NASA Technical Paper 2783

1987

ADA279722

Effects of Combining Vertical and Horizontal Information Into a Primary Flight Display

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Summary

Great advances in pilot situational awareness and workload reduction were made with the early moving-map, horizontal situation displays, wherein the pilot was provided horizontal flight-path information in an easily interpretable form. Current work at the Langley Research Center has further advanced these display trends by orienting the vertical display around the flight path of the vehicle. In parallel with these efforts, much research has been conducted on vertical situation displays using pictorial display formats. These pictorial formats have been advocated as providing rapid, qualitative information to the pilot. Of major interest in this study is the hypothesis that some of the potential benefits of these highly advanced, pictorial-type, primary displays may be the result of a reduction of visual scan area brought about by the integration of both vertical and horizontal information and not totally caused by the advanced display form. The goal in this simulation study, then, was to determine the effects of combining vertical and horizontal flight information onto a single display. Two display configurations were used. The first configuration consisted of two display formats, a primary flight display (PFD) format and a horizontal situation display (HSD) format, where each was placed on separate displays in a conventional PFD above the HSD orientation. For the second display configuration, the HSD format was combined with the PFD format. Four subjects participated in this study. The results of this study showed that, from a performance and subjective standpoint, the combined configuration was better than the separate configuration. Also, both the eye-transition and eye-dwell times for the separate HSD were notably higher than expected, where a 46-percent increase in available visual time would occur when going from a two-display configuration to a one-display configuration.

Introduction

Except in the most modern aircraft, conventional cockpit instrumentation basically provides the pilot with attitude and ground-track error information. Great advances in pilot situational awareness and workload reduction were made with the early moving-map, horizontal situation displays, wherein the pilot was provided horizontal flight-path information in an easily interpretable form. Current work at the Langley Research Center has further advanced these display trends by orienting the vertical display around the flight path of the vehicle (ref. 1). In parallel with these efforts, much research has been conducted on vertical situation displays using pictorial display formats. These pictorial formats have been advocated as providing rapid, qualitative information to the pilot (ref. 2). Of major interest in this study is the hypothesis that some of the potential benefits of these highly advanced, pictorial-type, primary displays may be the result of a reduction of visual scan area brought about by the integration of both vertical and horizontal information and not totally caused by the advanced display form. The goal in this study, then, was to determine the effects of combining vertical and horizontal flight information onto a single display.

The authors would like to express their appreciation to Daniel S. Lampkin, R. Tracy Mead, Eric B. Opitz, and Michael Rampey, U.S. Air Force, for their time and effort in participating as test subjects in this study.

Acronyms

AEP	auditory evoked potential
HSD	horizontal situation display
MAG	magnetic
NASA-TLX	NASA task load index (TLX)
PFD	primary flight display
P300	300-msec peak amplitude
rms	root mean square
SWAT	subjective workload assessment technique
TSRV	Transport Systems Research Vehicle

Description of Equipment

Simulation Facility

This study employed a fixed-base simulator configured as the research cockpit of the NASA Transport Systems Research Vehicle (TSRV) airplane (ref. 3). This simulation included a six-degree-of-freedom set of nonlinear equations of motion as well as functionally representing the aspects of the advanced flight control configuration of the airplane with nonlinear models of the servo-actuators. The processing of the equations was performed in a Control Data Corporation (CDC) CYBER 175 digital computer at a 32-Hz iteration rate. A standard-atmosphere model with no winds was used.

Electronic primary and navigation displays were provided in the form of an over-and-under arrangement for vehicle control and guidance as well as center-mounted displays for systems management. The formats for these displays were generated on an Adage AGT 340 graphics computer. The graphics computer was linked via a digital buffer to the CDC CYBER 175 computer. The displays were stroke drawings utilizing 4 colors and contain no raster features. For this study, the primary and navigation displays were presented on cathode ray tubes (CRT) of approximately 8 inches diagonal. The cockpit arrangement of these displays can be seen in figure 1.

Airplane Control Modes

For this study, the velocity-vector control-wheel steering mode for this vehicle was used. The pilot flew the simulator through a two axis sidestick (fig. 2) rather than the panel-mounted controllers generally associated with this simulator. Manual throttles were also used throughout this study. Descriptions of the systems operations can be found in references 4 and 5.

Display Formats

The electronic primary flight display (PFD) in this simulator was tailored to the flight control system being employed. That is, the velocity-vector control-wheel steering mode was coupled to a display format which centered the displayed information about the velocity vector (refs. 1, 5, and 6). As can be seen in figure 3, the major information elements provided by this display are the velocity vector, attitude, horizon, roll indicator, pitch scale, horizontal path deviation, relative track-angle indicator, and airspeed and altitude information using moving-tape representations. These display elements were presented to the pilots in color. The color associated with each display element is shown in the table below. The airspeed and altitude symbology is further explained in references 7 and 8. The electromechanical altitude, airspeed, and vertical speed instruments in the cockpit were covered for the duration of this study.

In addition to the PFD, an electronic horizontal situation display (HSD) was provided (fig. 4). The major features of this display were a moving map, a track-angle tape with digital readout and path-track pointer, an ownship symbol, and a trend vector. The map scale for this study was fixed at 1 n.mi./in. The ownship symbol, about which the map was oriented, was located one-third upward from the bottom of the display and was laterally centered. The upper tip of this symbol was the location of the aircraft in the horizontal plane. The trend vector presented the predicted path at 30 and 60 seconds ahead of the aircraft.

Since the focus of this study was to determine the effect of combining the primary flight information (vertical and horizontal) into a single display format, two display configurations were designed around the

Display element	Color
Velocity vector	White
Attitude	White
Horizon	Green
Roll indicator	White pointer, green scale
Pitch scale	Green
Horizontal path deviation	Yellow pointer, green scale
Relative track-angle indicator	White
Moving map	White
Track-angle tape	Blue
Digital readout	Green

PFD and HSD formats. The first configuration was considered the baseline configuration and consisted of the two display formats placed on separate displays in a conventional PFD above the HSD orientation. This configuration was deemed the "separate" configuration. For the second display configuration, the PFD format was overlaid by the HSD format. The only change to the original HSD format in this configuration was the deletion of the track-angle information and the ownship symbol. In this configuration, deemed the "combined" configuration, the upper tip of the velocity-vector diamond was also used as the ownship position for the moving map. Figure 5 is an example of this display. It should be noted that the symbol size and displacement for each particular element were the same for each configuration. It should also be noted that this combined display configuration is not being advocated as an actual flight display format, though formats of this nature have been considered for a flight environment (ref. 9), but was designed solely to determine the effect of a combined format.

Task Description and Conditions

Primary Task

Each simulation run was conducted along one of seven paths. All the paths included vertical maneuvers (climbs and/or descents), speed changes, and course changes. Each path required 180 sec to complete. One path, designated path 7, was considered as a low-workload path. This path required a climb, a level-off, a turn to the left, and an acceleration. The remaining 6 paths, designated paths 1 to 6, were all designed to be of similar difficulty and to produce equivalent pilot workload and tracking deviations. These paths were all considered as moderate-to-high-workload paths, where the path changed in altitude (requiring no more than a 3° change in flight-path angle), speed (requiring no more than a 20-knot change), course (requiring no more than a 20° bank angle), or some combination of the three at approximately 15-sec intervals. These moderate-to-high-workload paths were designed to require constant attention for vertical tracking, horizontal tracking, and speed maintenance.

Altitude and speed changes were shown on the display by the altitude and airspeed reference pointers. These reference values were ramped over a 5-sec period to avoid discrete changes in the values. Course changes were shown by the horizontal path on the moving map. The paths were designed so that no aircraft configuration changes were required. The airplane was initialized at an airspeed of 150 knots, with flaps at 25°, in level flight, and on the path. The pilot's primary task was to fly the airplane along this path with a minimum of deviation in altitude, airspeed, and cross-track error. With the exception of path 7, no foreknowledge of the paths was provided to the pilots.

Mental Workload Estimation and Secondary Task

To determine the mental workload of the pilot during the primary flight task, an electrical brain response measurement method was used. The procedure (ref. 10) is as follows: a series of auditory tones (high- and low-pitched tones) are presented to the pilot, the pilot is instructed to mentally count only the low-pitched tones, and the auditory evoked potential (AEP) to each tone is recorded. The pilot's total count was recorded at the end of each simulation run. When the counting is the pilot's only task, the brain activity waveform peaks at approximately 300 msec (P300) in response to the counted, low-pitched tones, and not to the uncounted, high-pitched tones. When the pilot is heavily engaged in a flight task, the waveform changes. An example of this is shown in figure 6, where the area of interest in this figure is between approximately 200 and 400 msec. The attention that the pilot is devoting to the counting task is related to the difference between the AEP waveform to the counted tones and the noncounted tones. This technique has been shown to reliably discriminate between task and no-task conditions. As a secondary part to this study, AEP data obtained were used to assess this measurement technique for the ability to discriminate gradations between the task and no-task extremes (that is, mental-demand effects between the two display configurations). In addition, since the pilots were required to count the low-pitched tones, this measurement technique was in itself an auditory, secondary workload task.

Data

Sampled data were gathered throughout the run and included path performance parameters, pilot-control inputs, auditory evoked response parameters, oculometer measurements, and heart rate. Through the use of questionnaires, subjective pilot opinion was gathered after each simulation run. (See appendix.) Included in the questionnaire data of the appendix was scoring for the subjective workload assessment technique (SWAT) of references 11 and 12 and for the NASA task load index (NASA-TLX) of reference 13.

Conditions

Four evaluation pilots were used in this study. All the pilots were U.S. Air Force operational pilots, qualified in multiengine jet airplanes. The pilots were briefed prior to the simulation tests with respect to the display configurations, the control system, the secondary workload task, and the recorded performance measurements. In addition, each pilot was provided with approximately 12 hours of familiarization and practice in the simulator prior to the actual test runs. The low-workload path, path 7, and several representative high-workload paths were used in practice. With the exception of a general description of the task, no familiarization or briefing was provided regarding the actual, moderate-to-high-workload, flight profiles.

Each pilot flew a total of 32 data runs in the simulator. All runs were flown in the velocity-vector control-wheel steering mode through a sidestick controller and with manual throttles. The test sequence is given in table I. The order of the test was counterbalanced within each block of eight runs to reduce carryover effects.

Simulation Results and Discussion

In this study, the statistical results were deemed significant at the 95-percent confidence level. (See ref. 14.) Additionally, differences in results between the display configurations were deemed experimentally significant only if the difference in mean values, across all runs for that configuration, was greater than 20 percent. (The 20-percent value was chosen prior to the data analysis as a level for practical significance.) For example, the difference in root-mean-square (rms) altitude error for the separate and

Table I. Test Sequence

Run	Configuration	Path	Pilot	Run	Configuration	Path	Pilot
1	Separate	7	1	33	Separate	2	2
2	Combined	7	1	34	Combined	3	2
3	Separate	3	1	35	Separate	6	2
4	Combined	1	1	36	Combined	4	2
5	Separate	5	1	37	Separate	5	2
6	Combined	4	1	38	Combined	1	2
7	Separate	2	1	39	Separate	7	2
8	Combined	6	1	40	Combined	7	2
9	Separate	4	1	41	Combined	7	2
10	Combined	5	1	42	Separate	7	2
11	Separate	1	1	43	Separate	3	2
12	Combined	2	1	44	Combined	5	2
13	Separate	6	1	45	Separate	1	2
14	Combined	3	1	46	Combined	2	2
15	Combined	7	1	47	Separate	4	2
16	Separate	7	1	48	Combined	6	2
17	Separate	1	1	49	Combined	7	2
18	Combined	2	1	50	Separate	7	2
19	Separate	5	1	51	Separate	5	2
20	Combined	3	1	52	Combined	3	2
21	Separate	4	1	53	Separate	4	2
22	Combined	6	1	54	Combined	2	2
23	Combined	7	1	55	Separate	6	2
24	Separate	7	1	56	Combined	1	2
25	Separate	7	1	57	Separate	3	2
26	Combined	7	1	58	Combined	4	2
27	Separate	6	1	59	Separate	2	2
28	Combined	4	1	60	Combined	6	2
29	Separate	2	1	61	Separate	1	2
30	Combined	1	1	62	Combined	5	2
31	Separate	3	1	63	Separate	7	2
32	Combined	5	1	64	Combined	7	2

Table I. Concluded

Run	Configuration	Path	Pilot
65	Combined	7	3
66	Separate	7	3
67	Combined	2	3
68	Separate	1	3
69	Combined	6	3
70	Separate	5	3
71	Combined	3	3
72	Separate	4	3
73	Separate	7	3
74	Combined	7	3
75	Combined	1	3
76	Separate	3	3
77	Combined	5	3
78	Separate	6	3
79	Combined	4	3
80	Separate	2	3
81	Combined	6	3
82	Separate	1	3
83	Combined	3	3
84	Separate	5	3
85	Combined	2	3
86	Separate	4	3
87	Separate	7	3
88	Combined	7	3
89	Combined	1	3
90	Separate	2	3
91	Combined	5	3
92	Separate	6	3
93	Combined	4	3
94	Separate	3	3
95	Combined	7	3
96	Separate	7	3

Run	Configuration	Path	Pilot
97	Combined	4	4
98	Separate	6	4
99	Combined	3	4
100	Separate	1	4
101	Combined	2	4
102	Separate	5	4
103	Combined	7	4
104	Separate	7	4
105	Combined	6	4
106	Separate	2	4
107	Combined	1	4
108	Separate	3	4
109	Combined	5	4
110	Separate	4	4
111	Separate	7	4
112	Combined	7	4
113	Separate	7	4
114	Combined	7	4
115	Combined	5	4
116	Separate	1	4
117	Combined	3	4
118	Separate	2	4
119	Combined	4	4
120	Separate	6	4
121	Combined	7	4
122	Separate	7	4
123	Combined	2	4
124	Separate	5	4
125	Combined	1	4
126	Separate	4	4
127	Combined	6	4
128	Separate	3	4

combined configurations had to exceed 20 percent for one to be considered better than the other.

Performance

The combined configuration produced a smaller number of throttle reversals (where a reversal is a condition for which the pilot responded in a manner opposite to what the situation required) than the separate configuration (1.5 percent and 2.1 percent of the total number of throttle inputs, respectively). No other performance results were found to be significant.

Subjective

This section focuses on the responses to the questionnaire of the appendix. In analyzing these responses, each response for each question was assigned a numerical score from 1 to 5, with 1 being the best rating (accurate, clear, liked) and 5 being the worst rating (inaccurate, confusing, disliked). Additionally, 5 subgroupings were used: situational awareness, workload, performance, eye scan, and preference. The questions relating to each of these areas are shown in table II, where the number shown in the table is the question number in the questionnaire.

Table II. Questions Used in Detailed Subjective Analysis

	Questions used
Situational awareness	13, 14, 15, 16, 22, 23, 24, 30, 31, 32, 33, 36, 37
Workload	8, 17, 25
Performance	9, 10, 11, 18, 19, 20, 26, 27, 28
Eye-scan	12, 21, 29, 34
Preference	40

The mean values of the responses to these questions are listed in table III. Similar to the quantitative analysis, the differences in responses were deemed experimentally meaningful only if the differences in mean values, across all runs, were greater than 20 percent. (The 20-percent value was used because this was equivalent to 1 block on the questionnaire.) Using this criterion, an increase of situational awareness and a reduction of eye-scan problems were shown for the combined configuration. Although not experimentally significant, the average of all the ratings given by all pilots to the combined configuration was better (statistically significant with 1.81 and 2.10 for the combined and separate configurations, respectively).

Table III. Results of Detailed Subjective Analysis

	Mean value for—	
	Separate configuration	Combined configuration
Situational awareness	[a]2.25	[a]1.86
Workload	2.61	2.37
Performance	2.20	2.07
Eye-scan	[a]2.41	[a]1.63
Preference	1.97	2.00

[a]Meaningful result.

Oculometer

Although it is obvious from the experimental design that differences should occur in the eye-scan behavior, the magnitude of these differences was notable. Two time measurements were important in understanding these data; cumulative dwell time, which is the cumulative amount of time that the eye is stabilized on some object, and cumulative transition time, which is the amount of time that the eye is moving from one object to another. It is also noteworthy to understand that the eye does not gather information while it is in transition. (See ref. 15.)

In this study, the average transition time was 33.44 sec and 22.77 sec for the separate and combined configurations, respectively. These transition times are shown graphically in figure 7. The major point of interest was that of the 33.44 sec spent in transition in the separate configuration, 15.64 sec were spent transitioning to and from the HSD. These 15.64 sec represent over 8 percent of the total time available (180 sec). Also, 41.66 sec of dwell time were obtained on the HSD with the separate configuration; this represents over 23 percent of the total time available. Because the lateral control task was relatively low frequency and the lateral path changes could be previewed, both the transition and dwell times for the HSD were notably higher than what was expected prior to this test. Additionally, from these data it can be seen that a 46-percent increase in available time would occur when going from a two-display configuration to a one-display configuration. If the visual time available for the primary display is considered critical, as in a forward-looking terrain-following display, or when one considers how this relates to pictorial, primary-display formats, where the vertical and horizontal information is included in a single display, then this last result is significant.

No other measurements were found to be either statistically or experimentally significant. This includes both SWAT (49.1 and 47.0 for the combined and separate configurations, respectively) and the NASA-TLX (51.7 and 54.2 for the combined and separate configurations, respectively), which showed no significant differences in workload between the two display configurations.

Concluding Remarks

A ground-based aircraft simulation study was conducted to determine the effects of combining vertical and horizontal flight information into a single display. Two display configurations were used in this study. The first configuration consisted of two display formats, a primary flight display (PFD) format and a horizontal situation display (HSD) format, where each was placed on separate displays in a conventional PFD above the HSD orientation. For the second display configuration, the HSD format was combined with the PFD format. The symbol size and displacement for each display element were the same for each configuration. Four subjects participated in this study, and each subject performed 32 runs. Based on the results of this study, the following conclusions are presented.

The combined display showed a reduction in throttle control errors. No other significant differences in performance were noted between the two configurations. Significant differences were found in several areas of the subjective ratings (situational awareness and eye-scan problems), with the combined display more favorably rated. Additionally, the average subjective rating given by all pilots to the combined configuration was better than that given for the separate configuration. From a performance and subjective standpoint, the combined configuration was judged to be better than the separate configuration.

A potentially important result was shown in the eye-scan behavior data. While it is obvious from the experimental design that differences should occur in the eye-scan behavior, the magnitude of these differences was notable. Because the lateral control task was relatively low frequency and the lateral path changes could be previewed, both the eye-transition and eye-dwell times for the separate HSD were higher than expected. The oculometer data showed that a 46-percent increase in available time would occur when going from a two-display configuration to a one-display configuration. This result is potentially meaningful when one considers how it relates to pictorial, primary-display formats, where the vertical and horizontal information is presented on a single display.

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November 12, 1987

Appendix

Map Display Questionnaire

SWAT

1. Time ______ Mental Effort ______ Psychological Stress ______

NASA

2. Mental Demand
   Very Low — Very High

3. Physical Demand
   Very Low — Very High

4. Temporal Demand
   Very Low — Very High

5. Performance
   Perfect — Failure

6. Effort
   Very Low — Very High

7. Frustration
   Very Low — Very High

For the following items, place a check mark [√] on the line that best reflects your opinion.

Example:

Preferred Hand

left	______	______	______	√	______	right

Speed Control

8.	easy to do	______	______	______	______	______	difficult to do
9.	few errors	______	______	______	______	______	many errors
10.	small deviations	______	______	______	______	______	large deviations
11.	few control reversals	______	______	______	______	______	many control reversals
12.	scan area minor in causing errors	______	______	______	______	______	scan area major in causing errors
13.	good situational awareness	______	______	______	______	______	poor situational awareness
14.	usually knew "actual" value	______	______	______	______	______	rarely knew "actual" value
15.	usually knew if fast or slow	______	______	______	______	______	rarely knew if fast or slow
16.	display helped situational awareness	______	______	______	______	______	display hindered situational awareness

Horizontal Tracking

17.	easy to do	______	______	______	______	______	difficult to do
18.	few errors	______	______	______	______	______	many errors
19.	small deviations	______	______	______	______	______	large deviations
20.	few control reversals	______	______	______	______	______	many control reversals
21.	scan area minor in causing errors	______	______	______	______	______	scan area major in causing errors
22.	good situational awareness	______	______	______	______	______	poor situational awareness

23.	display helped situational awareness	_____ : _____ : _____ : _____ : _____	display hindered situational awareness
24.	trend info helped situational awareness	_____ : _____ : _____ : _____ : _____	trend info hindered situational awareness

Vertical Tracking

25.	easy to do	_____ : _____ : _____ : _____ : _____	difficult to do
26.	few errors	_____ : _____ : _____ : _____ : _____	many errors
27.	small deviations	_____ : _____ : _____ : _____ : _____	large deviations
28.	few control reversals	_____ : _____ : _____ : _____ : _____	many control reversals
29.	scan area minor in causing errors	_____ : _____ : _____ : _____ : _____	scan area major in causing errors
30.	good situational awareness	_____ : _____ : _____ : _____ : _____	poor situational awareness
31.	usually knew "actual" value	_____ : _____ : _____ : _____ : _____	rarely knew "actual" value
32.	usually knew if high or low	_____ : _____ : _____ : _____ : _____	rarely knew if high or low
33.	display helped situational awareness	_____ : _____ : _____ : _____ : _____	display hindered situational awareness

Miscellaneous

34.	eye scan easy	_____ : _____ : _____ : _____ : _____	eye scan difficult
35.	colors helped legibility	_____ : _____ : _____ : _____ : _____	colors hindered legibility
36.	easy to acquire path after deviation	_____ : _____ : _____ : _____ : _____	difficult to acquire path after deviation
37.	display did not cause path acquisition difficulties	_____ : _____ : _____ : _____ : _____	display caused path acquisition difficulties

38. aircraft handling did not cause path acquisition difficulties	______ :	______ :	______ :	______ :	______	aircraft handling caused path acquisition difficulties
39. adequate separation of symbology	______ :	______ :	______ :	______ :	______	inadequate separation of symbology

40. Please check one of the following lines:

______ prefer moving map below primary display

______ prefer moving map integrated into primary display

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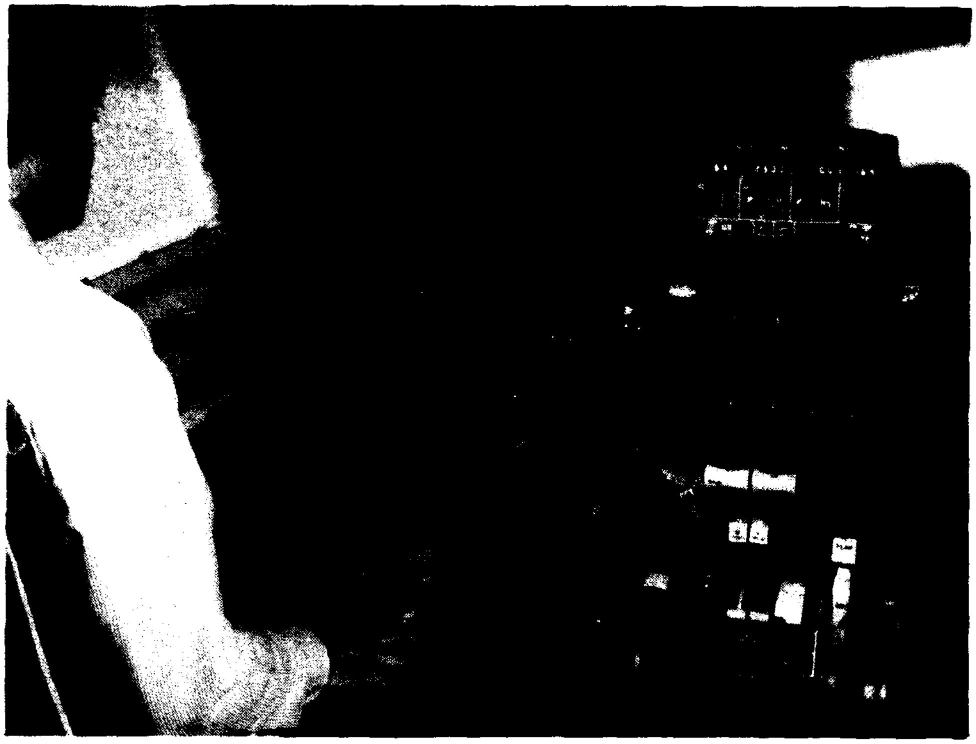

L-80-2111

Figure 1. Simulator cockpit.

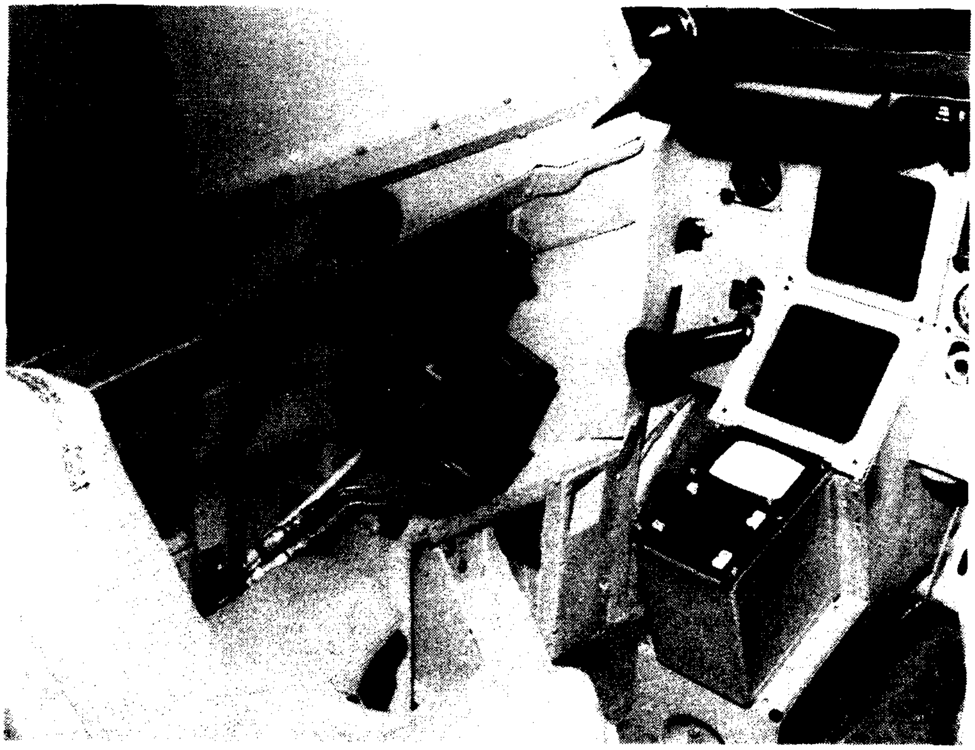

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Figure 2. Two-axis sidestick controller.

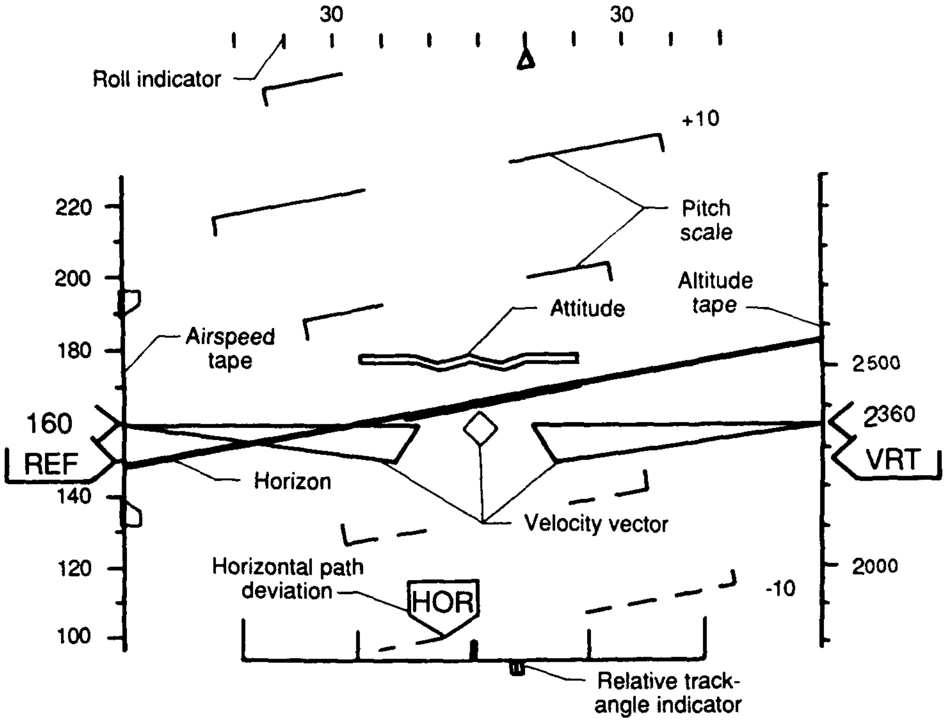


Figure 3. Primary flight display (PFD) format.

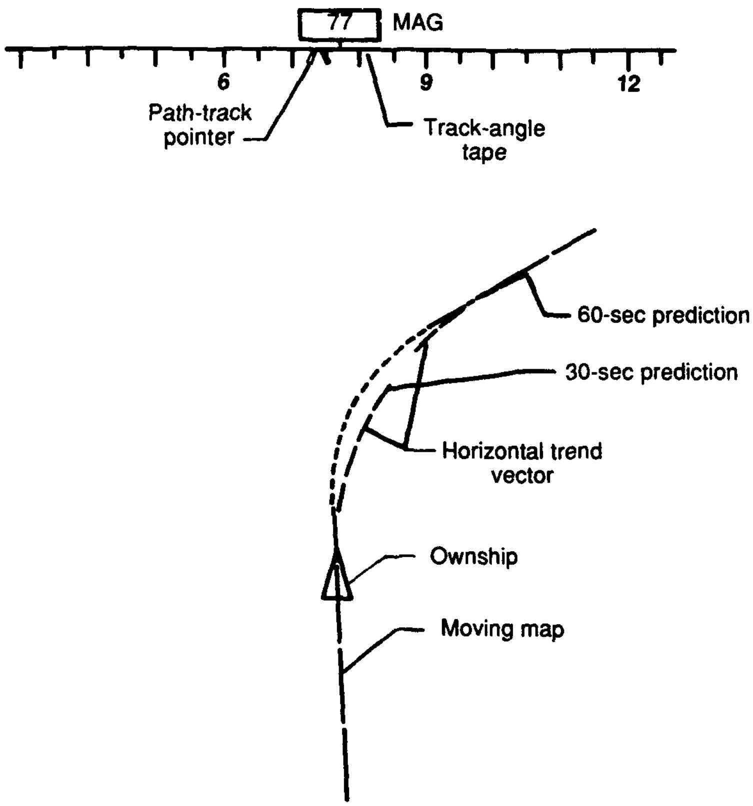


Figure 4. Horizontal situation display (HSD) format.

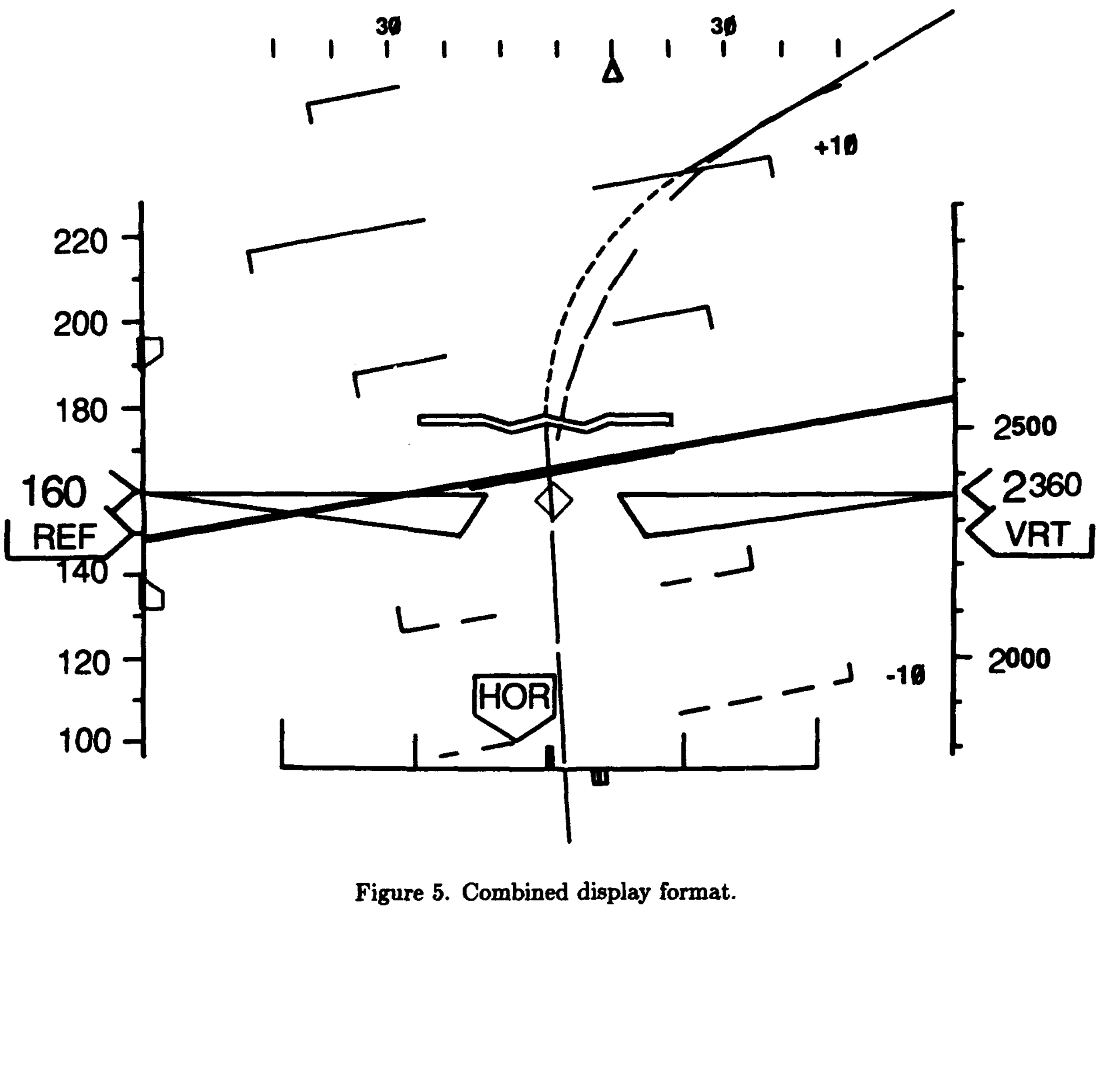
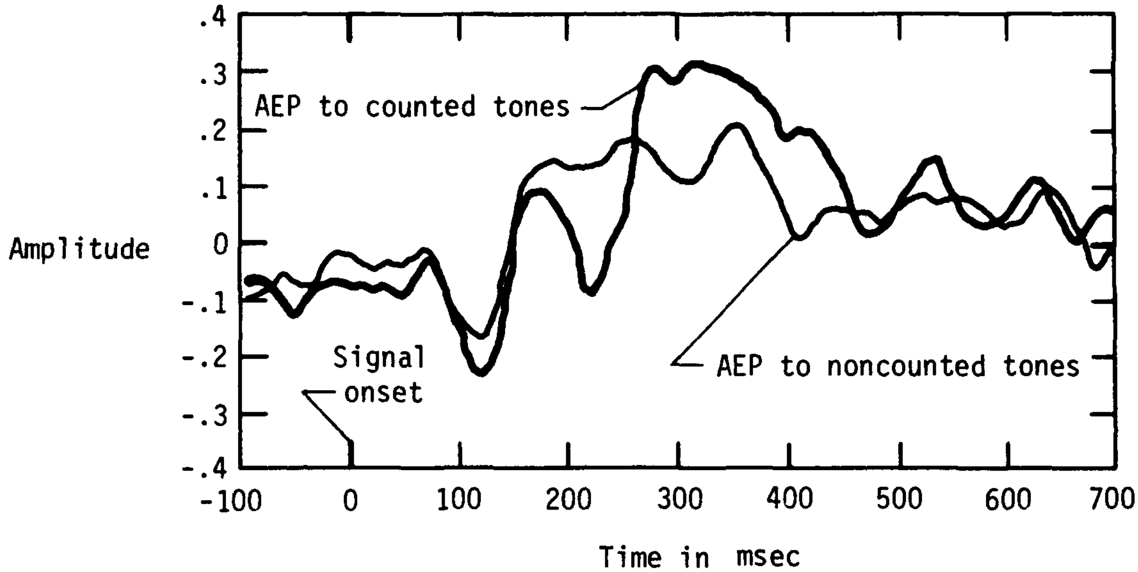
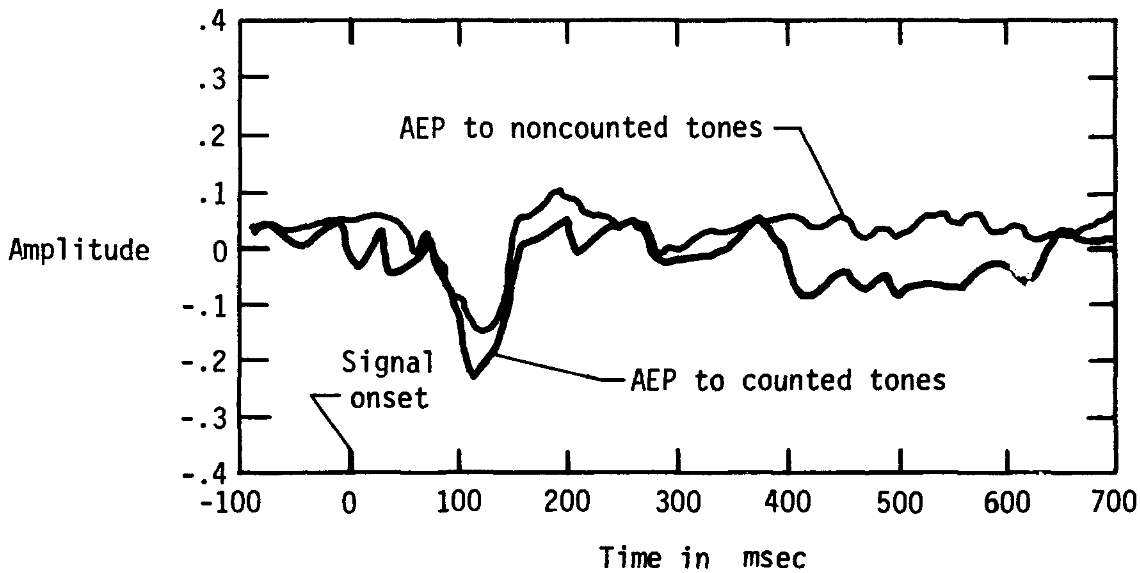


Figure 5. Combined display format.



(a) AEP when no flight task is being performed.



(b) AEP when flight task is being performed.

Figure 6. Example of mental-demand effects on auditory evoked potential (AEP).

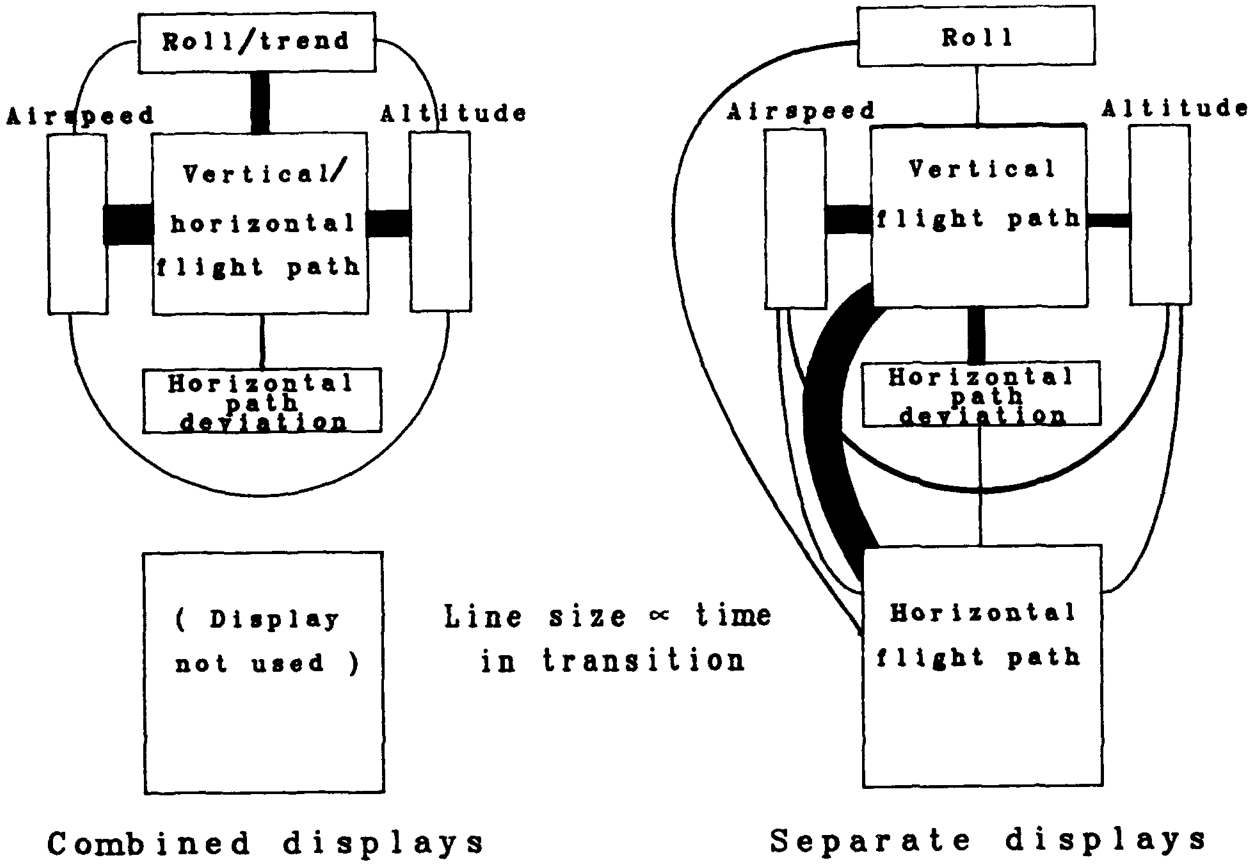


Figure 7. Scan behavior evaluation of the two display configurations.

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Report Documentation Page

1. Report No. NASA TP-2783	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Effects of Combining Vertical and Horizontal Information Into a Primary Flight Display		5. Report Date December 1987
		6. Performing Organization Code
7. Author(s) Terence S. Abbott, Mark Nataupsky, and George G. Steinmetz		8. Performing Organization Report No. L-16366
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665-5225		10. Work Unit No. 505-67-41-02
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546-0001		13. Type of Report and Period Covered Technical Paper
		14. Sponsoring Agency Code

15. Supplementary Notes

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Mark Nataupsky: U.S. Air Force, detailed to Langley Research Center, Hampton, Virginia.

16. Abstract

A ground-based aircraft simulation study was conducted to determine the effects of combining vertical and horizontal flight information into a single display. Two display configurations were used in this study. The first configuration consisted of two display formats, a primary flight display (PFD) format and a horizontal situation display (HSD) format, where each was placed on separate displays in a conventional PFD above the HSD orientation. For the second display configuration, the HSD format was combined with the PFD format. Four subjects participated in this study. Data were collected on performance parameters, pilot-control inputs, auditory evoked response parameters (AEP), oculometer measurements (eye scan), and heart rate. Subjective pilot opinion was gathered through questionnaire data and scorings for both the subjective workload assessment technique (SWAT) and the NASA task load index (NASA-TLX). The results of this study showed that, from a performance and subjective standpoint, the combined configuration was better than the separate configuration. Also, the eye-transition and eye-dwell times for the separate HSD were higher than expected, where a 46-percent increase in available visual time would occur when going from a two-display configuration to a one-display configuration.

17. Key Words (Suggested by Authors(s)) Cockpit display Aircraft guidance Workload	18. Distribution Statement Unclassified—Unlimited Subject Category 06

19. Security Classif.(of this report) Unclassified	20. Security Classif.(of this page) Unclassified	21. No. of Pages 18	22. Price A02

NASA FORM 1626 OCT 86 NASA-Langley, 1987

For sale by the National Technical Information Service, Springfield, Virginia 22161-2171