment was flown in VFR conditions using ATC only for radar traffic advisories if at all. All of the altitudes on the approach plates were increased to insure operation well above aircraft using the associated airports. This was with the exception of the last approach in which we requested radar vectors to final from Norfolk approach control

The three evaluation pilots were all senior experimental test pilots employed by the NASA Langley Research Center.

The script for each of the scenarios illustrated in Fig. B-1 is summarized below.



SCENARIO A

SCENARIO C

SCENARIO B

Figure B-1. Operational Scenarios, Experiment I

- Scenario A -- The following clearance was issued to the pilot just before departure. "NASA 503 is clear to the Patrick Henry Airport via the Harcum 134 deg radial to Bazoo intersection; then the Norfolk 041 deg radial to the Norfolk Vortac; direct. Maintain 3,000, expect 7,500 ten minutes after departure, squawk 1200, contact Norfolk departure control 125.4 leaving 2,500." Altitude restrictions were issued during the climb and were usually timed to coincide with intercepting the 134 deg radial. Once established on the 134 deg radial and just before reaching the Bazoo intersection (about 1 min) the following clearance was issued. "Hold west of the Norfolk Vortac on the Norfolk 290 deg radial left turns. Maintain 6,500 ft and expect further clearance to the Patrick Henry Airport at ________ time now ________." As the pilots became familiar with Scenario A the holding clearance was revised as follows. "You are cleared to the Deems intersection via the Norfolk 041 deg radial Norfolk Vortac. Victor 1 Deems. Hold east of Deems on the Elizabeth City 346 deg radial." Once in the holding pattern the following clearance was read. "Cleared to the Patrick Henry Airport via heading 350 deg to intercept the Norfolk 298 deg radial jaws intersection direct. Maintain 6,500." The pilot was asked to rate his workload (to be discussed subsequently) after copying this last clearance. In all cases the pilots were required to execute the published missed approach which involved either flying outbound on the back course or front course of the Patrick Henry ILS and entering a holding pattern. Once in the holding pattern a clearance for another approach was issued including a specific time to depart the holding pattern. This required the pilot to calculate the number of turns and adjust the holding pattern legs appropriately in order to depart the holding fix at the correct time. The pilots were asked to make ratings of their workload in the missed approach holding pattern and on the ground after the last approach.

- Scenario B -- The pilots were issued the following clearance on the ground just prior to departure. "NASA 506 is cleared to the Hopewell Airport via the Norfolk 290 deg radial Waiks intersection, then the Flat rock 134 deg radial Flat rock Vortac, Victor 16 Richmond Vortac, Victor 260 Hopewell Vortac direct. Maintain

3,000 ft, expect 6,000 ft 10 min after departure. Squawk 1200. Contact Norfolk departure control 125.7 leaving 2,000 ft." As with Scenario A the pilot was issued altitude restrictions and speed restrictions to increase his workload while intercepting the Norfolk 290 deg radial. Three minutes from the Waiks intersection the pilot was read the following clearance. "NASA 506 is cleared to the Waiks intersection hold south of Waiks on the Hopewell 178 deg radial. Expect further clearance to Hopewell at _______ time now _______. Maintain 5,500 ft and contact Norfolk departure control 124.9." From Fig. 17 it can be seen that holding south of Waiks intersection on the Hopewell 178 deg radial involved a parallel entry. The clearance was read to the pilot 3 minutes before reaching the Waiks intersection (in accordance with the minimum time recommended by the FAA). Inasmuch as the parallel holding pattern entry requires a considerable amount of planning the pilot workload tended to be quite high during the 3 minutes before Waiks. In accomplishing such planning, the pilots were required to collect a considerable amount of information in short-term memory to be executed once reaching the Waiks intersection. Speed restrictions were issued just prior to Waiks which tended to wipe out considerable parts of short-term memory, in many cases, requiring the pilots to look back at their charts and recheck tuning of VOR's, DME, etc. This tends to support the Fig. 2 pilot model in which it is hypothesized that an overridingly important piece of information (a request by ATC) tends to eliminate information existing in the short-term memory. Blunders tended to occur as the pilot worked on restoring the appropriate information in short-term memory (checking radio frequencies, omni bearing selectors, and his chart). In the holding pattern at Waiks intersection, the following clearance was issued. "NASA 506 is cleared to the Hopewell Airport via the Flat rock 134 deg radial to intercept Victor 213 then via Victor 213 to the Hopewell Vortac direct. Depart the holding pattern at ________ time now ________." Before executing the departure from the holding pattern the pilot was asked to perform his ratings while the safety pilot continued to fly in the race track pattern. After executing the VOR approach to the Hopewell Airport the pilot was requested to execute the published missed approach and was read the following clearance once established in the holding pattern at the Hopewell VOR. "NASA 506 is cleared to the Patrick Henry Airport via the Hopewell 140 deg radial Swing intersection, then the Norfolk 298 deg radial, Jaws intersection, direct. Maintain 4,500 and contact Norfolk approach control 124.9 passing the Swing intersection." After executing the ILS approach to Patrick Henry Airport the pilots were asked to rate the final segment of Scenario B.

- Scenario C -- The pilots were read the following clearance on the ground just before departure. "NASA 506 is cleared to the Westpoint Airport via heading 080 deg to intercept the Norfolk 008 deg radial Gwynn intersection, Victor 286 to Faged intersection, Victor 33 to the Harcum Vortac direct. Maintain 7,500, squawk 1200, contact Norfolk departure control 125.4 leaving 1,500 ft." Once established on Victor 286 the pilot was read the following clearance. "NASA 506 is cleared to the Model intersection via Victor 286 to the Richmond 071 deg radial, direct Model. Hold west of Model on the Richmond 071 deg radial." Reference to Fig. 26 indicates that the pilot was required to execute a parallel entry into the holding pattern. Once established in the holding pattern the pilot was requested to make his workload ratings while the safety pilot flew in the race track pattern. After accomplishing the rating, the pilot was read the following clearance. "NASA 506 is cleared to the Westpoint Airport via direct the Harcum VOR direct. Descend and maintain 6,500, report reaching. Contact Norfolk approach control 119.45. Report crossing the Harcum Vortac inbound out of procedure turn." After executing the VOR approach to Westpoint, and the missed approach, the pilot was requested to give his workload ratings once established in a holding pattern at the Harcum VOR. After completing those ratings, he was asked to actually contact Norfolk approach control for radar vectors for an ILS approach to Patrick Henry Field. Scenario C required somewhat longer to accomplish than Scenarios A or B.

Scenario C required about 1:20 whereas Scenarios A and B required about 1:00 to complete.

Scenarios A, B, and C were used in Phase I. The instrument approaches shown in Figs. 8 and 9 were added during Phase 2 in lieu of scenarios B and C.

B. INSTRUMENT PANELS ON TEST AIRCRAFT — EXPERIMENT I

Four instrument panel configurations were utilized in these tests as shown in Figs. B-2 through B-5.

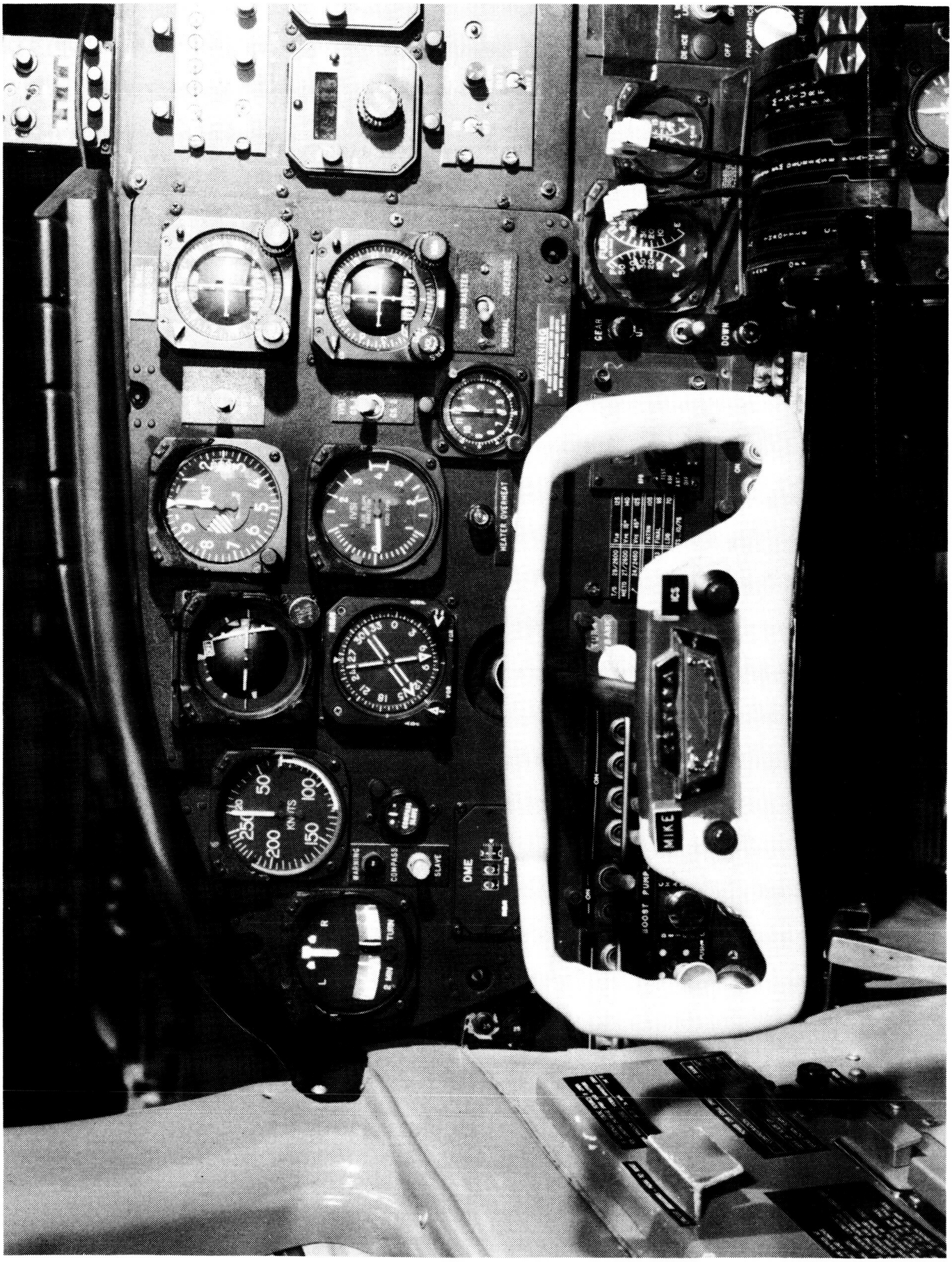


Figure B-2. Cessna 310 Instrument Panel Used in Phase 1 of Experiment I

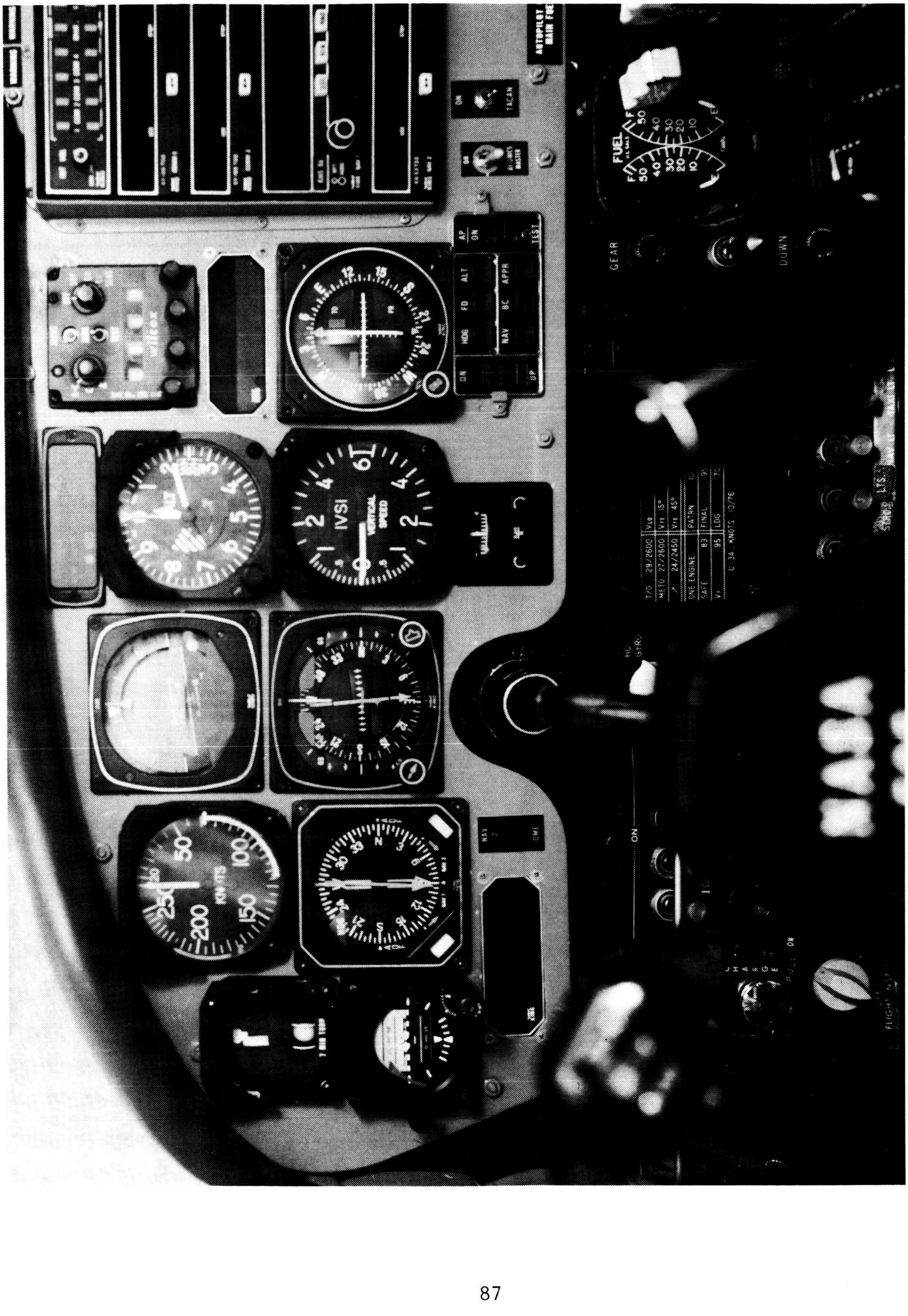


Figure B-3. Cessna 310 Instrument Panel Used in Phase 2 of Experiment I

NASA
L-81-5327

Figure B-4. Beech Queenair Instrument Panel Used in Phase 1 of Experiment I

L-82-4,625

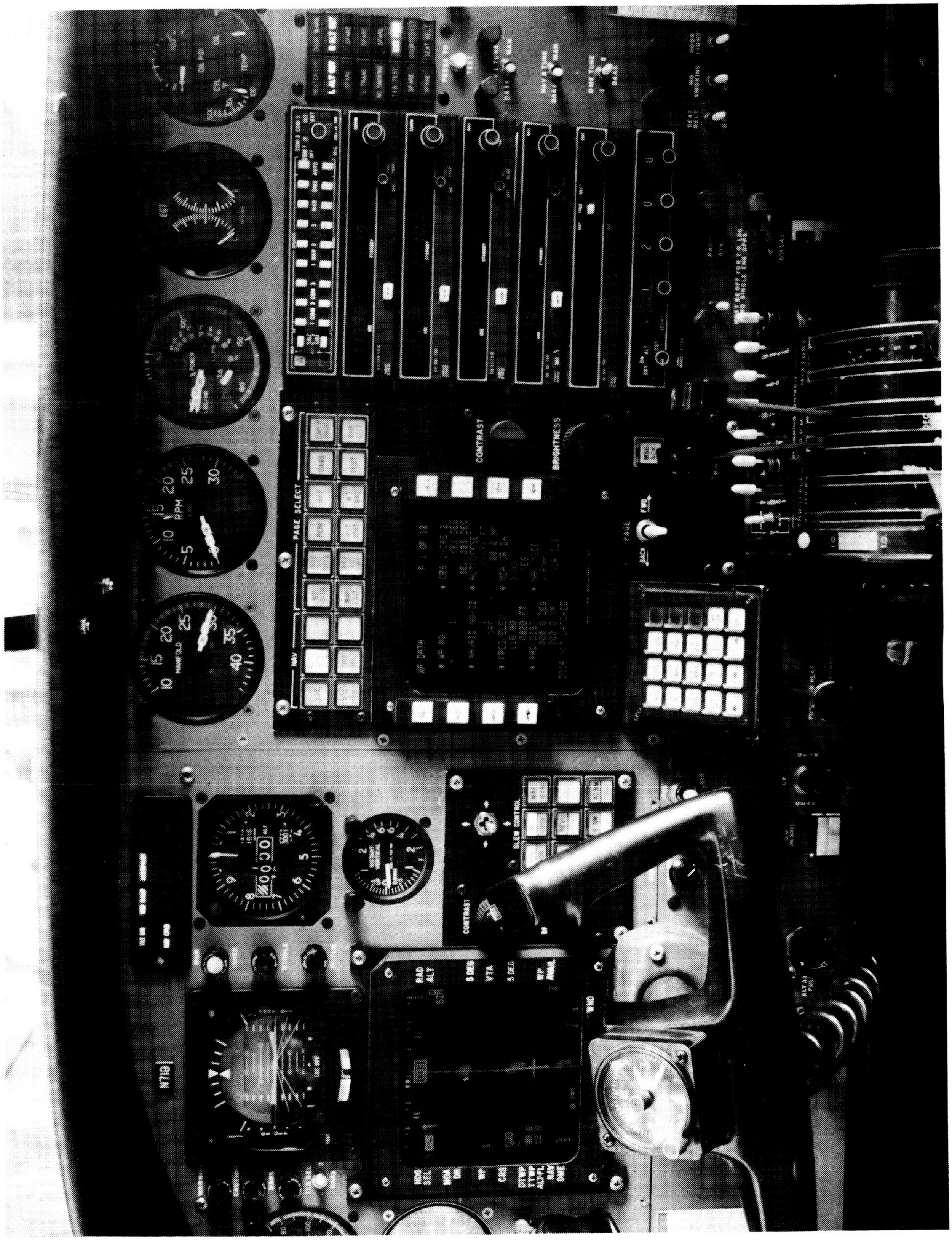


Figure B-5. Cessna 402B Instrument Panel with Moving Map Display Used in Phases 1 and 2 of Experiment I

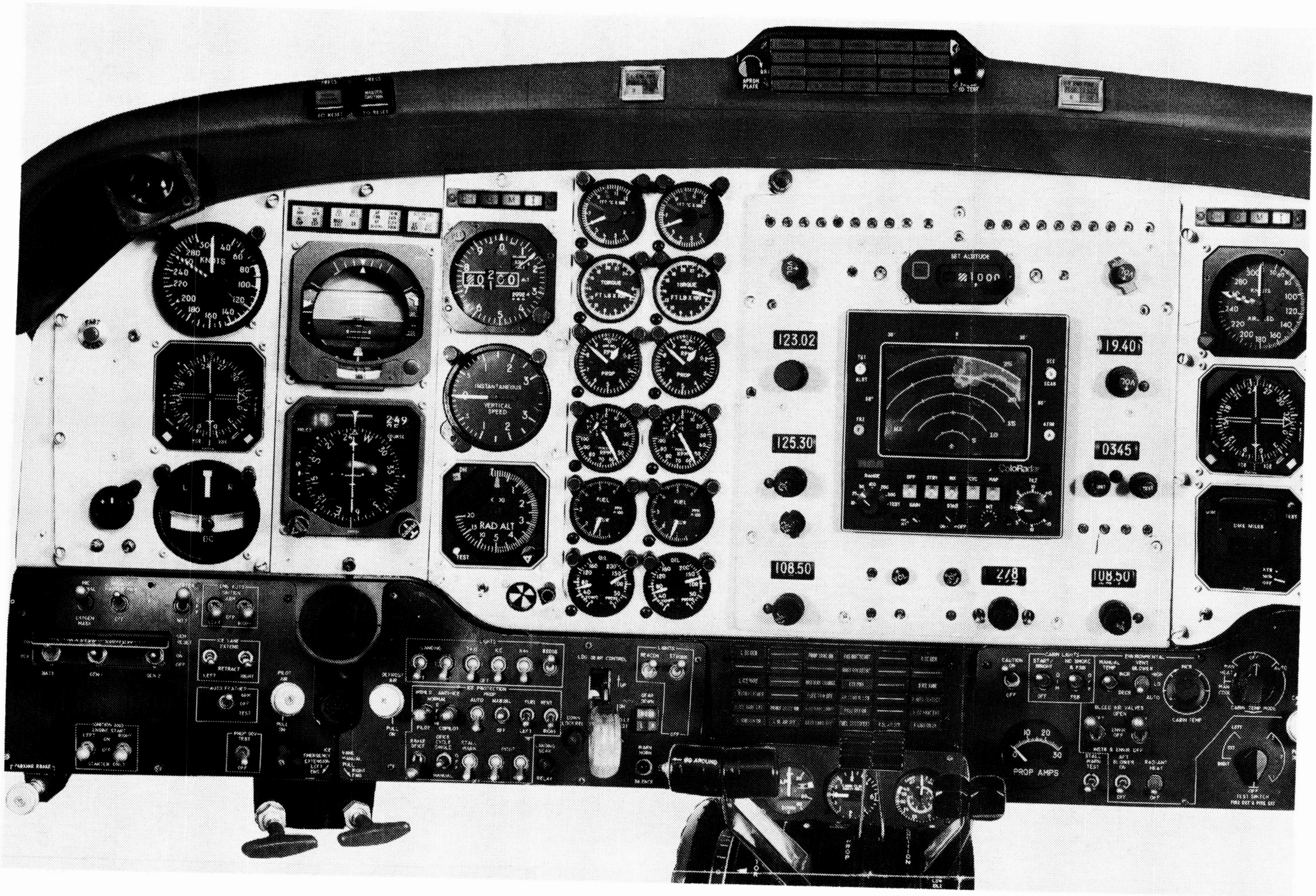


Figure B-6. Beech King Air Instrument Panel Used in Experiment II (Flight Safety Task Simulator)

APPENDIX C

SCENARIOS AND DISPLAY CONFIGURATION USED IN EXPERIMENT II

The instrument panel for the Beech King Air as it existed in the Flight Safety International simulator used in Experiment II is shown in Fig. B-6.

SPIFR SCENARIO 1 — Abort to San Jose (SJC)

Situation -- Aircraft departed LAX enroute to SEA and is currently over the San Francisco Bay area south of Oakland.

Weather -- Widespread area of low ceilings between 500 and 1000 ft. with visibilities between 1 and 3 miles decreasing to 1/2 mile in rain showers. This system extends over the entire western United States. Tops between 17000 and 30000 ft.

LAX 2 OVC 1/2 FRW

SEA 5 OVC 1 1/2 --R

Initial Condition

- IMPLY intersection (on V107 south of OAK)
- 39 deg 33 min 10 sec N Lat and 121 deg 57 min.

  55 sec W Long, or OAK 114 deg rad at 16 nm.
- Heading = 294 deg.
- Altitude = 29,000 ft.
- Wind is 50 kts. from 290 deg mag.

SCRIPT

Instructor -- Chip light on (left or right engine) shortly after initiating simulation.

Pilot -- Shuts down and secures engine and advises ATC of his problem.

Instructor -- Suggest San Jose as the best alternate with 1500 overcast and 3 miles visibility.

Pilot -- Advises of intention to proceed to San Jose.

Instructor -- Asks pilot when ready to copy and subsequently reads clearance "King Air 1234A is cleared to the SFO airport via V107E to the SUNOL intersection, V334 to the SJC Vortac, direct, descend and maintain 5000, cross SUNOL at 5000, if unable hold east of SUNOL on the Stockton (SCK) 229 deg radial. Squawk 1379. Report reaching 5000, or established in the holding pattern. Expect ILS R30L approach."

Instructor -- Moderate turbulence at 15,000 ft.

Instructor -- Restrict descent if necessary to guarantee necessity for holding at SUNOL intersection.

Instructor -- Moderate icing at 10,000 ft.

Pilot -- Turn on anti-icing equipment.

Instructor -- at 8000 ft., turn on chip light and low oil pressure light for operating engine, and fire warning a few seconds later.

Pilot -- Shuts down operating engine and starts engine which was shut down earlier. Advises ATC of emergency.

Instructor -- Reads clearance: "King Air 1234A is cleared for the SJC ILS Runway 12R approach, present position direct to the SJC Vortac, descend and maintain 3000, squawk 4374, contact Bay Approach on 120.1."

Pilot -- Reads back clearance, contacts Bay Approach, and secures dead engine while setting out for SJC.

Instructor -- "This is Bay Approach, report inbound out of procedure turn to SJC tower on 124.0, say altitude leaving."

Instructor -- Icing off at 4000.

Instructor -- Wind shift to 210 deg at 10 kts out of 4000 ft.

Pilot -- Reports inbound to SJC tower on 124.0.

Instructor -- "King Air 1234A is cleared to land Runway 12R, wind 210 deg at 10 gust to 15.

Pilot -- Lands and gives ratings.

SPIFR SCENARIO 2 -- Abort to San Francisco (SFO)

Initial Conditions

- BUSH intersection (on V107 south of OAK)
- Heading 301 deg.
- Altitude 30,000 ft.
- Wind is 50 kts from 290 deg.

SCRIPT

Instructor -- Chip light on (left or right engine) shortly after initiating simulation.

Pilot -- Shuts down and secures engine.

Instructor -- Advises that SFO is the best place to go in terms of weather.

Instructor -- Reads clearance "King Air 1234A is cleared to the SFO airport via V107E to the OAK Vortac, direct BRIJJ. Expect the runway 28R ILS approach. Cross the SUNOL intersection at 5000, if unable hold west of SUNOL on the 093 deg radial of the OAK Vortac. Squawk 4173. Report reaching 5000, or established in the holding pattern. The SFO weather is 400 overcast, visibility 1/2 in light rain showers, wind is 240 deg at 10 gust to 20."

Instructor -- Moderate Turbulence at 17,000.

Instructor -- Moderate icing at 12,000.

Pilot -- Turns on anti-icing equipment.

Instructor -- At 10,000 ft., turn low oil pressure light and reduce oil pressure to value for mandatory shut-down on operating engine, and initiate fire warning a few seconds later.

Pilot -- Shuts down operating engine, activates fire bottle and starts engine which was shut down earlier. Advises ATC of new emergency.

Instructor -- Reads clearance: "King Air 1234A is cleared for the SFO runway 28R ILS approach via present position, direct the BRIJJ outer compass locater. Descend and maintain 3000, squawk 5386, contact Bay Approach 120.1."

Pilot -- Reads back clearance, contacts Bay Approach, and secures dead engine while setting out for BRIJJ.

Instructor -- "This is Bay Approach, report inbound out of procedure turn to SFO tower on 120.5."

Instructor -- Icing off at 4000 ft.

Instructor -- Wind shift to 180 deg at 10 kt. out of 4000 ft.

Pilot -- Reports inbound to SFO tower on 120.5.

Instructor -- "King Air 1234A is cleared to land Runway 28L, wind 180 deg at 10 kt gusts to 15 kt.

Pilot -- Lands and gives ratings.

SPIFR SCENARIO 3 — LAX to SAN, Abort to LGB Due to Engine Fire

Weather -- LAX 400 overcast, visibility 1 mile in fog. Wind is 240 deg at 20 kts. Moderate rain showers east. SAN 200 overcast, visibility 1/2 in moderate rain. Widespread area of low ceilings with visibilities between 1 and 3 miles, throughout California, Nevada, and Arizona. Visibilities less than 1 mile in rain showers. Tops between 20,000 and 25,000 ft. Pilots report moderate turbulence below 20,000 ft. and moderate mixed icing in clouds above 4000 ft.

Initial Conditions

On ground at LAX. All checklists complete and in position for takeoff.

SCRIPT

Instructor -- Reads clearance "King Air 1234A is cleared to the San Diego Lindbergh Airport via V25 Mission Bay Vortac, direct. Maintain 13000. Maintain runway heading to 1000, then turn left to intercept V25, on course. Squawk 5431 just before departure. Contact LAX departure control 124.3 out of 2000, and tower on 119.3 when ready for takeoff."

Instructor -- Fail an engine just after liftoff - turn on fire warning, oil pressure, and fuel pressure lights on failed side.

Pilot -- Advises ATC of his problem.

Instructor -- "King Air 1234A is cleared to climb on runway heading to 1000 ft., and then turn left to a heading on 070 deg for a vector to the LAX runway 24R final approach course." Maintain 2500 ft.

Instructor -- When aircraft is abeam LAX advise pilot that "LAX is below minimums (ceiling zero, RVR = 600 ft.). Santa Monica, Long Beach, and Hawthorne airports are above minimums. Advise when ready to copy weather."

Instructor --

- LGB is 800 overcast, visibility 1 mile wind is 300 deg at 5 kts. ILS runway 30 approach in use.
- SMO is 600 overcast, visibility 1 1/4 mile in moderate rain, wind 350 deg at 20, gusts to 30. VOR alpha approach in use.
- Hawthorne is 600 overcast, visibility 1 mile wind 170 deg at 20, gusts to 30.

Pilot -- Selects LGB. If not, he is convinced to do so.

Instructor -- Asks pilot when he is ready to copy clearance to LGB. Reads clearance. "King Air 1234A is cleared to the LGB airport via present position to intercept V25, ALBAS intersection. Maintain 5000 ft. Squawk 5201. Expect ILS Runway 30 approach."

Pilot -- Copies clearance, and gets out approach plate.

Instructor -- Advises pilot to contact coast approach on 127.2.

Pilot -- Contacts coast approach.

Instructor -- Advises pilot that "the LGB ILS is out of service, expect the VOR runway 30 approach. Squawk 4432 and ident."

Instructor -- At the ALBAS intersection, read the following clearance, "King Air 1234A is cleared for the VOR runway 30 approach to the LGB airport. Report inbound out of procedure turn to the tower on 119.4 and squawk 4432 and ident."

Instructor -- Set simulated winds to 090 deg at 15 kts.

Instructor -- Fail number one compass while pilot is copying clearance.

Pilot -- Completes procedure turn and reports inbound.

Instructor -- Clears 1234A for the approach.

Pilot -- Initiates missed approach.

Instructor -- Terminates simulation.

SPIFR SCENARIO 4 -- LAX to SAN, Abor to SMO due to Engine Problems

Weather -- LAX 400 overcast, visibility 1 mile in fog. Wind is 240 deg at 10 kts. Moderate rain showers east. Altimeter 29.90. SAN 200 overcast, visibility 1/2 in moderate rain. Widespread area of low ceilings with visibilities between 1 and 3 miles, throughout California, Nevada and Arizona. Visibilities less than 1 mile in rain showers. Tops between 20,000 and 25,000 ft. Pilots report moderate turbulence below 20,000 ft. and moderate mixed icing on clouds above 4000 ft.

Initial Conditions

On ground at LAX. All checklists complete and in position for takeoff.

SCRIPT

Instructor -- Reads clearance "King Air 1234A is cleared to the San Diego Lindbergh Airport via V25 Mission Bay Vortac, direct. Maintain 13000. Maintain runway heading to 1000, then turn left to intercept V25, on course. Squawk 5431 just befor departure. Contact LAX departure control 124.3 out of 2000, and tower on 119.3 when ready for takeoff."

Instructor -- Fail an engine just after liftoff -- turn on oil pressure, and fuel pressure lights on failed side.

Pilot -- Advises ATC of his problem.

Instructor -- "King Air 1234A is cleared to climb on runway heading to 1000 ft., and then turn left to a heading of 070 deg for a vector to the LAX runway 24R final approach course. Maintain 2200 ft."

Instructor -- When aircraft is abeam LAX advise pilot that "LAX is belew minimums (ceiling zero, RVR = 600 ft.). Santa Monica, Long Beach, and Hawthorne airports are above minimums. Advise when ready to copy weather."

Instructor --

- LGB is 200 overcast, visibility 1/2 mile in moderate rain. Wind is 360 deg at 20 kts. ILS runway 30 approach in use.
- SMO is 1500 overcast, visibility 1 1/2 mile in light rain, wind is light and variable, VOR alpha approach in use.
- Hawthorne is 600 overcast, visibility 1 mile, wind 170 deg at 20, gusts to 30. VOR runway 25 approach in use.

Pilot -- Selects SMO. If not, he is convinced to do so.

Instrument -- Asks pilot when he is ready to copy clearance to SMO. Reads clearance. "King Air 1234A is cleared to the SMO airport via present position direct SLI Vortac, V8 to the POM 164 deg radial, the POM 164 deg radial to the VNY 096 radial, the VNY 096 radial to Darts intersection, direct. Maintain 4000, and expect 5000 in 10 miles. Expect VOR alpha approach to SMO.

Pilot -- Copies clearance, and gets out approach plate.

Instructor -- Advises pilot to contact Los Angeles Approach on 124.5.

Pilot -- Contacts LAX Approach.

Instructor -- Squawk 4432 and ident. Climb and maintain 5000, report reaching.

Pilot -- Reports reaching 5000.

Instructor -- "Report Elmoo intersection. SMO weather now 600 overcast, visibility 1 mile in light rain and fog, altimeter 29.87."

Instructor -- Set simulated winds to 280 deg at 15 kts.

Instructor -- Sets up simulator so landing gear must be extended manually.

Pilot -- Reports Elmoo intersection.

Instructor -- "King Air 1234A is cleared for the VOR alpha approach to SMO, report Bevy intersection to the tower on 120.1. Maintain 5000 until established on the final approach course. Current SMO altimeter is 29.87."

Pilot -- Reports problem with landing gear.

Instructor -- If pilot is on tower frequency, have him change to Approach on 124.5 and read the following clearance "King Air 1234A is cleared to hold north of Darts on the SMO 032 radial. Maintain 5000. Report established in the holding pattern, and advise when ready to initiate the approach."

Pilot -- Advises he is ready.

Instructor -- King Air 1234A is cleared for the VOR alpha approach, contact the tower on 120.1 at Bevy.

Instructor -- "King Air 1234A is cleared to land runway 21, wind is 280 deg at 15.

Pilot -- Initiates missed approach.

Instructor -- Terminates simulation.

SPIFR SCENARIO 5 — LAX to SAN, Abort to HHR Due to Engine Failure

Weather -- LAX 400 overcast, visibility 1 mile in fog. Wind is 240 deg at 10 kts. Moderate rain showers east. SAN 200 overcast, visibility 1/2 in moderate rain. Widespread area of low ceilings with visibilities between 1 and 3 miles, throughout California, Nevada, and Arizona. Visibilities less than 1 mile in rain showers. Tops between 20,000 and 25,000 ft. Pilots report moderate turbulence below 20,000 ft. and moderate mixed icing in clouds above 1000 ft.

Initial Conditions

On ground at LAX. All checklists complete and in position for takeoff.

SCRIPT

Instructor -- Reads clearance "King Air 1234A is cleared to the San Diego Lindbergh Airport via V25 Mission Bay Vortac, direct. Maintain 13000. Maintain runway heading to 1000, then turn left to intercept V25, on course. Squawk 5431 just before departure. Contact LAX departure control 124.3 out of 2000, and tower on 119.3 when ready for takeoff."

Pilot -- Calls LAX departure.

Instructor -- King Air 1234A climb and maintain 13000.

Instructor -- Turns on chip light on one engine as aircraft passes through 500 ft. This is followed by a low oil pressure light and failure of the engine.

Pilot -- Advises ATC of his problem.

Instructor -- Advises pilot that "LAX is below minimums (ceiling zero, RVR = 600 ft.). Santa Monica, Long Beach, and Hawthorne airports are above minimums. Advise when ready to copy weather."

Instructor --

- LGB is 200 overcast, visibility 1/2 mile, wind is 350 deg at 25 kts. ILS runway 30 approach in use.
- SMO is 600 overcast, visibility 1 1/4 mile in moderate rain, wind 350 deg at 20, gusts to 30. VOR alpha approach in use.
- Hawthorne is 800 overcast, visibility 2 mile, wind is light and variable. Localizer approach to runway 25 in use.

Pilot -- Selects HHR. If not, he is convinced to do so.

Instructor -- Turns on moderate icing.

Instructor -- Asks pilot when he is ready to copy clearance to HHR. Reads clearance. "King Air 1234A is cleared to the HHR airport via resent position direct SLI Vortac, the SLI 022 deg radia to LAHAB intersection, direct. Maintain 4000. Expect the Localizer approach to runway 25."

Pilot -- Copies clearance, and gets out approach plate.

Instructor -- Advises pilot to contact LAX approach on 124.9.

Pilot -- Contacts Los Angeles Approach.

Instructor -- "King Air 1234A Squawk 4457 and ident. Hawthorne weather is measured 900 overcast, visibility 1 mile in fog, altimeter is 29.89. Report passing SLI Vortac and the LAHAB intersection. Maintain 4000."

Instructor -- After crossing SLI Vortac "King Air 1234A is cleared for the VOR Runway 25 approach, contact the tower 121.1 over Belli intersection."

Instructor -- Sets up simulator for a low inverter voltage condition half way between SLI and the LAHAB intersection.

Pilot -- Initiates missed approach.

Instructor -- Terminates simulation after one turn in the holding pattern at the LIMBO intersection.

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Final Report

16. Abstract

An analytical and experimental research program was conducted to develop criteria for pilot interaction with advanced controls and displays in single pilot instrument flight rules (SPIFR) operations. The analytic phase reviewed fundamental considerations for pilot workload taking into account existing data, and using that data to develop a divided attention SPIFR pilot workload model. The pilot model was utilized to interpret the two experimental phases. The first experimental phase was a flight test program that evaluated pilot workload in the presence of current and near-term displays and autopilot functions. The second experiment was conducted on a King Air simulator, and investigated the effects of co-pilot functions in the presence of very high SPIFR workload. The results indicate that the simplest displays tested were marginal for SPIFR operations. A moving map display aided the most in mental orientation, but had inherent deficiencies as a stand alone replacement for an HSI. Autopilot functions were highly effective for reducing pilot workload. The simulator tests showed that extremely high workload situations can be adequately handled when co-pilot functions are provided.

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