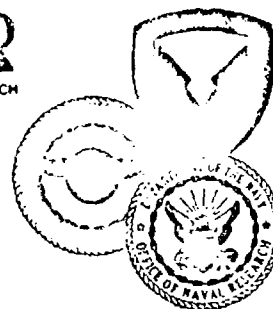


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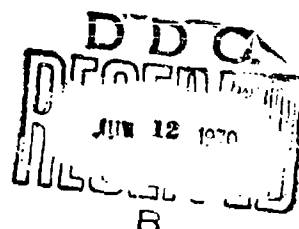
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VISUAL REQUIREMENTS STUDY FOR HEAD-UP DISPLAYS

FINAL REPORT-PHASE I

Prepared by
T. Gold
A. Hyman
March 1970



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SUMMARY

An experimental study was conducted to determine critical values of the essential optical and electronic design parameters for head-up displays based on the visual requirements of the pilots who will use these displays. This information will provide a basis for future specifications covering this type of display. The investigation covered two areas, size of exit pupil and binocular disparities due to optical distortions.

The exit pupil study was conducted in a flight simulator in which a wide field (25 degrees) head-up display with a large aerial exit pupil was installed. Four pilots with military flight experience served as test subjects. The results indicate that the minimum size of exit pupil required is three inches in diameter, for wide-field systems in which the pilot's head position is no more than 10 inches behind the exit pupil.

A laboratory telecentric viewing system was developed for the binocular disparity study. This equipment made possible experiments in which disparate, dynamic, head-up display images were presented to subjects who viewed these images against a static view of a real world background. Three test subjects were employed in these tests. The results show that binocular disparity tolerances are considerably lower when head-up display images are viewed against a real world background, compared with a homogeneous background of moderate brightness. Maximum disparity levels are one mil for sustained viewing with adequate comfort for vertical disparities and divergent horizontal disparities. Convergent horizontal disparities may be as large as 2.5 mils for the same level of comfort.

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SECTION 1

INTRODUCTION

A. BACKGROUND

The head-up display is a relatively new cockpit display technique that provides flight situation and control information to the pilot as he looks through the windshield. One way of doing this is shown in figure 1. Images on the face of a cathode ray tube (CRT) pass through a collimating optical system. The light rays are then reflected by a combining glass to the pilot's eye as he views the real world through the windshield. The pilot has the visual impression that the images generated by the CRT are located in the real world, in front of the aircraft. The images are called virtual images because the light rays that produce them do not pass through their apparent locations. The head-up display is an extension of the reflecting gun sight systems, used extensively in World War II, applied to flight control problems other than airborne fire control.

Several unique advantages for flight control result with head-up displays. Information is presented to the pilot in a form that requires almost no diversion from his view of the real world from the cockpit. The pilot is not required to shift his visual attention from the real world to the instrument panel during critical maneuvers. The associated changes in visual focusing (accommodation and convergence) from large distances to the near cockpit panel are also eliminated.

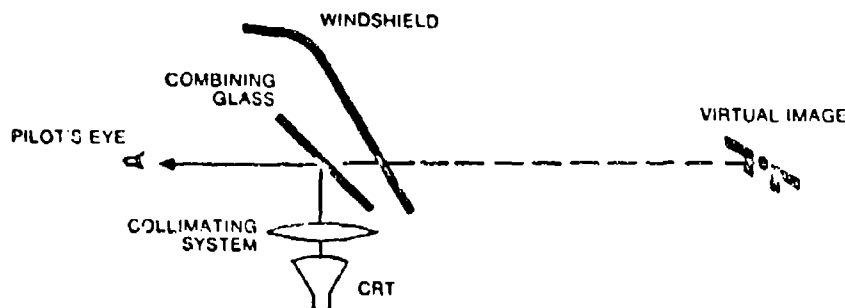


FIGURE 1. SCHEMATIC OPTICAL ARRANGEMENT OF HEAD-UP DISPLAY

These advantages are common to all head-up displays using optical projection techniques. However, more sophisticated head-up displays, such as those currently being developed for the Naval Air Systems Command by Sperry, include images closely related to figures in the real world. These projected images are designed to overlay the real figures visually. Some examples of these figures are a runway, the landing deck on a carrier, and a ground target. Head-up displays with this overlay capability provide fully compatible flight control means for both visual (VFR) and instrument (IFR) flight (reference 1)*. For example, during landing the pilot performs the approach to the real carrier deck in VFR, or in the same way to the image representing the deck under IFR before visual breakout. These capabilities have led to the development of head-up display systems for general flight maneuvers, terrain-following at high speed, field and carrier landings, and weapon delivery.

*For this and other references, refer to page 68.

Optical projection systems with large fields of view, and with qualities which permit considerable freedom of head movement for the pilot, are desirable. High accuracy in positioning the images, both in relation to each other and to the real world, is also required. Ideally, this precision should be independent of the pilot's head position, and the same image should be presented to each eye if the head-up display is viewed binocularly.

Unfortunately, the visual requirements for projection systems based on existing literature in vision have led to large, complex, heavy, costly optics. Perhaps these visual requirements may be relaxed. However, to date there has been no scientific basis for doing so.

In fact, there is evidence that some head-up displays have manifested undesirable visual characteristics. In a flight evaluation of a head-up display in an A-5A aircraft at the Naval Air Test Center (reference 2) the findings indicated that it was necessary for pilots to refocus their eyes when shifting their view from external objects to the HUD symbols. In a flight program conducted for the Federal Aviation Agency by Sperry (reference 1) one pilot reported, "Optics problem of double image at edge of field. Feel it made me tire visually". These reports affirm that visual design criteria for head-up displays must be carefully generated.

The experimental studies described herein provide results which objectively define the visual requirements relating to the design of wide field (25 degrees), virtual image, optical projection systems. These studies were conducted with highly specialized viewing apparatus demanded by the research. The results permit the design of the optical systems to be matched to the visual characteristics of the human pilot.

B. OBJECTIVES

The objectives of this study were to determine the essential optical and electronic design parameters for head-up displays, based on the visual requirements of the pilots who will use these displays.

The key parameters investigated were:

- Minimum permissible size of exit pupil, as a function of pilot head position
- Permissible binocular disparities produced by optical distortions, including the effect of:
 - Image brightness
 - Image motion
 - Real world background
 - Image line thickness
 - Overlapping monocular fields.

SECTION 2

VISUAL REQUIREMENTS FOR HEAD-UP DISPLAYS

A. REQUIREMENTS RELATED TO BINOCULAR VISION

A well-designed optical projection system should provide a large exit pupil to permit some freedom of head movement for the pilot. When this exit pupil is larger than the interpupillary distance of the eyes, viewing becomes binocular, and image distortion presents a major problem. With monocular viewing, distortion would cause an overlay error in those cases where display symbology must superimpose on real world elements, and tolerance for distortion at various eye positions with respect to the exit pupil would have been determined by the permissible overlay error. When viewing is binocular, differences in image distortion for the two eyes becomes a critical matter. Such differences can cause eyestrain, display image doubling, and an apparent depth displacement of display elements.

In the normal visual environment, the perception of the depth can arise from a number of monocular and binocular cues (references 3 and 4). With a virtual image optical projection display viewed binocularly, however, only differences in image distortion for the two eyes which result in retinal disparities need to be considered. (Images from display points that do not fall on corresponding points on the two retinas are said to be disparate.) Perceptually, points having horizontal disparate separation in the two eyes are interpreted as being localized in different frontal planes.

Figure 2 illustrates how a horizontal disparity occurs for the two eyes when two objects are displaced in depth in the real world. The upper part of the figure, A, shows a plan view of two vertical rods, F and N, separated in depth and viewed simultaneously by the left eye and the right eye. Rod F is fixated and hence imaged on the foveae (f' and f'') of the two eyes. This causes the image of rod N to fall left of the fovea in the left eye and right of the fovea in the right eye. The resultant monocular and binocular perceptions are shown in the lower part of figure 2. The view shown in B illustrates what is perceived if the right eye is occluded; D, if the left eye is occluded; and C, if both eyes view the display simultaneously. In the last instance, the rods are perceived as separated in depth as well as laterally. This is a case of stereoscopic depth perception, i. e., perception of depth based on retinal disparity.

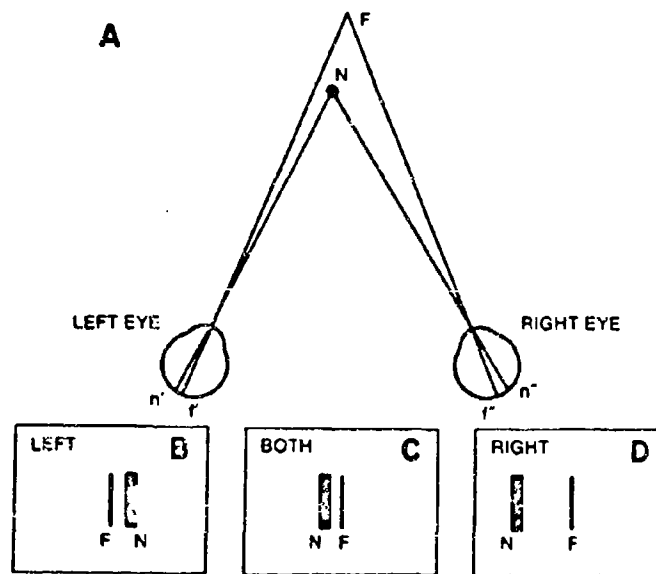


FIGURE 2. EFFECT OF HORIZONTAL BINOCULAR DISPARITY

Stereoscopic depth perception does not require real stimuli separated in depth. Any device which would present view B to the left eye and view D to the right eye would be interpreted as the situation represented in A. This is the principle employed in the stereoscope where two disparate pictures (i.e., stereograms) are viewed, one by each eye (reference 3). It is to be noted that the magnitude of the disparity, i.e., the difference between the angles subtended by the two eyes at N and at F, is the same whether N is fixated, or some other point not shown is fixated.

The binocular perception of a single rod at N, does depend, however, upon the location of the fixation point. If the latter is much beyond or much in front of rod N this rod will be seen as double (binocular diplopia) rather than single (visually fused). The fore and aft region of single vision about a fixation point (i.e., Panum's area) is a function of the lateral angular separation between target and fixation point (references 5, 6, and 7). The greater the separation, the greater is the permissible retinal disparity for single vision.

Horizontal retinal disparities occur naturally when real world objects separated in depth are viewed by the two eyes. Optical systems, however, can generate disparities in which a vertical component is also present. How are these perceived? By a perceptual mechanism not fully understood, vertical disparities causing retinal image size differences can be converted into equivalent horizontal disparities (induced size effect, reference 5), and subjectively interpreted as depth displacements. Thus retinal disparities whether horizontal or vertical, when small, can give rise to perceptions of depth displacement, and when large, to image doubling. By introducing both vertical and horizontal disparities, it is possible to either enhance or to decrease the depth effect. What occurs depends on the direction and magnitude of these disparities.

The virtual image optical projection display presents conditions comparable to the situations previously described. If, as in figure 2, F is a real world object and N is a display system symbol which because of differences in image distortion is seen as in B by the left eye and as in D by the right eye, then F and N will appear to be separated in depth. If F were at optical infinity and N had a retinal disparity of 5 mils, for an observer with an interpupillary separation of 2.5 inches N would be perceptually located about 42 feet forward of the observer. In this case, would a pilot have a vision

problem under conditions of prolonged viewing when H must be considered as an overlay in the plane of F ? On the basis of the classical literature (reference 5), one would not expect this simple configuration to generate meaningful visual discomfort or a perceptual problem. However, what happens if the display figure is not a simple rod but a more complex figure? While such a situation may generate a perceptual conflict to an observer, it is not certain that it will create a vision problem, for his task is not to localize accurately the display in space but merely to superimpose it on the real world. However, studies concerned with binocular disparity have not to date considered this problem.

Applied experimental studies specifically directed to help establish permissible disparities in head-up display configurations are required to resolve questions. These studies must determine the acceptability of various binocular disparities typical of virtual image optical projection systems. Also, the displays employed in these studies must include complex configurations characteristic of the symbology developed for projection displays generating dynamic virtual images.

B. REQUIREMENTS RELATED TO HEAD MOVEMENT

In every optical system there is a diaphragm, lens rim, or other element which acts to limit the extent of an object, or the field of view, that will be represented in the image. This element is known as the field stop. There is also another physical stop, called an aperture stop, which determines the size of the bundle of rays reaching any given point in the image. These stops establish the region in which an eye will see an image and the field angle in which this image can occur. Detailed discussions of the theory of stops are given in references 8, 9, and 10.

In analyzing the behavior of an optical system, it is not necessary to deal directly with the stops and the associated optical components. One can study system characteristics in terms of image plane locus, exit port, and exit pupil. (The exit port and exit pupil are, respectively, the images of the field stop and the aperture stop in image space.) Figures 3, 4, 5, and 6 represent some characteristic situations that can occur with wide field, virtual image, optical projection systems. The rule to be followed is that only rays which are unobstructed by the exit port and pass through the exit pupil are physically realizable. Since exit ports and exit pupils are "imaginary" apertures, the eye can be located in front of them as well as behind them. The eye, however, must be located beyond the last optical component of the system.

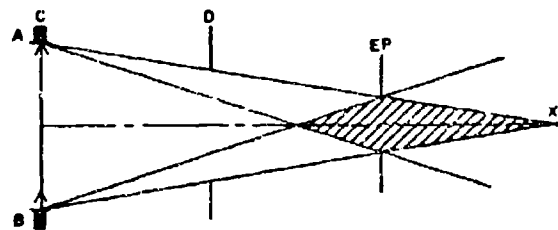


FIGURE 3. ENVELOPE OF VIEWING POSITIONS FOR INSTANTANEOUS FULL FIELD

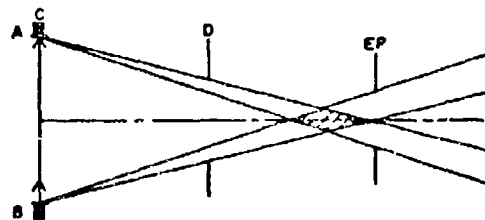


FIGURE 4. EFFECT OF SMALLER STOP ON VIEWING POSITION ENVELOPE FOR FULL FIELD

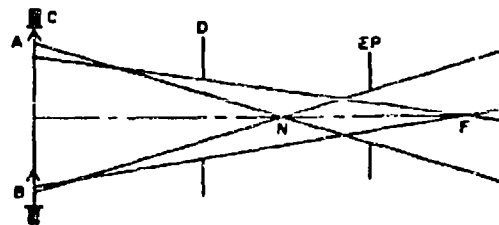


FIGURE 5. EFFECTS OF LONGITUDINAL EYE POSITIONS OUTSIDE OF ENVELOPE FOR FULL FIELD

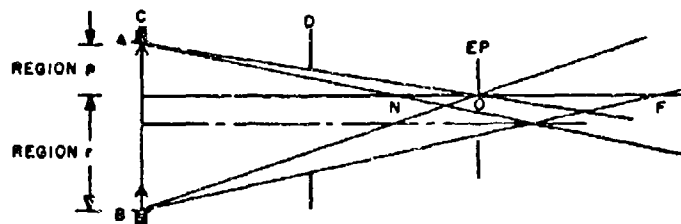


FIGURE 6. EFFECTS OF OFF-AXIS EYE POSITIONS ON FIELD OF VIEW

Figure 3 illustrates the case where the image AB and the exit port C are in the same plane. The exit pupil is located at EP. The cross-hatched area defines the region where rays from all object points are present. If both eyes of the observer are within this region, he will obtain a binocular view of the total field. It is to be noted that the presence of an additional stop will have no effect on the display if the image of that stop has an aperture greater than the extreme rays drawn in the figure. Such a case is represented by aperture D. If the diameter of D were smaller, D would have become the exit port for these eye positions where the field of view was determined by D. Figures 4, 5, and 6 illustrate what occurs when D acts as the exit port.

The cross-hatched area in figure 4 again represents the region where the full field of view can be seen. A comparison with figure 3 shows this region to have become smaller. Also, its largest cross-section has moved closer to the image. If this cross-section is smaller than the interpupillary distance for the observer's eyes, binocular viewing of the total field is not possible for any head position. The effect of forward and aft movement of the head beyond the cross-hatched region, when the viewing eye is on axis, is shown in figure 5. In either case the instantaneous field of view, as represented by the extreme rays possible at the given eye position, is less than the total possible field of view. However, hidden portions of the field can be scanned by transverse (off-axis) movement of the head.

The instantaneous fields obtained at several off-axis eye positions are shown in figure 6. When the eye is at N, region p is seen, and when at F, region r is seen. At O, of course, the total field is seen.

The net effect with off-axis eye positions which occur with binocular viewing and a field stop that provides an instantaneous field less than the total available field of view, is shown in figure 7. R is the portion of the total instantaneous field seen only by the right eye, L is the portion seen only by the left eye, and B is the portion seen binocularly. In the parts of the field seen by one eye only, there would be "wash-out" of projected imagery should retinal rivalry occur (references 3, 4, and 7).

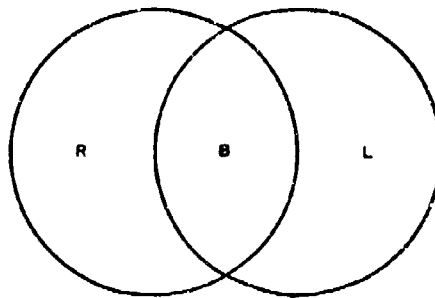


FIGURE 7. BINOCULAR FIELD OF VIEW BASED ON DUAL
OVERLAPPING MONOCULAR FIELDS

Must the optical designs, therefore, reduce these monocularly viewed regions to a minimum? It should be remembered that binocularly viewed regions can present undesirable retinal disparities, a phenomenon which is not possible in monocularly viewed regions. Also, systems which have large binocular fields are complex, heavy, and costly. To help establish a trade-off, one must determine the magnitude of retinal disparity permissible at the boundary between the monocular and binocular regions.

SECTION 3

EXIT PUPIL STUDIES

A. RESEARCH APPARATUS

The exit pupil studies were conducted in a B-47 Flight Simulator which was developed from a model S6A Flight Trainer for the B-47 aircraft (figure 8). A head-up display with a wide field of view (25 degrees) and a large aerial exit pupil (5 inches wide by 3 inches high) were used as the optical display medium. The configuration of this display system is shown in figure 9.

The exit pupil in the display could be reduced by inserting aperture stops in the optical system. This permitted the study to encompass smaller exit pupils. In addition to the full 3 by 5-inch size, circular exit pupils of 3-, 2-, 1-, and 1/2-inch diameters were used for a total of five exit pupil sizes. The location of the pilot's eye could be adjusted relative to the exit pupil by fore and aft change in seat position in the cockpit. The study covered three head positions for the pilot, for which his eyes were in the plane of the exit pupil, five inches aft of the exit pupil, and ten inches aft of the exit pupil.

The exit pupil studies were designed to measure pilot's reaction time or latency in locating an image in the field of view of the head-up display, starting with a head position laterally displaced from the limits of the exit pupil.

The latency criterion was selected because normal operations in the cockpit frequently require body motions by the pilot which remove his eyes from the exit pupil. It is operationally necessary that the pilot recover the exit pupil rapidly.

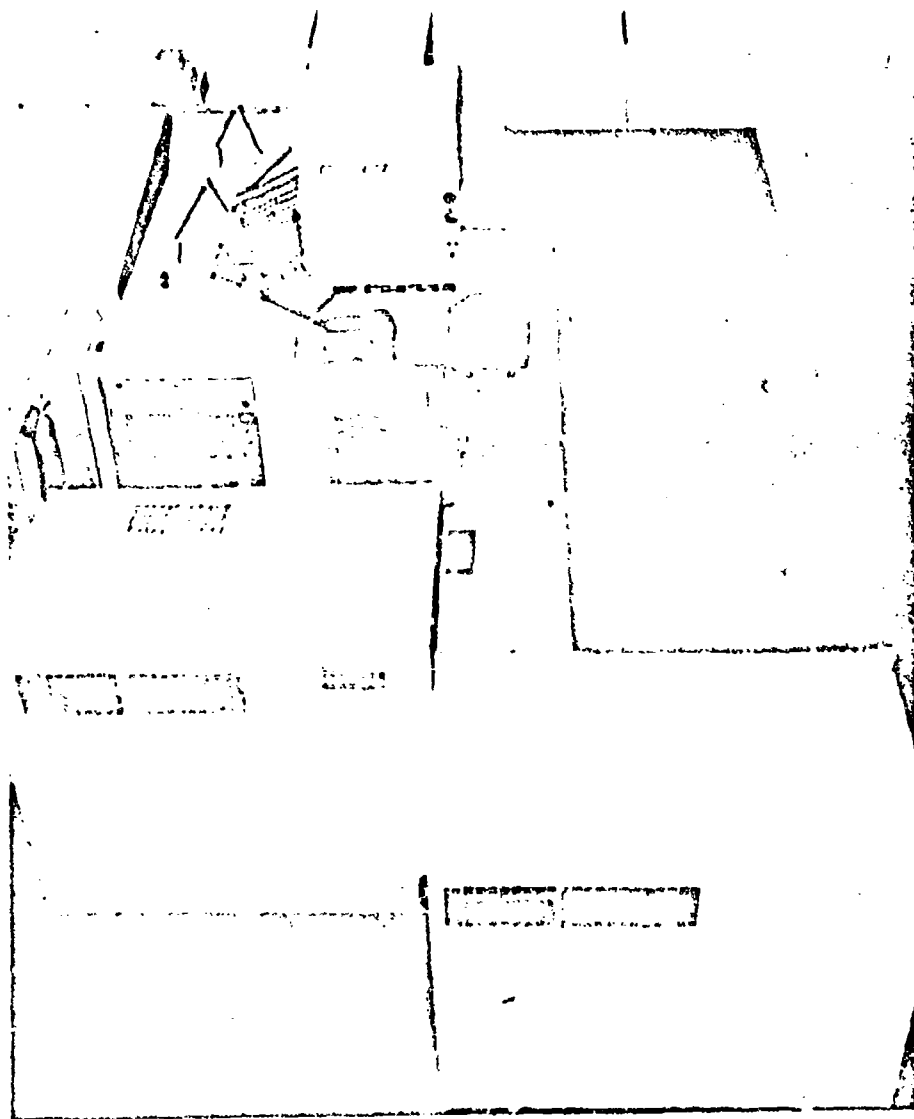
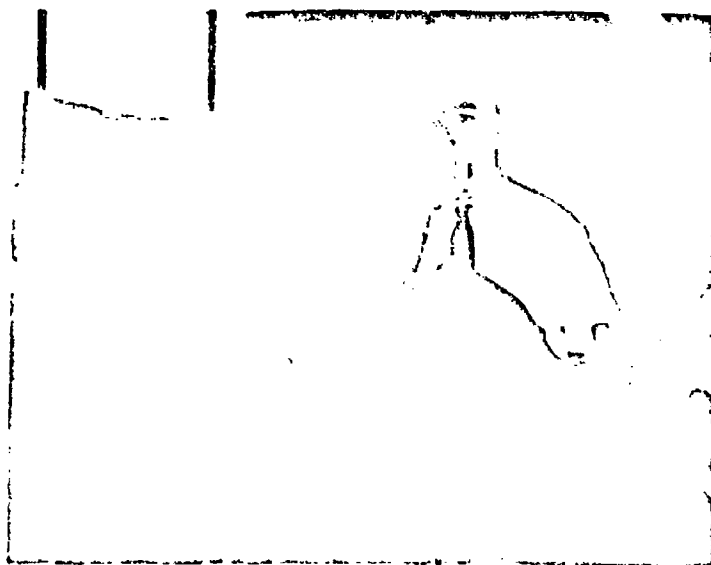
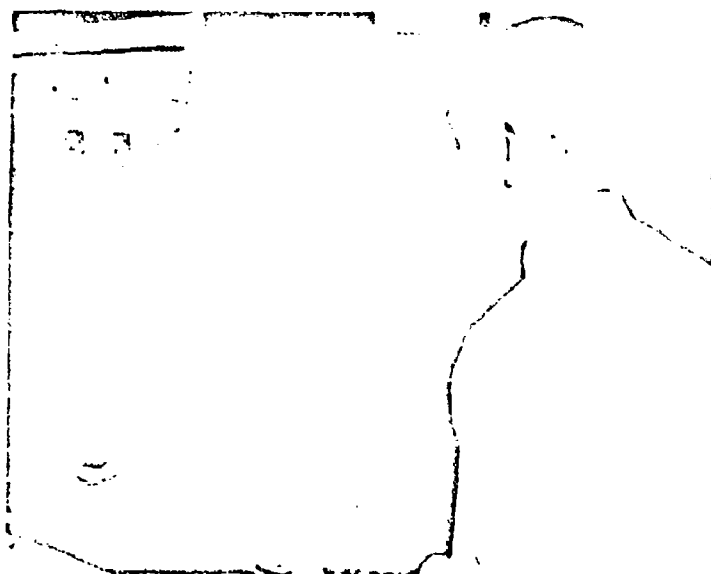


FIGURE 8. B-47 FLIGHT SIMULATOR SYSTEM



WIDE-FIELD OPTICAL PROJECTION SYSTEM
INSTALLED IN COCKPIT OF B-47 SIMULATOR



REAR VIEW OF WIDE-FIELD OPTICAL PROJECTION SYSTEM
IN B-47 SIMULATOR

FIGURE 9. WIDE FIELD OPTICAL PROJECTION SYSTEM INSTALLED
IN B-47 FLIGHT SIMULATOR

The pilots normal loading task was to maintain prescribed heading and altitude using a simple head-up display and panel instruments as required. The experimenter was to remove the head-up display images at some point in time to simulate a display failure; the pilot is advised of this situation by a warning light. The pilot then must reach to his low left to throw a switch that returns the display and also energizes an image (circle) in one of sixteen possible positions in the field of view (figure 10). During the physical motion required to actuate the switch the pilots eyes are removed from the exit pupil. At the same time, a timer is started to measure latency. When the pilot locates the display image he presses a switch button on his control wheel, which removes the circle image and stops the timer. The pilot advises the experimenter regarding the position of the image in the 4 by 4 matrix, e.g., A2, to assure that there has been no guessing. The timer is stopped by the pilot when he located the image in the display, so the time consumed by the pilot in responding verbally to the experimenter is not included in the measured reaction time. Furthermore, the absence of the circle does not permit the pilot to reassess the situation after the timer has been stopped.

The switching scheme to permit the routine described is presented in the block diagram in figure 11. The experimenter controls the presence and location of the test symbol in the display, and turns the normal head-up display symbology off at the desired time. The test subject turns the test symbol on and starts the timer. He also simultaneously turns the test symbol off and stops the timer when he locates the symbol in the display. A photograph of the experimenter's control station is shown in figure 12.

B. DESIGN AND CONDUCT OF EXPERIMENTS

1. Test Procedures

Four pilots with military flight experience served as test subjects in the exit pupil studies. One of the pilots was currently in professional service in executive air transport operations. The visual capabilities of the subjects were not critical for the conduct of the exit pupil studies.

The pilots were given a few hours in the simulator to familiarize them with the cockpit layout, the head-up display, and the handling qualities of the B-47 aircraft before the start of any formal tests.

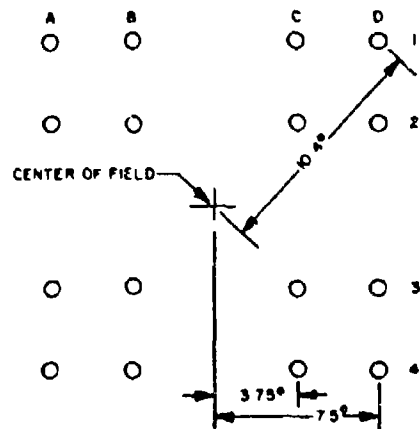


FIGURE 10. MATRIX OF POSITIONS FOR TARGET IMAGE IN HEAD-UP DISPLAY

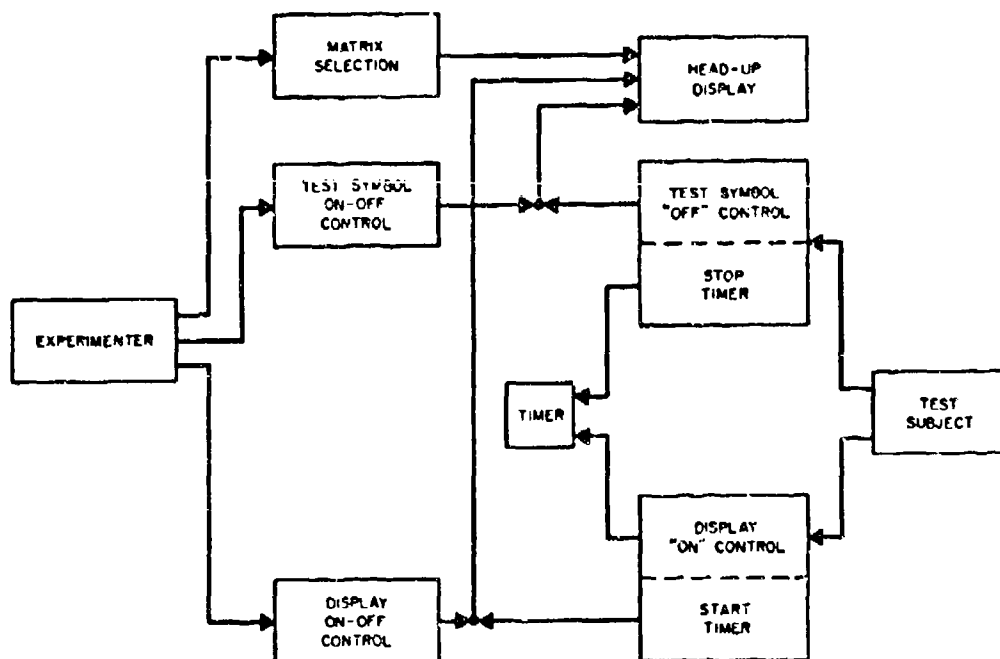


FIGURE 11. BLOCK DIAGRAM OF SWITCHING ARRANGEMENT FOR EXIT PUPIL TESTS

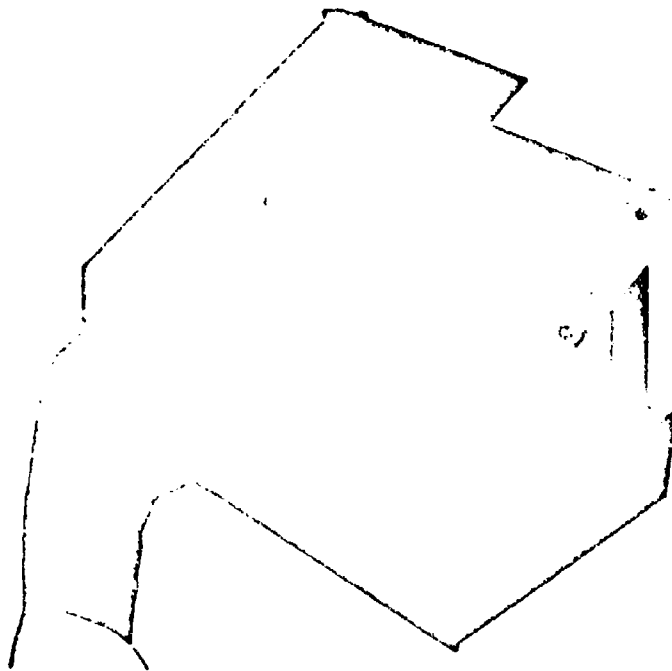


FIGURE 12. EXPERIMENTER'S CONTROL STATION

Each pilot was tested in each of the three head positions, using five exit pupil sizes at each position. An experimental session was conducted with a single head position. Exit pupils were changed after every six presentations (trials) for which reaction times were measured. The location of the test symbol in the display field was varied randomly from trial to trial. The first of each set of six trials was considered a practice run, and the results were not included in the analyses of the data.

Each set of tests was replicated four times in a session. Therefore, a total of 100 data points were obtained in each experimental session, consisting of 5 exit pupil sizes x 5 points per exit pupil x 4 replications per exit pupil. Each pilot participated in at least three sessions, covering the three head positions studied. Additional replicated sessions were accomplished with some of the pilots as permitted by their availability. The number of sessions obtained with each pilot for each head position is summarized in table 1.

TABLE 1. NUMBER OF TEST SESSIONS ACCOMPLISHED
WITH EACH OF THE PILOTS

Pilot	At Exit Pupil	Eye Position	
		5 in Behind Exit Pupil	10 in Behind Exit Pupil
A	2	2	2
B	1	1	1
C	2	1	1
D	2	1	1

The pilots were directed to maintain specified altitudes and headings as a normal cockpit work load. They were requested to make changes in altitude of 500 feet, or 30-degree changes in heading, after each set of six presentations for a particular exit pupil. The experimenter changed the size of the pupil while the pilot was occupied with this flight maneuver.

2. Data Reduction

Mean reaction times were determined for each set of five data trials in all of the experimental sessions. Therefore, four mean reaction times were obtained for every exit pupil size used in each session. These data are given in tables 2 through 5 for each of the four pilots. Each table includes the results obtained for each of the three head positions. The number of data points in each table is a function of the number of test sessions obtained with each pilot (table 1). Grand mean reaction times for all combinations of exit pupil size and head position are also shown in tables 2 through 5.

The grand mean reaction times for each pilot were plotted as a function of exit pupil size, for each of the three head positions in figures 13 through 16. The results are a consistent family of J-curves, with increasing reaction time as the exit pupil is reduced. The curves are also displaced vertically to increasing reaction time as the pilot's head position is displaced aft of the exit pupil.

TABLE 2. MEAN REACTION TIMES* FOR PILOT A

Eye Position	Session	Size of Exit Pupil				
		Full	3 in.	2 in.	1 in.	1/2 in.
At exit pupil	1	2.12	1.64	2.68	2.72	3.64
		2.38	1.76	2.16	2.42	2.60
		1.80	1.87	2.09	2.30	2.44
		1.52	1.60	2.25	2.09	2.53
	2	1.69	2.27	1.94	2.58	2.27
		1.88	1.61	2.16	2.17	2.84
		1.77	1.59	1.99	1.81	2.62
		1.38	1.34	1.55	2.29	2.13
	Mean	1.82	1.71	2.10	2.30	2.76
	1	1.96	1.86	2.60	2.48	5.07
		2.00	2.09	2.41	5.29	8.27
		1.97	2.18	2.18	3.29	3.56
		1.42	1.63	2.28	2.83	5.74
	2	1.63	1.94	2.65	6.36	5.92
		1.69	2.18	2.13	2.27	2.85
		1.33	2.36	2.61	4.20	5.26
		1.80	1.78	1.77	2.68	5.09
	Mean	1.72	2.00	2.33	3.61	5.14
5 inches behind exit pupil	1	1.35	7.21	3.45	13.27	26.88
		1.71	2.31	2.10	8.56	5.62
		1.40	1.59	2.57	3.56	12.12
		1.55	1.50	2.49	4.63	14.47
	2	2.14	1.67	4.05	4.82	13.36
		2.19	2.21	3.59	8.40	16.12
		1.85	1.74	3.03	4.75	8.03
		1.71	2.20	3.47	4.29	6.20
	Mean	1.74	2.55	3.10	6.32	11.91
10 inches behind exit pupil	1	1.35	7.21	3.45	13.27	26.88
		1.71	2.31	2.10	8.56	5.62
		1.40	1.59	2.57	3.56	12.12
		1.55	1.50	2.49	4.63	14.47
	2	2.14	1.67	4.05	4.82	13.36
		2.19	2.21	3.59	8.40	16.12
		1.85	1.74	3.03	4.75	8.03
		1.71	2.20	3.47	4.29	6.20
	Mean	1.74	2.55	3.10	6.32	11.91

*Reaction times shown are in seconds.

TABLE 3. MEAN REACTION TIMES* FOR PILOT B

Eye Position	Session	Size of Exit Pupil				
		Full	3 in.	2 in.	1 in.	1/2 in.
At exit pupil	1	1.40	1.33	1.71	2.55	3.08
		1.23	0.98	1.25	1.65	3.78
		1.32	1.29	1.31	1.54	1.93
		1.25	0.92	1.14	1.20	3.38
	Mean	1.30	1.13	1.35	1.74	3.04
5 inches behind exit pupil	1	1.27	0.93	1.22	1.78	2.41
		1.32	1.24	1.26	3.26	4.78
		0.93	1.02	1.39	1.57	2.86
		1.08	1.13	0.96	1.96	1.69
	Mean	1.16	1.09	1.21	2.14	2.94
10 inches behind exit pupil	1	1.22	1.03	1.73	1.39	8.80
		0.84	1.11	1.73	2.18	4.41
		1.02	1.07	2.09	3.41	2.06
		1.38	1.36	1.59	3.92	3.05
	Mean	1.12	1.15	1.79	2.97	4.73

 *Reaction times shown are in seconds.

TABLE 4. MEAN REACTION TIMES* FOR PILOT C

<u>Eye Position</u>	<u>Session</u>	<u>Size of Exit Pupil</u>				
		<u>Full</u>	<u>3 in.</u>	<u>2 in.</u>	<u>1 in.</u>	<u>1/2 in.</u>
At exit pupil	1	0.97	0.82	0.88	1.20	1.48
		0.85	0.87	0.87	1.96	1.38
		0.93	0.89	0.96	0.97	1.09
		0.93	0.98	1.04	1.62	1.42
	2	0.72	0.69	0.76	0.92	0.86
		0.70	0.80	0.67	0.94	1.17
		0.82	0.78	0.82	0.93	0.87
		0.79	0.81	0.94	0.98	1.17
	Mean	0.84	0.83	0.87	1.18	1.19
	5 inches behind exit pupil	0.72	0.88	1.48	2.73	4.38
		0.93	0.85	1.03	1.90	4.91
		0.95	1.00	1.50	2.71	1.85
		1.13	0.94	1.24	2.23	4.75
	Mean	0.93	0.92	1.31	2.39	3.97
10 inches behind exit pupil	1	1.12	1.08	1.67	3.85	5.50
		0.95	0.94	2.04	4.20	5.78
		0.89	0.96	1.34	3.29	6.73
		0.86	1.12	0.99	3.74	9.91
	Mean	0.96	1.03	1.51	3.77	6.99

*Reaction times shown are in seconds.

TABLE 5. MEAN REACTION TIMES* FOR PILOT D

<u>Eye Position</u>	<u>Session</u>	<u>Size of Exit Pupil</u>				
		<u>Full</u>	<u>3 in.</u>	<u>2 in.</u>	<u>1 in.</u>	<u>1/2 in.</u>
At exit pupil	1	1.49	1.45	1.78	2.02	4.25
		1.72	1.90	1.56	3.54	3.68
		1.36	1.62	1.69	2.15	3.66
		1.17	1.37	1.43	1.51	3.19
	2	0.92	0.81	0.99	1.44	2.40
		0.81	1.11	0.99	1.22	1.84
		1.12	1.22	1.01	1.04	1.25
		0.84	1.30	0.76	1.67	2.82
	Mean	1.18	1.35	1.28	1.82	2.88
	5 inches behind exit pupil	1.81	1.75	2.60	3.24	6.72
		1.74	1.34	2.54	4.11	4.08
		1.54	1.98	2.23	2.59	2.52
		1.61	1.60	1.57	3.54	4.51
	Mean	1.68	1.66	2.24	3.37	4.34
10 inches behind exit pupil	1	1.47	1.52	6.31	6.10	6.36
		1.48	1.79	4.15	8.67	4.87
		1.88	1.27	2.80	5.81	9.82
		1.13	1.72	5.18	3.38	11.86
	Mean	1.49	1.58	4.61	5.99	7.71

*Reaction times shown are in seconds.

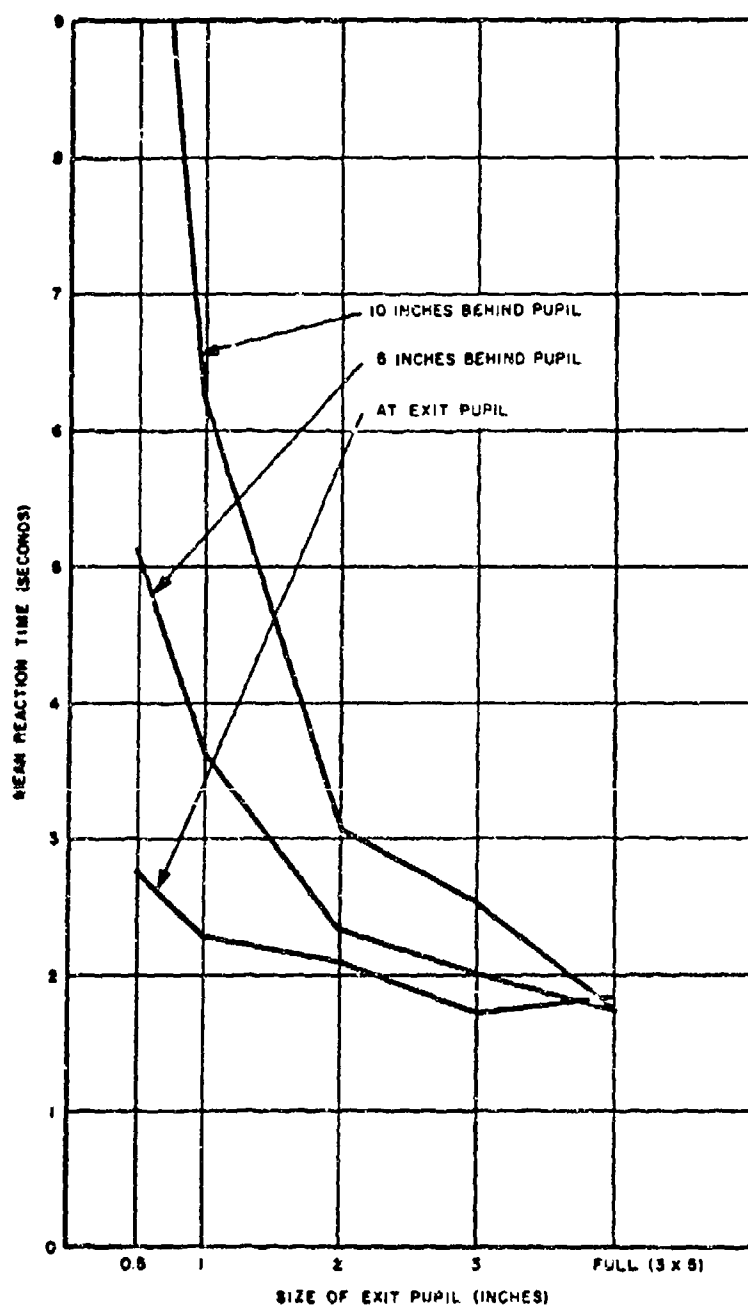


FIGURE 13. MEAN REACTION TIME FOR PILOT A AS A FUNCTION OF EXIT PUPIL SIZE AND HEAD POSITION

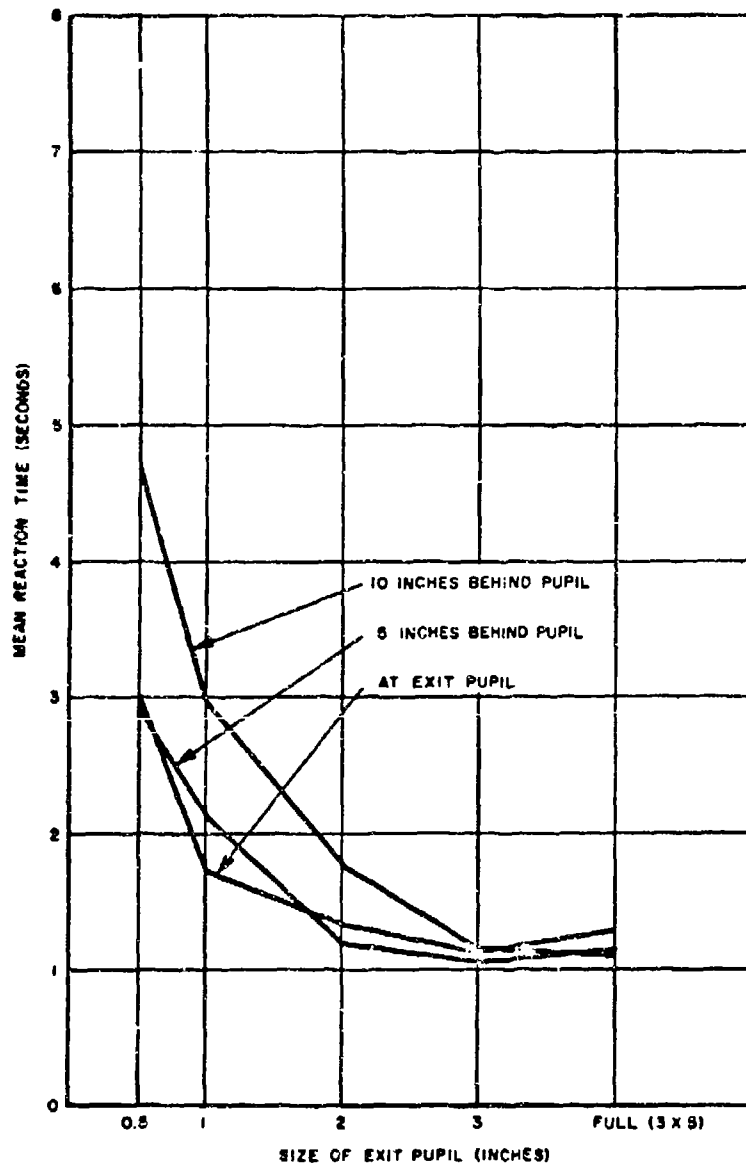


FIGURE 14. MEAN REACTION TIME FOR PILOT B AS A FUNCTION OF EXIT PUPIL SIZE AND HEAD POSITION

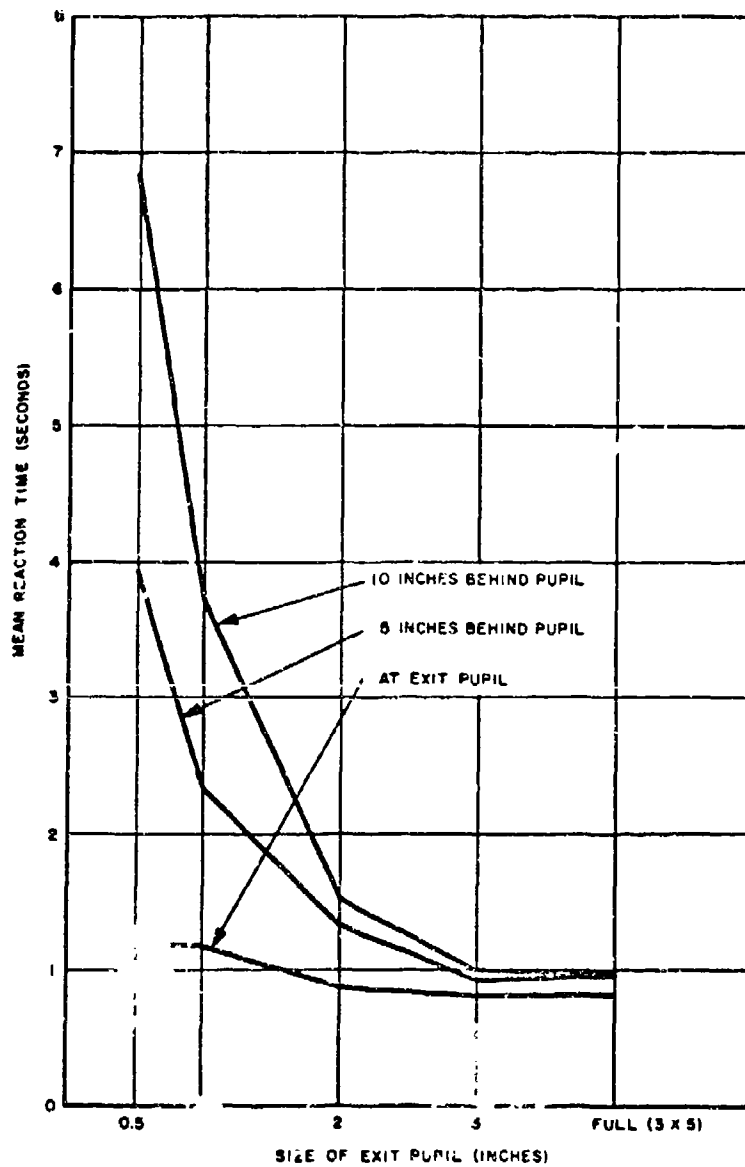


FIGURE 15. MEAN REACTION TIME FOR PILOT C AS A FUNCTION OF EXIT PUPIL SIZE AND HEAD POSITION

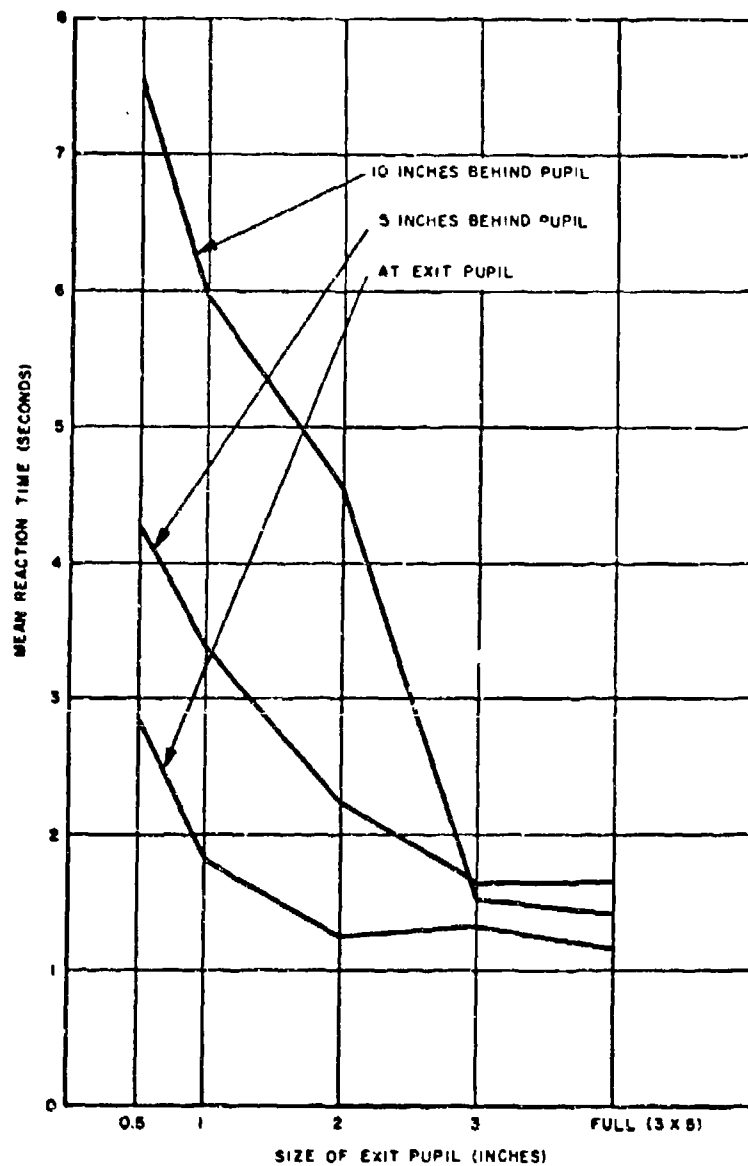


FIGURE 16. MEAN REACTION TIME FOR PILOT D AS A FUNCTION OF EXIT PUPIL SIZE AND HEAD POSITION

The results of the tests for each pilot indicate consistent behavior patterns as exit pupil size and head position are varied. Therefore, the data for all four pilots were combined; the results are presented in table 6 and plotted in figure 17. The combined results parallel those obtained for the individual pilots, with smoother variation with exit pupil sizes and head positions as shown in figure 17.

TABLE 6. GRAND MEAN REACTION TIMES* FOR ALL PILOTS

Eye Position	Size of Exit Pupil				
	Full	3 in.	2 in.	1 in.	1/2 in.
At exit pupil	1.28	1.26	1.40	1.76	2.47
5 inches behind exit pupil	1.37	1.42	1.77	2.88	4.10
10 inches behind exit pupil	1.33	1.58	2.75	4.76	7.85

*Reaction times shown are in seconds.

C. RESULTS AND IMPLICATIONS

The results of the exit pupil studies are best summarized in the plots in figures 17 and 18. The mean time to locate an image in the head-up display (reaction time) is plotted as a function of size of exit pupil, for three longitudinal head positions, in figure 17. Figure 19 is a replot of figure 17, with the addition of the 95-percent confidence limits for the mean values of reaction time for each of the three head positions presented. The statistical significance of the differences in mean reaction time for the various head positions, for all but the largest exit pupils, are demonstrated by these data. A cross-plot of these data, showing reaction time as a function of head position for the five exit pupil sizes studies, is presented in figure 18.

Figure 18 indicates that for large exit pupils, 3-inch diameter and larger, there are only small decrements in performance, i.e., higher reaction times, with a shift in head position aft of the exit pupil. The smaller exit pupils lead to increases in reaction time, which become more marked as head position moves aft. The rates of change of reaction time with aft movement of head position increases monotonically as the size of the exit pupil is reduced (figure 18).

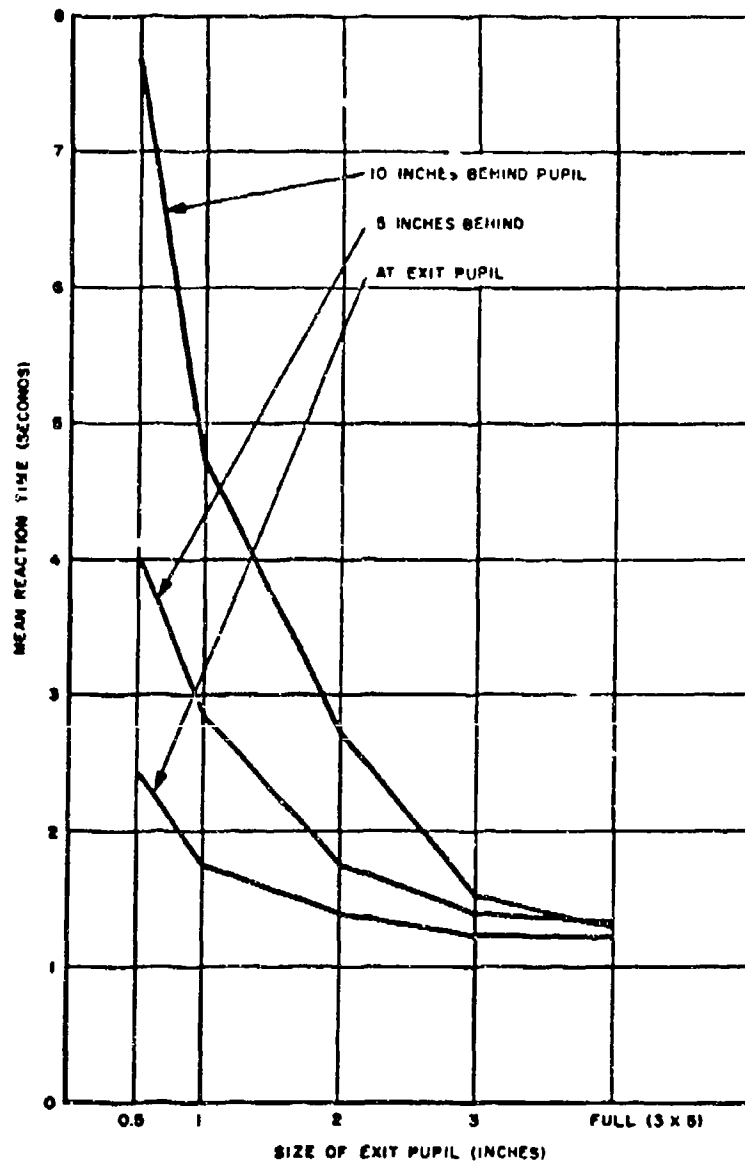


FIGURE 17. MEAN REACTION TIME FOR ALL PILOTS AS A FUNCTION OF EXIT PUPIL SIZE AND HEAD POSITION

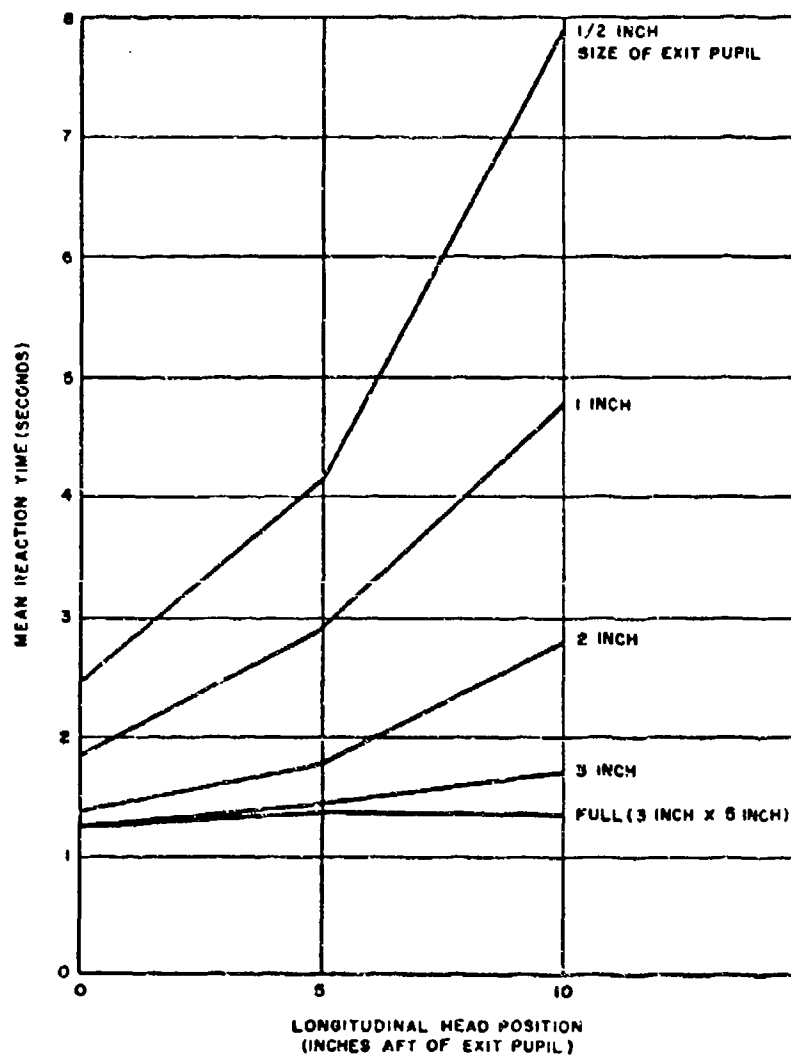


FIGURE 18. CROSS-PLOT FOR MEAN REACTION TIME FOR ALL PILOTS

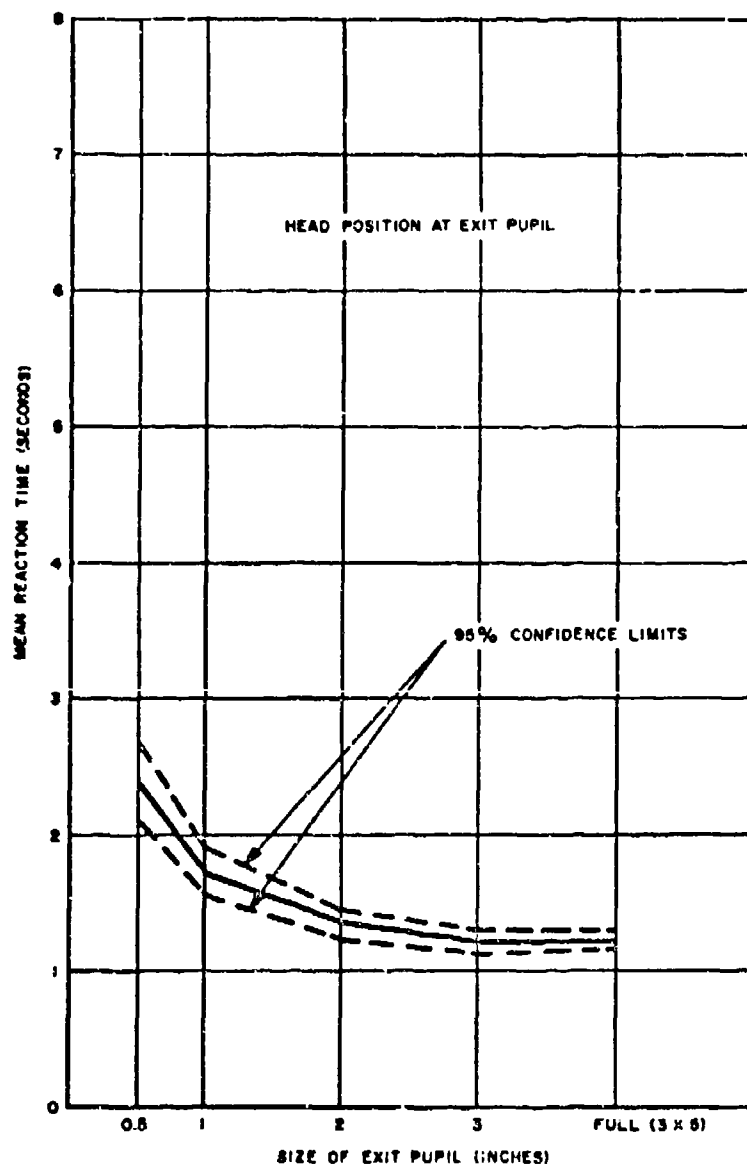


FIGURE 19A. 95-PERCENT CONFIDENCE LIMITS FOR MEAN REACTION TIMES

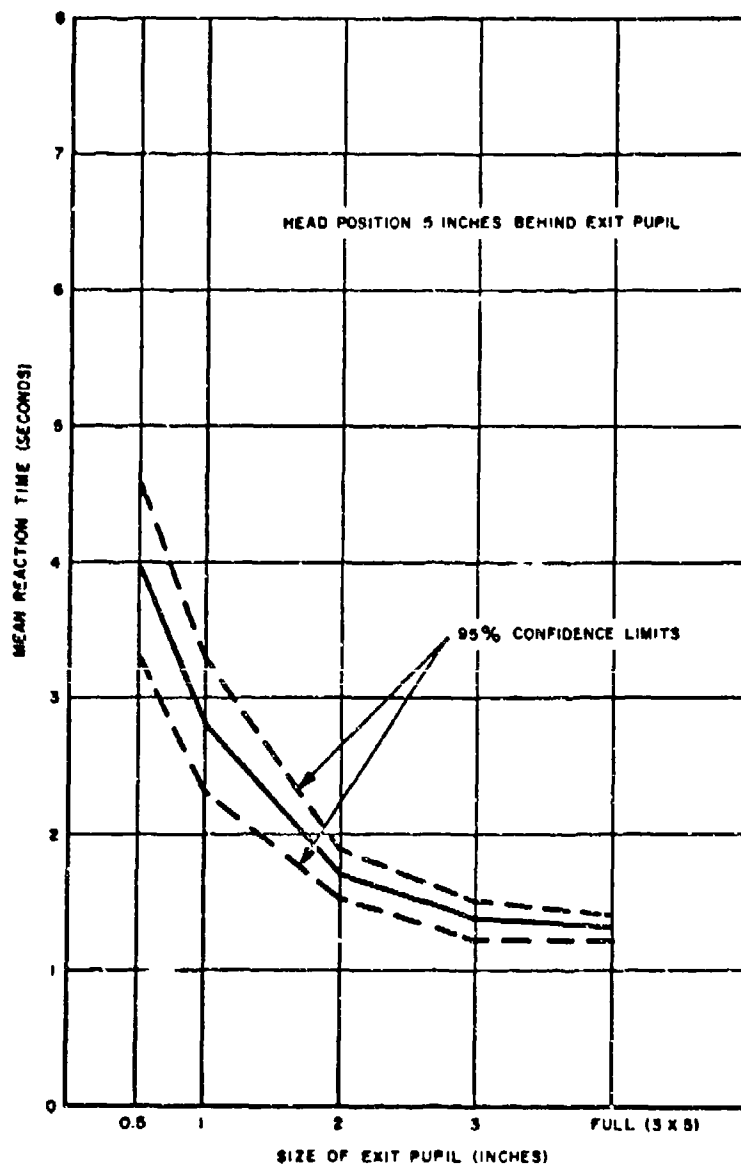


FIGURE 19B. 95-PERCENT CONFIDENCE LIMITS FOR MEAN REACTION TIMES

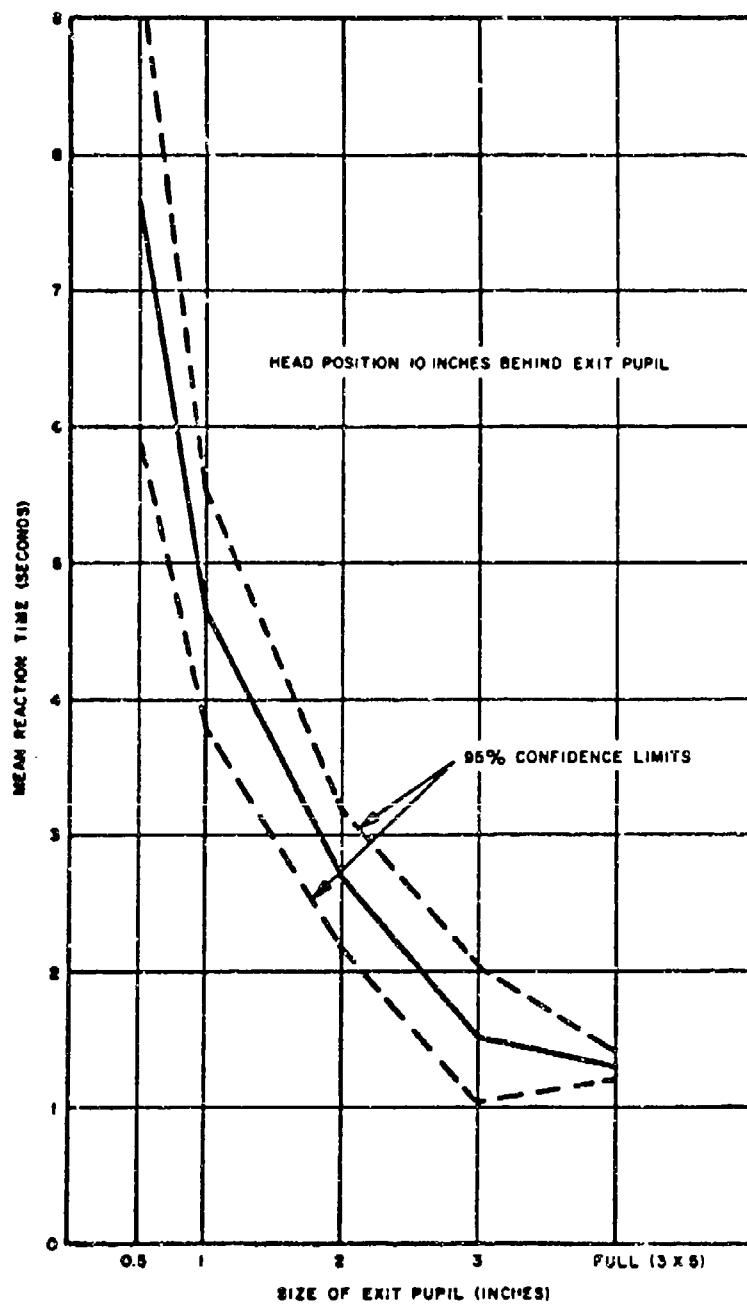


FIGURE 19C. 95-PERCENT CONFIDENCE LIMITS FOR MEAN REACTION TIMES

The significance of these results may best be appreciated by the optical diagram in figure 3. The presence of either eye within the cross-hatched area will permit the pilot to view the entire field, extending from A to B, instantaneously. In the present study head positions were at the exit pupil (EP), and both 5 inches and 10 inches behind, i.e., to the right, of this position. The four locations at the corners of the matrix delineating the search field (figure 10) are at 10.4 degrees from the center of the visual field in the display. The aft limit-X of the full field cone represented by the cross-hatched area in figure 3 is a function of the size of the exit pupil. For a 10.4-degree half-field, the locations of point X behind the exit pupil EP are as follows:

Size of Exit Pupil (inches)	Position-X Behind Exit Pupil (inches)
5.0	13.6
3.0	8.2
2.0	5.4
1.0	2.7
0.5	1.4

If the pilot is aft of the exit pupil and he cannot position one eye within the full field cone, he must search the field by vertical and lateral head motion. His two eyes will provide him with two search "beams", whose angular subtense is a function of the size of the exit pupil and his head position aft of the pupil.

When the pilot's head position is in the plane of the exit pupil, his search problem is one of locating the actual exit pupil, which of course becomes difficult with small pupils say of 1.0 and 0.5 inches in diameter. This is manifested by the bottom curve in figure 17 with its more rapid rise in reaction time for these small exit pupils.

When the pilot's head is five inches aft of the exit pupil he requires virtually an on-axis eye position to see the extremities of the field at once with a two-inch exit pupil. With the smaller exit pupils, the field must be scanned in piecemeal fashion to located an image. With a head position 10 inches behind the exit pupil, the field scanning technique is required with an exit pupil as large as three inches. However, the

scanning beams are large with the three-inch pupil, so the task is not difficult. With the small exit pupils, the search beams are small and the search task becomes increasingly difficult as head position is moved aft. These considerations explain the orientation and shapes of the curves in figure 17.

These studies were conducted without simulating the cockpit motion produced by turbulent air in actual flight. Head motion produced by turbulence will make the pilot's search problem somewhat more difficult. Search of the technical literature revealed little relevant data covering pilots' head motion in air turbulence. However, in heavy turbulence the pilot will be physically constrained by his seat harness, which will limit head motion considerably. Therefore, on the basis of the data presented in figure 17, a three-inch diameter minimum exit pupil size is recommended for wide-field head-up displays (25 degrees), with pilot head positions as far back as 10 inches aft of the exit pupil.

The interpupillary distance between the eyes of an adult is about 64 mm or 2.5 inches. Although this figure varies among adults, an exit pupil as large as three inches virtually assures that binocular vision is possible at the exit pupil for all adults. In the exit pupil tests conducted in this study, the subjects may have detected the target image binocularly or monocularly, for the three-inch and full exit-pupil sizes. This factor may have contributed to some variability in performance for these larger pupil sizes. On the other hand, the images were certainly viewed monocularly with the exit pupils two inches and smaller. With monocular viewing, there is of course no possibility of binocular disparity effects produced by optical distortions.

SECTION 4

BINOCULAR DISPARITY STUDIES

A. RESEARCH APPARATUS

1. Optical System

a. Description

A telecentric viewing system was designed and fabricated to permit the binocular disparity studies to be accomplished with dynamic head-up display imagery viewed against a real world background.

The viewing device is an optical system designed on the principles of on-axis viewing through telecentric systems. Each eye is provided with an identical viewing system so that even an extremely small distortion, if it should occur, is identical for both eyes and, hence, will generate no binocular disparity. Further precision is obtained by having both systems view a common object, the cathode ray tube. Therefore, there is no problem concerning the accuracy of object replication for the two viewing systems. The optical schematic of the telecentric viewing system is shown in figure 20.

This telecentric viewing system functions in the following manner. For right-eye viewing, the light from a display symbol presented on the CRT face is transmitted through a prism beam splitter P, totally reflected by mirror M_{R1} , collected by lens L_{R1} , and totally reflected by mirror M_{R2} . The light is then converged by lens L_{R2} , passes through aperture stop AS_R and shutter S_R , diverges, and is collected by lens L_{R3} . After total reflection by mirror M_{R3} , an image is formed in the plane of field stop FS_R . This image is viewed by the right eye after it is collimated by lens L_{R4} , and reflected by the half-silvered mirror M_{R4} .

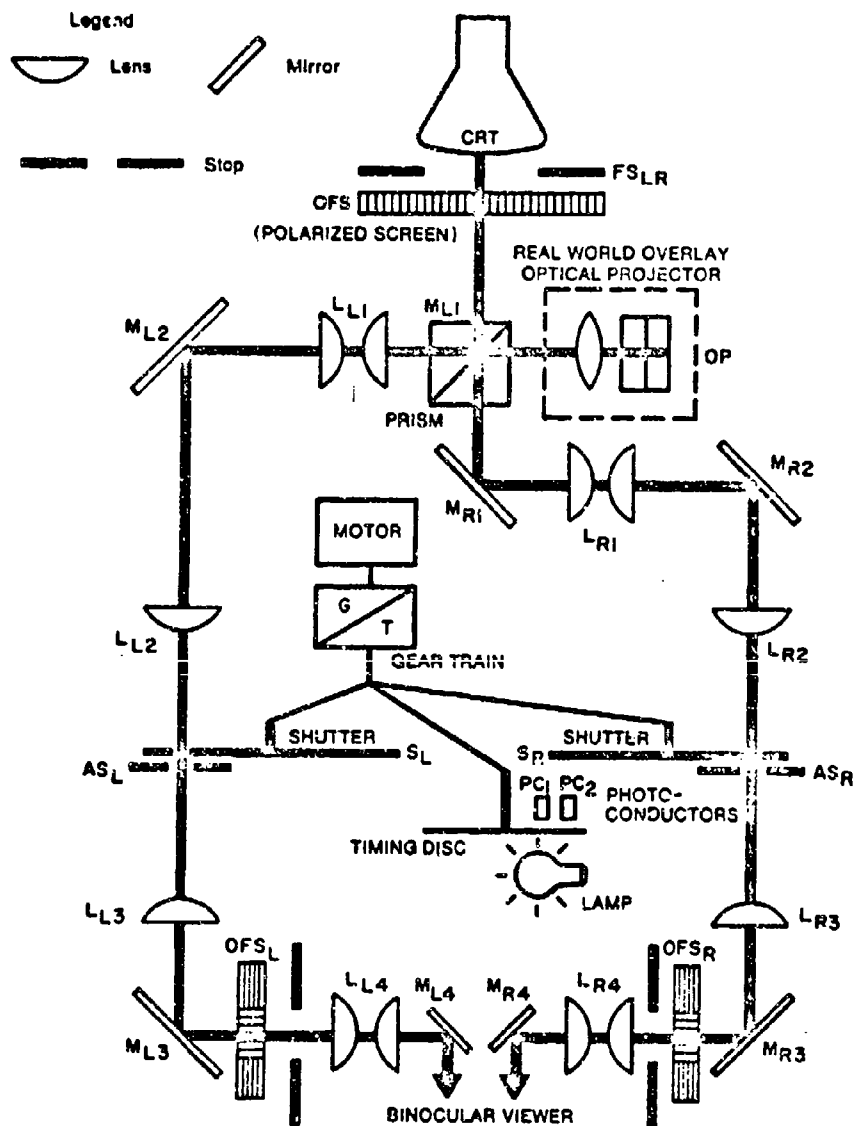


FIGURE 20. OPTICAL SCHEMATIC OF TELECENTRIC VIEWING SYSTEM

In a comparable manner light from the CRT reaches the left eye through the left half of the system. Interpupillary distance is adjusted by moving mirrors M_{L4} and M_{R4} in unison, fore or aft. The subject's head position is stabilized with a chin and head support.

The field-of-view is determined by field stops FS_{LR} , FS_R , and FS_L . FS_{LR} is common to both eyes, while FS_R and FS_L affect only the field for the right eye and left eye, respectively. Alternate presentations to the eyes are made by proper phasing of shutters S_R and S_L . The two shutters are driven by a common motor through a timing belt and geared pulley arrangement. Luminance matching of the two systems is accomplished by inserting appropriate neutral density filters near lenses L_{R1} and L_{L1} . Aperture and field stops can be varied in discrete steps.

Binocular overlay viewing is done by an optical projection system (OP) which transmits the image of a 35-mm color transparency to the two optical channels from the right side of the prism beam splitter. An aerial view of real terrain including a few buildings was used for the static rendition of the real world background.

Binocular disparities are obtained by presenting disparate images on the CRT alternately to the two eyes at a frequency above flicker fusion. Disparate CRT images are generated by inserting X and Y displacements of the displayed images into one of the sequential fields. The shutters are synchronized so that one eye views the images in an undistorted field, while the other eye sees the distorted field only.

Dual overlapping monocular fields for the images generated on the CRT are done with polarized screens in front of the face of the CRT at OFS , and at OFS_L and OFS_R in the two viewing channels. OFS and OFS_L are cross-polarized for all but a circular central portion of the field, representing one monocular image field in the display. The same cross-polarization is accomplished for OFS_L and OFS_R . Suitable lateral placement of OFS_L relative to OFS_R will produce the desired dual overlapping fields, as shown in figure 21. The circular central portions of OFS_L and OFS_R are polarized in the same direction as OFS , to provide uniform luminance for the real world overlay across the full field.

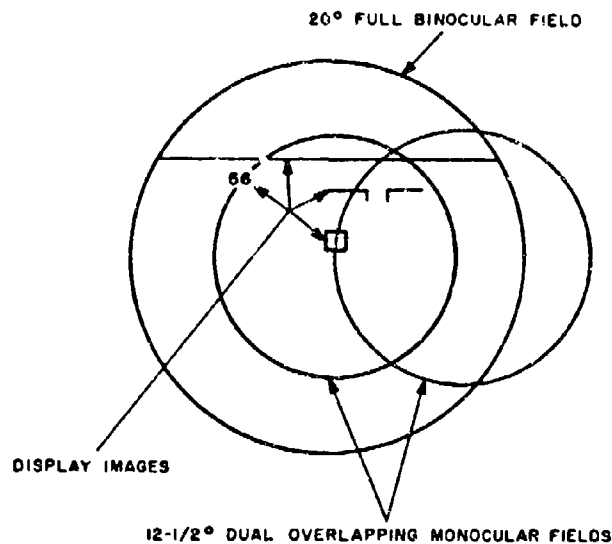


FIGURE 21. DISPLAY IMAGERY AND FIELDS OF VIEW

The optical characteristics of the system produce an overall system magnification of unity. All lens components are identical, with a focal length of 192 mm and a diameter of 52 mm. An assembled pair has an aperture of approximately f2. The optical aperture of each channel is controlled by a series of Waterhouse stops on a disc.

The lens barrels are held in clamp mounts. The fittings which secure the lens assemblies to the base structure use oversize holes and shims for final adjustment of position and angular alignment of the lenses. Three spring/stud mounts allow adjustment of the mirrors and the beam splitter.

b. Shutter/Synchronization Drive System

This equipment provides the following functions in the telecentric viewing apparatus:

- Shutter operation for the alternate presentation of the common CRT display to each eye

- Timing for the proper positioning of the disparate CRT display images for each of the optical channels
- Synchronization pulses to trigger the start of the display image patterns generated by the electronic equipment driving the CRT.

These functions must be synchronized precisely and stably to one another irrespective of changes in the absolute speed at which the primary shutter function is being operated. The mechanical drive system that was selected is shown in figure 22. A central drive motor operates the shutter and timing discs through a toothed-chain timing belt which drives geared pulleys on all of the rotating shafts. The primary drive motor is a 400-Hz synchronous motor operating at 12,000 rpm. The two shutter discs operate at 1500 rpm, the speed reduction is by a 4X gear drive and a 2X increase in pulley size from the gear drive output to the two discs shafts. Each shutter disc has a 180-degree slot to open its optical channel for half a cycle.

The timing disc also operates at 1500 rpm and provides two sets of pulses. A wide 180-degree pulse provides levels with 50-percent duty cycle for image disparity switching. Two narrow pulses provide trigger signals for the start of each full cycle of operation. The timing disc has a pattern of holes passing in front of two sources of light generated by two small bulbs in an enclosure. Photosensing is done with two TI type H-35PN diffused silicon photo diodes, which are gated by the light passing through the apertures in the disc.

c. General Construction

The structure of the telecentric viewing system is self-supporting, and is formed with plates and strut shapes. The main deck supports all of the equipment except the electronic assemblies. A CRT is supported by a cradle in the face region and at the deflection coils. The assembled equipment is shown in figure 23.

The head rest and chin support assembly for the test subjects is a Bausch and Lomb unit, Catalog No. 71-91-10. The head rest is secured to the supporting structure under the main deck.

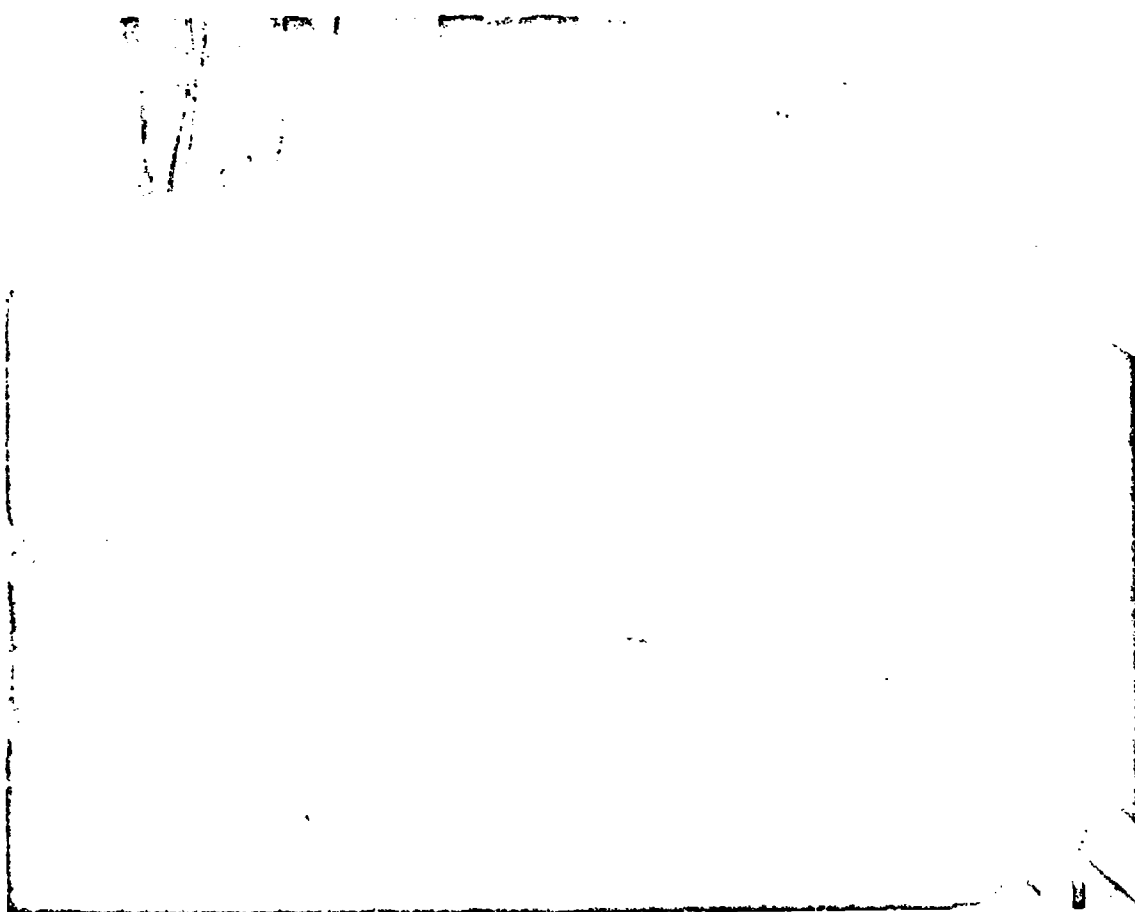


FIGURE 22. REAR QUARTER VIEW OF TELECENTRIC VIEWING ASSEMBLY

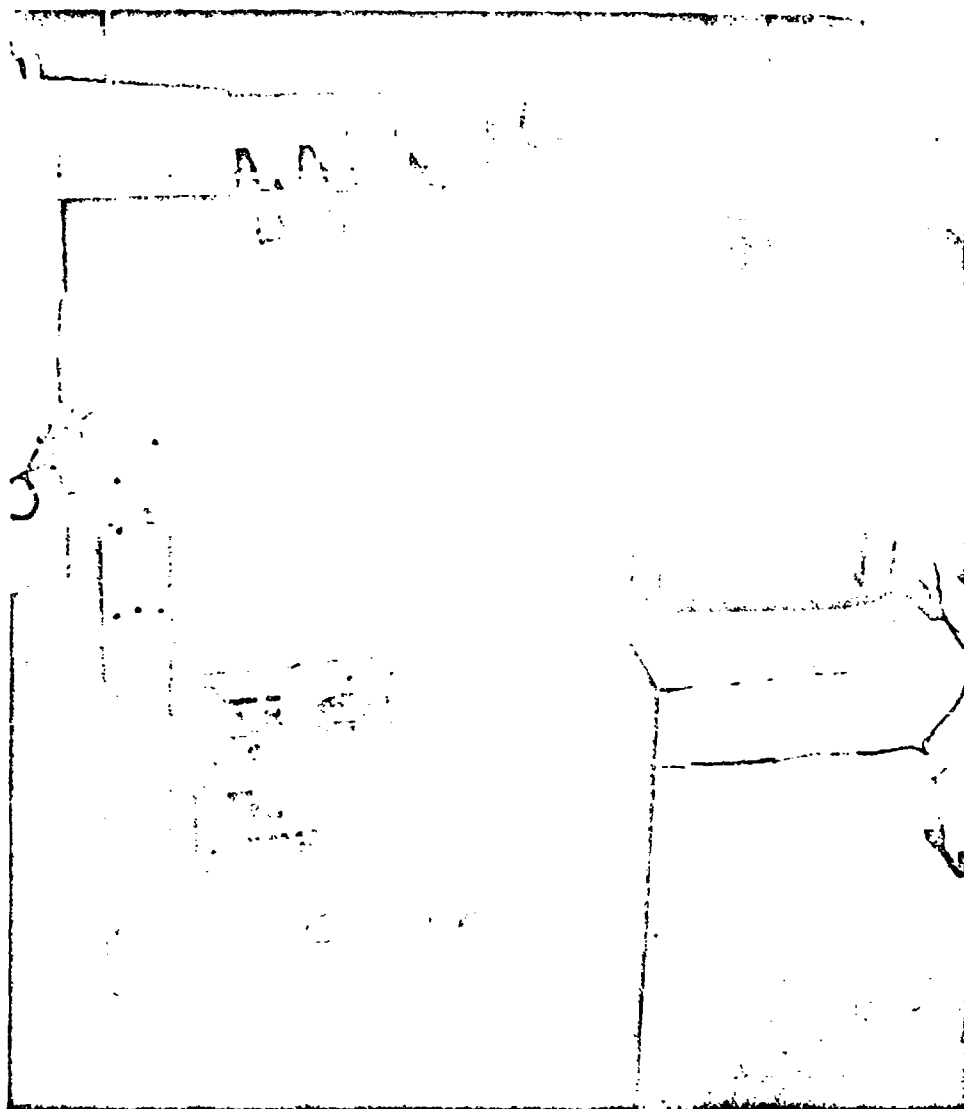


FIGURE 23. SIDE VIEW OF TELECENTRIC VIEWING ASSEMBLY

2. Electronic Display System

a. Description

A display generator provides four typical flight information images and displays them on a CRT. These are a horizon line, a flight path marker, a square, and a two-digit numeral as shown in figure 21. The images may be fixed to form a static display or continuously varied in position to form a dynamic display.

The display generator is triggered by synchronization pulses from the shutter assembly timing disc at a rate of 50 pulses per second. One complete set of images is generated for each trigger pulse. The timing of the display is synchronized with alternate openings of the left- and right-eye shutters. The viewer sees the appropriate display with either eye at the rate of 25 times per second. This provides flicker fusion at the light levels used, so the display appears continuous to both eyes.

Means are provided within the display generator to displace the position of the display images for either eye. This is accomplished by changing the gains and offsets of the CRT deflection amplifiers from one set of values to another during alternate display presentations. Due to the synchronization between the display and the shutters, the eyes see two displays with a controlled relative placement. The effect is that of binocular disparity. Figure 24 is a functional block diagram of the electronics for the telecentric viewing system.

b. Display Generator

The symbol generator employs stroke writing techniques; stroke writing is the digital counterpart to analog Lissajous writing. The stroke generator applies digitally-controlled integrated impulses to the CRT deflection amplifiers instead of sine waves. The resultant images are virtually noise-free, and of uniform brightness and high resolution.

Pulses generated by the image and timing logic are fed to the x- and y-integrators. Since the pulse amplitude is constant, the output of the integrator is a linear ramp function. The amplitude of the ramp is proportional to the pulse duration. Therefore, the writing speed is constant and the length of the line is dependent upon the pulse duration. Brightness pulses are also generated by the image and timing logic, and are fed to the video amplifier to unblank the CRT when writing a symbol.

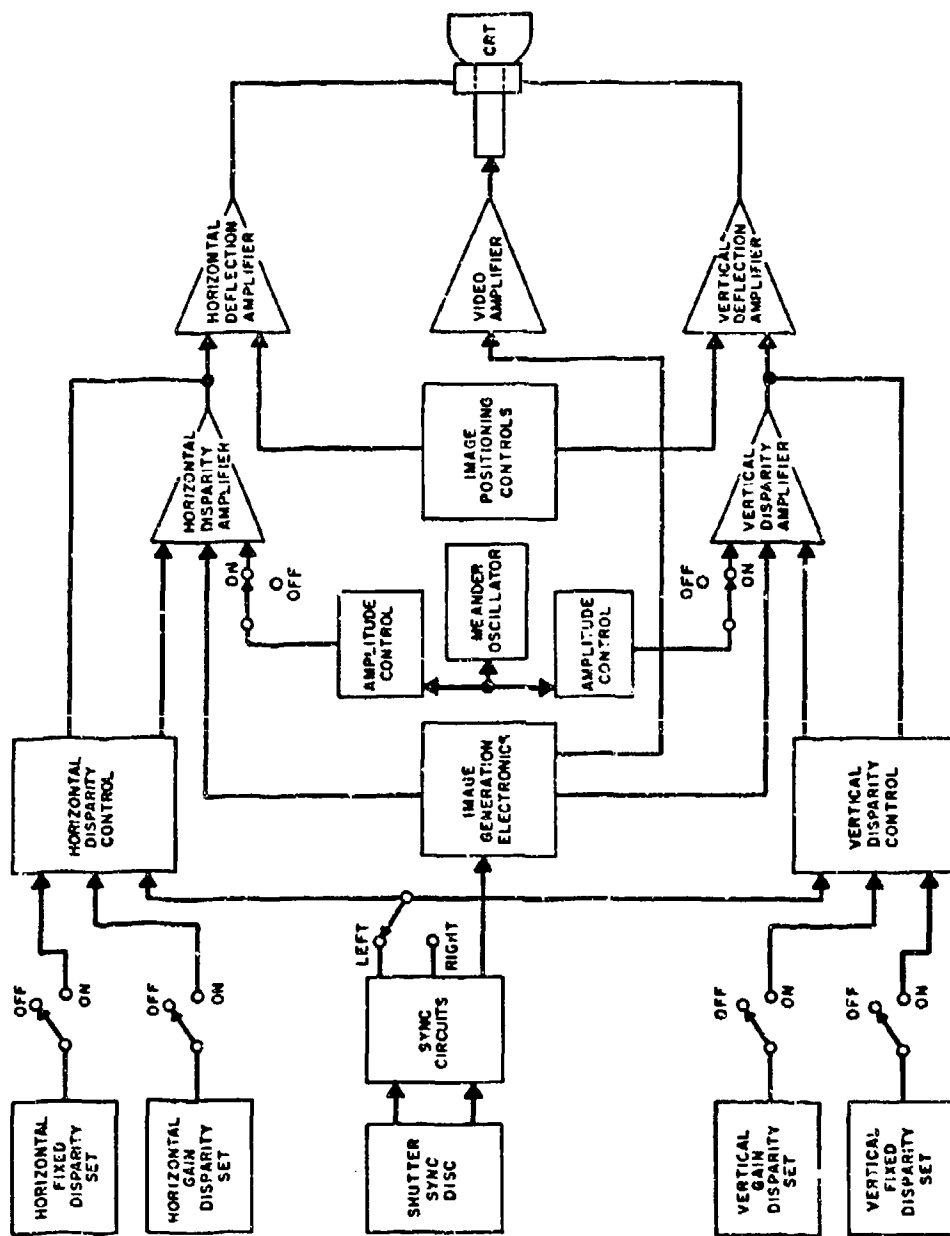


FIGURE 24. FUNCTIONAL BLOCK DIAGRAM OF TELECENTRIC VIEWING SYSTEM

Figure 25 is a simplified block diagram of the display generator electronics. The system is arranged so that a trigger sync pulse is required from the shutter system to start the image generation sequence. Only one set of symbols is written for each trigger sync pulse. The electronics can follow sync rates from zero to 60 pulses per second.

c. Disparity Generator

Two types of disparities are generated by the disparity generator for both the x- and y-axes, corresponding to horizontal and vertical disparities. These are a constant disparity and a disparity varying as a function of position on the CRT. The disparity generator is an operational amplifier whose bias signal input and gain characteristic may be changed electronically and in time synchronization with the shutter system.

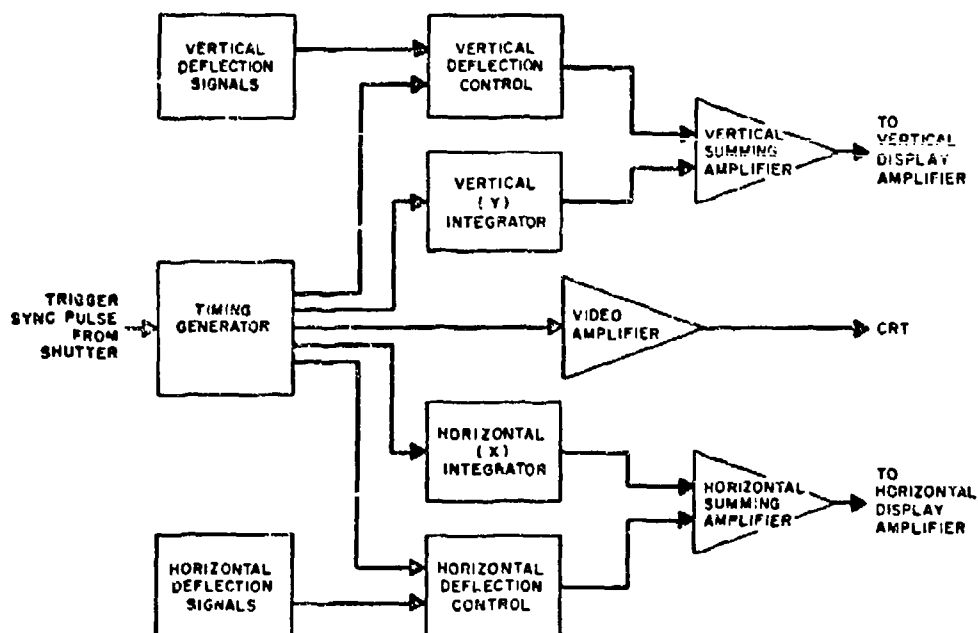


FIGURE 25. BLOCK DIAGRAM OF IMAGE GENERATING SYSTEM

Fixed disparity is accomplished by inserting constant bias signals into the appropriate horizontal and/or vertical deflection channels. The desired bias signal may be selected by the experimenter for either the left eye image or the right eye image, by changing the switch position.

Varying disparities as a function of position, which produce disparity gradients are accomplished by using different deflection amplifier gains for the right eye and left eye displays. Referring to figure 26, let the voltage inputs to the x- and y-axes be e_x and e_y . If k_x and k_y are the deflection amplifier gains relating position to voltage in one of the channels, the CRT deflection in that channel will be given by:

$$x_1 = k_x e_x$$

$$y_1 = k_y e_y$$

If the changes in gain for the second channel are Δk_x and Δk_y , the deflections in the second channel will be

$$x_2 = (k_x + \Delta k_x) e_x$$

$$y_2 = (k_y + \Delta k_y) e_y$$

The differences in deflection between the two channels is then

$$\Delta x = x_2 - x_1 = \Delta k_x e_x$$

$$\Delta y = y_2 - y_1 = \Delta k_y e_y$$

The slope of the line joining the two positions (x_1, y_1) and (x_2, y_2) is then

$$\frac{\Delta y}{\Delta x} = \frac{\Delta k_y}{\Delta k_x} \cdot \frac{e_y}{e_x}$$

If Δk_x and Δk_y are made proportional to k_x and k_y , this slope will be

$$\frac{\Delta y}{\Delta x} = \frac{k_y}{k_x} \frac{e_y}{e_x}$$

which is the same as the slope of the line from the center of the tube to the point 1, that is y_1/x_1 from the first two equations. Hence the displacement of point 2 from point 1 in figure 26 will be in the radial direction.

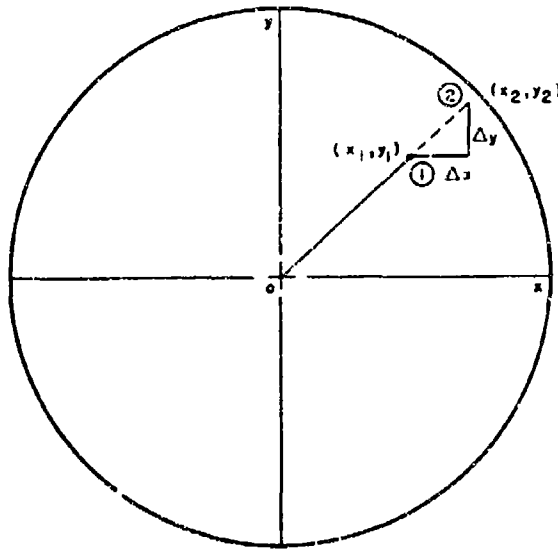


FIGURE 28. GEOMETRY OF RADIAL DISPARITY GENERATION

If the amplifier gains k_x and k_y are equal, the gain changes Δk_x and Δk_y must also be equal to provide a radial displacement of point 2 in figure 28.

d. Control Panel for Experimenter

The experimenter's control panel (figure 22) contains all the necessary controls to conduct a specific test, and some that are required only for the initial set-up of the particular test. These controls and their functions are as follows:

- Real World On-Off (R/W On-Off) - controls the power to illuminate the real world projection system.
- Washout On-Off - controls the ambient illumination of the CRT.
- Meander Oscillator Vertical Select - allows selection of a dynamic display moving along the vertical axis.

- Meander Oscillator Vertical Gain - controls the amplitude of the dynamic display movement along the vertical axis.
- Meander Oscillator Horizontal Select - allows selection of a dynamic display moving along the horizontal axis.
- Meander Oscillator Horizontal Gain - controls the amplitude of the dynamic display movement along the horizontal axis.
- Distortion Left-Right - selects the eye to which the displaced pattern is presented.
- Vertical Gain Disparity Select - allows the selection of either a fixed or a variable gain control of the CRT vertical deflection amplifier.
- Vertical Gain Disparity Control - allows manual control of the magnitude of the vertical gain disparity.
- Vertical Null Select - allows selection of the vertical null control.
- Vertical Null Control - allows manual control of the magnitude of the fixed (or offset) vertical disparity.
- Horizontal Gain Disparity Select - permits the selection of either a fixed or a variable gain control of the CRT horizontal deflection amplifier.
- Horizontal Gain Disparity Control - allows manual control of the magnitude of the horizontal gain disparity.
- Horizontal Null Select - allows selection of the horizontal null control.
- Horizontal Null Control - allows manual control of the magnitude of the fixed (or offset) horizontal disparity.
- Focus Control - allows control of the line thickness of the CRT display.

B. DESIGN AND CONDUCT OF EXPERIMENTS

1. Test Procedures

The binocular disparity studies were conducted with three test subjects. Two of the subjects were pilots with military flight experience, one currently an airline captain in scheduled air carrier service. The third subject was a flight test engineer who had extensive experience in aircraft under a wide range of weather conditions.

Two other subjects with military flight backgrounds also participated in some of the early tests. However, the extreme binocular disparities that confronted them caused high visual stress and, after short periods, visual fatigue accompanied by tearing of the eyes. Both these subjects felt compelled to withdraw from the program.

All subjects were given optometric examinations, including Ortho-Rater and duction tests. Their performance in these tests was found to be within normal limits.

The studies were designed to measure visual performance with various levels of horizontal and vertical binocular disparity, as functions of the following parameters:

- Brightness of images
- Image motion
- Real world background
- Line thickness of images
- Overlapping monocular fields.

Fourteen test conditions were established based on the use of these variables in different combinations, and these are summarized in table 7. The test condition 1 in table 7 consists of a slow oscillation of the display images at a 45-degree angle with the horizontal, with high brightness images consisting of thin lines, viewed against a static real world background. Both eyes viewed the same 20-degree circular field in the test condition.

Test conditions 2 through 6 are variations of the other classes of parameters one at a time. Image motion in the horizontal direction and static images were presented as test conditions 2 and 3. Images with low brightness and thin lines are involved in test conditions 4 and 5. The normal brightness of the images involved a luminance equivalent to ten times the luminance of the brightest region in the real world background. For the low brightness condition, the luminance of the images was reduced to one-tenth of its normal value, so that they matched the maximum luminance in the real world. The standard line width of the images was 2.4 minutes, and this was increased to six minutes to represent thick lines. A complex disparity having both horizontal and

TABLE 7. SUMMARY OF BINOCULAR DISPARITY TEST CONDITIONS

Test Conditions	Image Motion			Image Brightness		Line Thickness		Type of Disparity		Background		Display Field		Number of Sessions		
	Oblique (45°)	Horizontal	Static	High	Low	Fine	Thick	Simple	Complex	Real World	Homogeneous	Full Binocular	Overlapping	Subject A	Subject B	Subject C
1	•			•		•		•		•		•		6	2	1
2		•		•		•		•		•		•		1		
3			•	•		•		•		•		•		2	1	
4	•				•	•		•		•		•		2	1	
5	•			•			•	•		•		•		3	1	
6	•			•		•			•	•		•		2	2	
7	•			•		•		•			•	•		3		1
8	•			•		•		•		•			•	2	1	
9		•			•	•		•		•		•		1		
10			•	•		•		•		•			•	2		
11	•				•	•		•		•			•	1		
12	•			•			•	•		•			•	1	1	
13	•			•			•		•	•		•		1		
14			•	•		•		•			•	•		1		

Variable changed from test condition 1.

*Large complex disparity.

vertical components was presented in test condition 6. A homogeneous background representing flight within a cloud layer replaced the real world background to test condition 7. In test condition 8, dual overlapping fields of view were presented to each eye, displaced laterally to produce six degrees of overlap in the horizontal direction.

Test conditions 9 through 14 are departures from test condition 1 by the simultaneous change of two parameters; the combinations used are shown in table 7.

The disparity levels used in the tests were established by an extensive series of preliminary experiments, and these levels are summarized in table 8. Several facts are prominent in these data. The disparity ranges are much smaller for displays viewed against a real world compared with displays viewed against a homogeneous background. This is true for both horizontal and vertical disparities. For both horizontal cases, the ranges are larger for condition esophoria (cross-eyed) compared with exophoria (wall-eyed, divergent). For the vertical disparities, the ranges are the same for hypophoria (right eye low) and hyperphoria (right eye high).

A novel of visual performance was established for these binocular disparity studies. Tolerance for disparities is usually associated with the ability of an observer to retain single vision, i.e., to prevent visual doubling of objects or displays. However, in preliminary experiments, the subjects complained of visual stress and annoyance caused by disparities that are considerably smaller than those that produce doubling. Therefore, a psychometric rating system was developed to measure visual stress levels at disparity levels for which single vision exists, as well as for doubling phenomena.

After a 15-second exposure to a particular display situation, each subject was required to respond by rating his level of visual comfort in one of the following six response categories:

<u>Response Category</u>	<u>Visual Comfort Level</u>	
1	Excellent	} Comfortable
2	Comfortable, short of excellent	
3	Mildly uncomfortable	} Uncomfortable with single vision
4	Severely uncomfortable	
5	Doubling less than 50 percent of the time	} Double vision
6	Doubling more than 50 percent of the time	

On this basis, categories 1 and 2 represent two levels of comfortable vision, while categories 3 and 4 provide for two levels of discomfort, all with single vision. Image doubling is covered by categories 5 and 6, depending on the persistence of the doubling.

Each test, representing a horizontal or a vertical disparity experiment under a particular set of display conditions from table 7, involved ten replications of each of nine disparity levels from table 8, or a total of 90 data points. The disparity levels were presented in a random sequence to the test subjects. Considering both horizontal and vertical disparities for each display condition, a full test session included 180 data points. The responses of the subjects to each presentation were in one of the six rating categories.

The details associated with the conduct of the experiments are as follows. The interpupillary distance of a subject was measured, and the spacing of the two exit pupils in the binocular viewing apparatus was adjusted accordingly. The subject was then seated in the viewing compartment (figure 27) and his head rest and seat were adjusted to provide a comfortable viewing condition. The subject became adapted to the low level of ambient illumination and final adjustment of the interpupillary setting of the apparatus was made.

The subject was then given practice trials involving both horizontal and vertical disparities to familiarize him with the displays, the equipment, and the following test procedures. When the experimenter had set a particular disparity level into the apparatus, he advised the subject by calling "ready" over the intercom. When the subject was ready to proceed, he responded by pressing a buzzer. This procedure permitted the subject to proceed from trial to trial at his own pace. Upon hearing the buzzer, the experimenter started an electric timer and permitted the subject to view the display for fifteen seconds, at which time he requested the subject to respond by calling "read". The subject then pressed the buzzer one to six times corresponding to the visual comfort levels 1 through 6. The buzzer was used to transmit the response rather than voice communication to avoid errors caused by loss of intelligibility at the ambient noise levels produced by the running shutter drive system. The experimenter then recorded the response, reset the timer to zero, and proceeded with the next disparity level.

TABLE 8. BINOCULAR DISPARITY LEVELS USED IN TEST SCHEDULE

<u>Dial Setting</u>	<u>Horizontal Disparity (minutes)</u>		<u>Dial Setting</u>	<u>Vertical Disparity (minutes)</u>	
With Real World Background					
530	-18	Esophoria	520	+12	Hyperphoria
520	-12	(Convergent)	515	+9	(Right Eye High)
510	-6	(Near)	510	+6	
505	-3		505	+3	
500	0	Orthophoria	500	0	Ortho
495	+3		495	-3	
490	+6	Exophoria	490	-6	Hypophoria
485	+9	(Wall-Eye)	485	-9	(Right Eye Low)
480	+12	(Far)	480	-12	
With Homogeneous Background					
800	-180	Esophoria	570	+42	Hyperphoria
700	-120	(Convergent)	550	+30	(Right Eye High)
600	-60	(Near)	530	+18	
550	-30		515	+9	
500	0	Orthophoria	500	0	Ortho
475	+15		485	-9	
450	+30	Exophoria	470	-18	Hypophoria
400	+60	(Wall-Eye)	450	-30	(Right Eye Low)
350	+90	(Far)	430	-42	

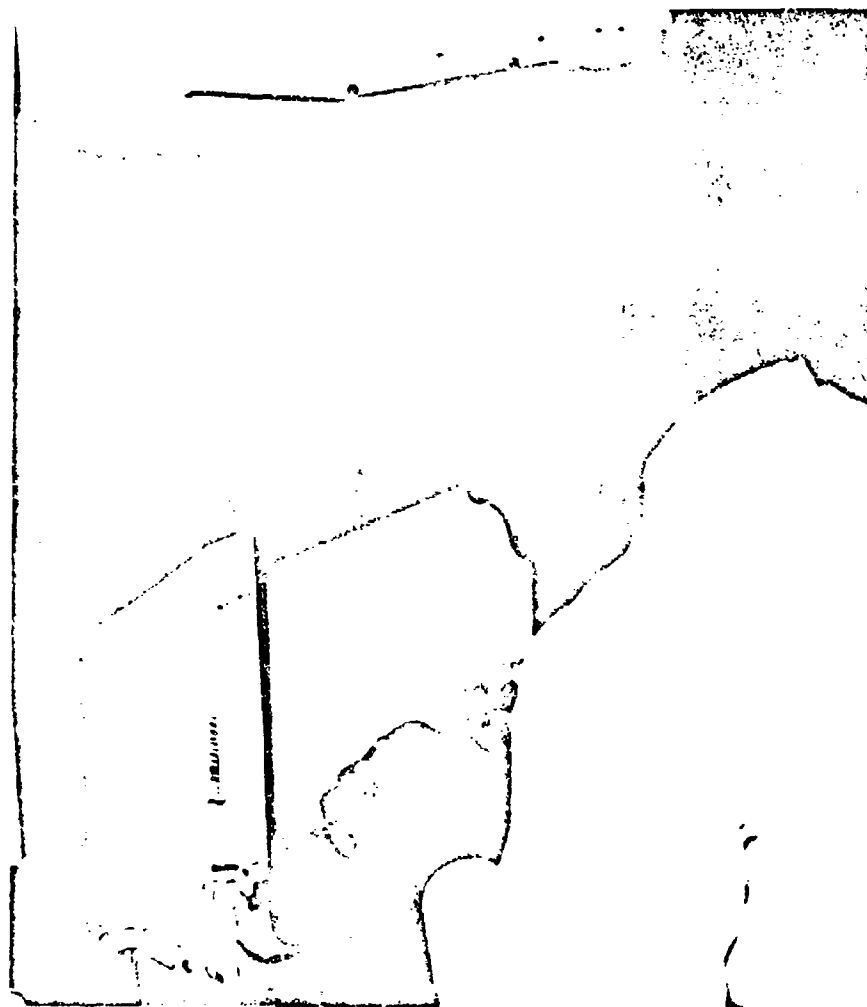


FIGURE 27. SUBJECT SEATED IN VIEWING COMPARTMENT

A set of experimental trials consisting of 30 disparity presentations lasted between 10 and 15 minutes. After this the subject was given a five-minute rest period; 10- to 15-minute rest periods were given after each two sets. A complete experimental session consisted of six sets, three involving horizontal disparities and three covering vertical disparities, thereby providing the 180 data points planned. An experimental session lasted about two hours. Each subject participated in two sessions per day and in some instances three sessions. When a third session was included, two test conditions were interlaced so that the presentations for the two conditions to be compared would be balanced on a day-to-day basis.

2. Data Reduction

Each test condition yielded 90 data points for horizontal disparities and 90 data points for vertical disparities. The 90 data points are distributed among the nine levels of disparity (table 8), with 10 points per disparity. The results for a typical test condition are presented in the two-way matrices in table 9, in which the responses are binned by category for each stimulus (disparity level, in minutes of arc).

The essential data in the matrices were reduced to graphical plots by considering the percentage of the responses that were equal to or better than response category 2, and equal to or better than response category 3. This was done for each disparity level and the results were plotted as in figure 28. The solid lines represent the variation of the sum of the responses categories of 2 or better, i.e., 1 plus 2, as a function of disparity level. The dotted lines represent the sum of the response categories of 3 or better, i.e., 1 plus 2 plus 3.

The curves in figure 28 show optimal performance levels at small disparities, near zero. However, this performance degrades as disparity, and, therefore, visual stress level rises in either direction. Smaller tolerances to disparity is manifest by narrow band or peaked curves in figure 28. Therefore, subjects are seen to be more sensitive to vertical disparities compared with horizontal disparities. In addition, for horizontal disparities, esophoric (convergent, cross-eyed) conditions provide lower stress levels than exophoric (wall-eyed) conditions. These two horizontal disparities will be designated as "near" and "far".

TABLE 9. DISTRIBUTION OF RESPONSES FOR
TYPICAL TEST SESSION

Disparity (minutes)	Response Category					
	1	2	3	4	5	6
Horizontal Disparity						
-18				1	9	
-12			3	5	2	
-6	1	8	1			
-3	6	3	1			
0	9	1				
+3	4	5		1		
+6			4	5	1	
+9				2	4	4
+12					1	9
Vertical Disparity						
+12						10
+9					3	7
+6			1	5	4	
+3	3	5	1	1		
0	8	2				
-3	9	1				
-6	1	6	2	1		
-9				3	7	
-12						10

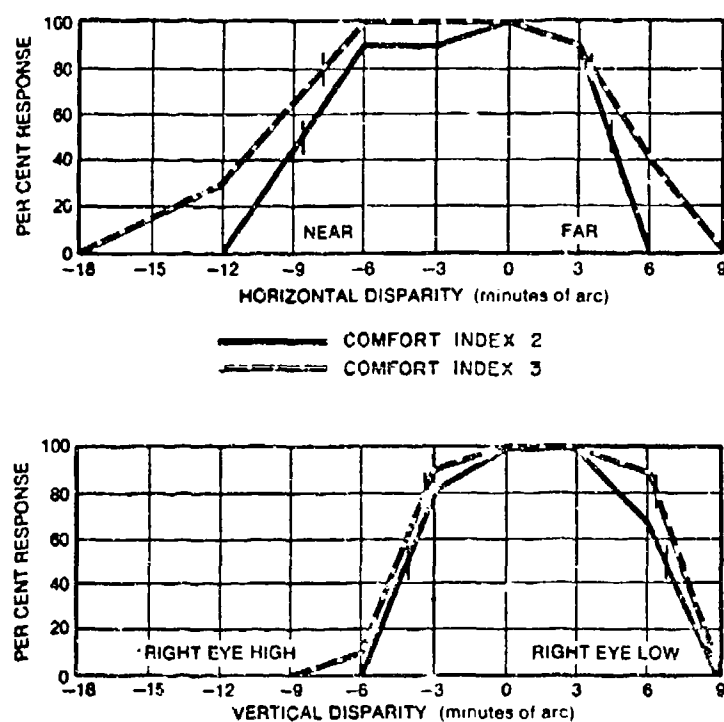


FIGURE 28. COMFORT LEVEL AS A FUNCTION OF BINOCULAR DISPARITY FOR TYPICAL TEST SESSION

The families of curves in figure 28 summarize the variation in visual performance as a function of horizontal and vertical disparity levels. To apply these data to the optical design problem for head-up displays, it is necessary to establish maximum permissible disparities. These in turn depends on minimum acceptable visual performance levels. Two criteria were specified for this purpose:

- Comfortable vision or better (Categories 1 or 2) 50 percent of the time was designated Comfort Index 2
- Mild discomfort or better (Categories 1, 2, or 3) 80 percent of the time was designated Comfort Index 3.

It was judged that a head-up display that met these criteria based on the data for sustained 15-second viewing used in these studies, would be satisfactory in real flight.

As an example of the application of these criteria to the data in figure 28, the maximum permissible disparities are:

Type of Disparity	Comfort Index	Maximum Disparity (minutes)	
		Near	Far
Horizontal	2	8.8	4.3
	3	7.8	3.6
Vertical		<u>Right Eye Low</u>	<u>Right Eye High</u>
	2	6.8	4.1
	3	6.3	4.5

The amount of data from each of the three test subjects is summarized in table 7, where the number of test sessions for each experimental condition is indicated. The horizontal and vertical disparities associated with Comfort Indices 2 and 3 for all of the test sessions are presented in table 10. The median disparity levels derived from replicated test conditions are also included in this table. Medians were used rather than arithmetic means, to include the effects of larger-than values which are beyond the disparity ranges covered, without permitting these data points undue weighting of the results. When two pieces of data are involved, the median and mean values are of course the same.

TABLE 10. SUMMARY OF BINOCULAR DISPARITY LEVELS
FOR TWO COMFORT INDICES

Test Condition and Subject	Session No.	Comfort Index 2				Comfort Index 3			
		Horizontal Disparity (minutes)		Vertical Disparity (minutes)		Horizontal Disparity (minutes)		Vertical Disparity (minutes)	
		Near	Far	Right Eye Low	Right Eye High	Near	Far	Right Eye Low	Right Eye High
SUBJECT A									
Condition 1, Reference	1	8.8	4.3	6.8	4.0	8.0	3.8	6.3	4.5
	11	4.5	2.0	4.5	2.8	>18.0	3.8	3.8	1.8
	14	11.0	4.5	5.0	5.0	>18.0	3.0	4.5	4.0
	23	8.0	5.3	4.5	7.0	18.0	4.3	3.8	6.8
	25	8.0	4.0	4.5	4.5	18.0	3.8	4.0	4.5
	28*	8.3	8.3	7.0	2.5	7.8	6.0	6.0	4.5
	Median	8.15	4.4	4.75	4.25	18.0	3.8	4.25	4.5
Condition 2, Horizontal Motion	21	8.3	4.8	4.0	4.0	13.8	4.0	3.5	3.5
Condition 3, Static	2	8.8	5.0	5.5	2.0	13.3	4.3	4.5	1.5
	13	12.0	3.5	4.3	1.8	>18.0	4.0	3.8	1.3
	Median	10.4	4.3	4.9	1.9	-	4.15	4.2	1.4
Condition 4, Low Bright- ness	4	10.5	5.0	4.5	4.5	18.0	4.0	4.0	3.5
	26	9.0	5.5	4.3	3.8	>18.0	6.0	3.8	3.8
	Median	9.8	5.3	4.4	4.2	-	5.0	3.9	3.7
Condition 5, Thick Lines	3	12.0	5.0	6.5	3.5	18.0	4.8	6.0	3.5
	15	9.5	4.8	3.5	6.0	>18.0	4.0	4.5	4.5
	24	9.8	5.0	4.0	2.3	18.0	4.5	3.5	3.5
	Median	9.8	5.0	4.0	3.5	18.0	4.5	4.5	3.5

*Half Session

TABLE 10. SUMMARY OF BINOCULAR DISPARITY LEVELS
FOR TWO COMFORT INDICES (Cont'd)

Test Condition and Subject	Session No.	Comfort Index 2				Comfort Index 3			
		Horizontal Disparity (minutes)		Vertical Disparity (minutes)		Horizontal Disparity (minutes)		Vertical Disparity (minutes)	
		Near	Far	Right Eye Low	Right Eye High	Near	Far	Right Eye Low	Right Eye High
Condition 6, Complex Disparity	5	9.3	4.5	4.5	3.0	15.0	4.3	4.3	3.5
	12	1.5	1.3	1.8	1.3	8.5	0.0	1.5	0.5
	Median	5.4	2.9	3.2	2.2	11.8	2.2	2.9	2.0
Condition 7, Homogeneous Background	18	53.0	27.0	15.0	8.0	72.0	35.0	21.0	10.0
	20	86.0	82.0	22.0	11.0	84.0	80.0	23.0	9.0
	27*	110.0	73.0	22.0	13.0	120.0	70.0	21.0	13.0
	Median	86.0	73.0	22.0	11.0	84.0	70.0	21.0	10.0
Condition 8, Overlapping Fields	7	7.0	5.3	2.5	3.5	14.0	5.0	1.5	1.5
	17	10.3	5.3	5.0	4.5	>18.0	4.0	6.0	3.5
	Median	8.7	5.3	3.8	4.0	-	4.5	3.8	2.5
Condition 9, Horizontal Motion and Low Bright- ness	22	8.8	6.0	3.8	3.0	>18.0	6.0	3.8	1.5
Condition 10 Static and Overlapping Fields	6	>18.0	4.8	2.5	4.8	>18.0	3.6	1.5	3.5
	16	13.8	6.0	3.5	4.0	>18.0	4.0	2.0	3.5
	Median	-	5.4	3.0	4.4	>18.0	3.9	1.8	3.5
Condition 11 Low Bright- ness and Overlapping Fields	9	11.0	4.8	4.0	4.3	>18.0	4.5	3.5	3.5

*Half Session

TABLE 10. SUMMARY OF BINOCULAR DISPARITY LEVELS
FOR TWO COMFORT INDICES (Cont'd)

Test Condition and Subject	Session No.	Comfort Index 2				Comfort Index 3			
		Horizontal Disparity (minutes)		Vertical Disparity (minutes)		Horizontal Disparity (minutes)		Vertical Disparity (minutes)	
		Near	Far	Right Eye Low	Right Eye High	Near	Far	Right Eye Low	Right Eye High
Condition 12, Thick Lines and Over- lapping Fields	8	9.0	4.5	5.0	3.8	>18.0	4.0	5.0	3.0
Condition 13, Thick Lines and Large Complex Disparity	10	-	-	-	-	-	-	-	-
Condition 14, Static and Homogeneous Background	19	37.0	30.0	14.0	13.0	69.0	25.0	21.0	12.0
<u>SUBJECT B</u>									
Condition 1, Reference	8	9.3	7.8	4.5	6.8	18.0	9.0	6.3	9.0
	3	3.0	6.0	6.0	5.3	18.0	7.0	6.3	7.0
	Median	6.2	6.9	5.2	6.1	18.0	8.0	6.2	8.0
Condition 3, Static	1	9.5	6.0	3.8	5.0	12.0	7.5	4.5	5.0
Condition 4, Low Bright- ness	7	12.0	6.0	3.5	4.5	>18.0	6.5	4.5	6.0
Condition 5, Thick Lines	2	9.0	6.8	5.0	5.3	14.5	12.0	9.0	9.5
Condition 6, Complex Disparity	4	8.5	5.5	4.0	4.0	>18.0	8.0	6.5	6.5
	9	12.0	7.3	4.8	6.5	>18.0	8.0	6.0	7.3
	Median	10.3	6.4	4.4	5.3	>18.0	8.0	6.3	6.9

TABLE 10. SUMMARY OF BINOCULAR DISPARITY LEVELS
FOR TWO COMFORT INDICES (Cont'd)

Test Condition and Subject	Session No.	<u>Comfort Index 2</u>				<u>Comfort Index 3</u>			
		<u>Horizontal Disparity (minutes)</u>		<u>Vertical Disparity (minutes)</u>		<u>Horizontal Disparity (minutes)</u>		<u>Vertical Disparity (minutes)</u>	
		<u>Near</u>	<u>Far</u>	<u>Right Eye Low</u>	<u>Right Eye High</u>	<u>Near</u>	<u>Far</u>	<u>Right Eye Low</u>	<u>Right Eye High</u>
Condition 8, Overlapping Fields	5	-	-	7.0	-	12.0	7.0	6.8	3.0
Condition 12, Thick Lines and Over- lapping Fields	6	-	-	7.3	5.0	> 18.0	6.8	10.0	9.0
<u>SUBJECT C</u>									
Condition 1, Reference	1	12.0	1.3	2.3	3.8	> 18.0	5.0	4.0	6.0
Condition 7, Homogeneous Background	2	60.0	34.0	23.0	32.0	127.0	84.0	32.0	34.0

C. RESULTS AND IMPLICATIONS

The results in table 10 cover the effects of the principal factors, one at a time, for two test subjects, A and B. In general, the effects of variables changed in pairs of two were investigated with subjects A and B, while only basic test data were obtained from subject C, to corroborate some key basic results.

The reference test condition 1 represents a baseline situation representing normal operation for the head-up display, with moving display images viewed against a static real world background. The disparities for Comfort Indices 2 and 3 for all subjects are summarized in table 11. The results are similar for both comfort indices. For horizontal disparities the tolerance for wall-eyed or exophoric conditions (far) is considerably less than for the convergent (near) or esophoric condition. Tolerances are uniformly low for vertical disparities. For both horizontal wall-eyed and vertical disparities, the tolerances are in the 1- to 2-mil range. Convergent horizontal tolerances are somewhat higher, about 2-1/2 mils. (The test data are expressed in minutes of arc, but the results are also converted to milliradians (mils), in which optical tolerances are conventionally expressed, in table 11. One milliradian is equivalent to 3.44 minutes of arc).

TABLE 11. SUMMARY OF BINOCULAR DISPARITY LEVELS FOR ALL SUBJECTS FOR REFERENCE TEST CONDITION

Subject	Comfort Index 2				Comfort Index 3			
	Horizontal Disparity (minutes)		Vertical Disparity (minutes)		Horizontal Disparity (minutes)		Vertical Disparity (minutes)	
	Near	Far	Right Eye Low	Right Eye High	Near	Far	Right Eye Low	Right Eye High
A	8.15	4.4	4.75	4.25	18.0	3.8	4.25	4.5
B	6.2	6.9	3.8	5.0	18.0	8.0	6.3	8.0
C	12.0	1.3	2.3	3.8	>18.0	5.0	4.0	6.0
Mean	8.8	4.2	4.4	4.7	18.0	5.6	4.9	6.2
Mean (mils)	2.6	1.2	1.3	1.4	5.2	1.6	1.4	1.8

The tolerances for all types of disparities are high for the two subjects tested when the display images are viewed against a homogeneous background (test condition 7). These results are summarized in table 10. The disparities exceed the comparable results for the reference condition by more than a factor of 10 in almost all cases. This represents the most significant finding in the disparity studies. Subjects can compensate for binocular disparities without loss of visual comfort by changes in eye positions, provided these compensatory relative eye positions can be maintained. This is the viewing condition with a uniform background that the subject may ignore visually. However, with an articulated background such as the real world, from which the pilot must obtain visual information, the situation is more demanding. Compensatory eye movements to handle binocular disparities in the display images must be relaxed when viewing the real world background. Hence, alternate changes in relative eye positions must be made, as attention is shifted from the display to the real world, and back to the display. Therefore, the permissible disparities are low under these relatively stringent conditions.

The pattern of tolerances is the same for both the reference condition and the homogeneous background. Convergent (near) disparities are appreciably larger than wall-eye (far) disparities, and permissible horizontal disparities are larger than vertical disparities.

Considering image motion, disparity tolerances for static images (test condition 3) are slightly lower than for moving images for both subjects A and B (table 10). The differences between test conditions are less than one mil. However, for subject A with vertical disparities, the tolerances with static images produced the lowest levels recorded, about 1/2-mil, and these data were supported in two tests.

Regarding image brightness, tolerances are comparable for both low brightness images (test condition 4) and the reference high brightness situation for both subjects.

Thick lines (test condition 5), in which the image line thickness is six minutes, compared with the standard fine line of 2.4 minutes, yield about the same disparity tolerances, for both subjects.

A complex disparity (test condition 6) is one in which both horizontal and vertical disparities are present concurrently. For the horizontal disparity tests, a constant three-minute vertical disparity (right eye low) was present; for the vertical disparity tests, a four-minute wall-eye horizontal disparity was superimposed. The complex disparity presented a more stringent condition for subject A, lowering his mean vertical disparity tolerance to one mil. Subject B had about the same tolerances with the complex disparity as with the simple disparity.

With dual overlapping fields (test condition 8), a portion of the display field is seen with one eye, another portion is seen with the other eye and a central portion is seen binocularly (figure 7). The fields are displaced laterally. Under these conditions, both subjects exhibited slightly lower vertical disparity tolerances compared with the reference test condition 1. Minimum tolerances are about one mil for both subjects.

Test conditions 9 through 14 involve the simultaneous manipulation of two parameters to eliminate possible interaction effects. Subject A was the key participant in the studies, and the results are included in table 10. No unusual effects are noted, with minimal tolerances still about one mil, except for one situation, horizontal motion with low brightness (test condition 9). Here, one vertical disparity tolerance was as low as 1.5 minutes or about 1/2 mil. The lowest vertical tolerances for horizontal motion (test condition 2) or low brightness (test condition 4) are about one mil. There may be an interaction effect present in the combined test condition 9, but the data from the one test is too limited to be conclusive.

Test condition 14 involves static imagery viewed against a homogeneous background. The results in table 10 indicate that there is a significant reduction in permissible disparities for the static condition compared with the moving imagery with the same background (test condition 7). However, the tolerances under the static condition are still large compared with the same images viewed against the real world.

The fact that two prospective test subjects, both with military flight experience, withdrew from the test program after a few preliminary test sessions is significant. Both complained of severe visual stress, accompanied by tears and visual fatigue, as a result of the test situations. These effects were undoubtedly produced by the binocular disparities with which they were confronted. There have been reports of test pilots complaining of eye fatigue after sustained flight with head-up displays. This condition may well have been caused by distortions in the optical systems of these displays.

In summary, it may be concluded that binocular disparity tolerances are considerably lower when head-up display images are viewed against a static real world background compared with a homogeneous background. Maximum disparity levels for viewing with adequate comfort are one mil for vertical disparities and wall-eye horizontal disparities. Convergent horizontal disparities may be as large as 2.5 mils for the same levels of visual comfort.

The foregoing studies have demonstrated that the presence of a static real world background significantly influences the permissible binocular disparities. In the tests which have been conducted, the simulated real world background was a static aerial view, typical of flight at higher altitude, with no appreciable rates of change of attitude or heading. The visual backgrounds remains quasi-static under these conditions. However, since presence of a real world background is important for binocular disparity tolerances, the effects of a dynamic background, typical of low level flight, should be investigated.

SECTION 5

CONCLUSIONS

1. The minimum size of exit pupil required for wide field (25 degrees) head-up display system is three inches when the pilot's head position is no more than 10 inches behind the exit pupil.
2. The binocular disparities permissible are considerably lower when head-up display images are viewed against a static real world background compared with a homogeneous background.
3. Maximum permissible disparity levels are one mil for sustained viewing with adequate comfort, for vertical disparities and divergent horizontal disparities. Convergent horizontal disparities may be as large as 2.5 mils.
4. The effects of thicker image lines, low image brightness, or dual overlapping monocular fields do not significantly change binocular disparity tolerances.
5. Disparity tolerances for static display images, and for combinations of vertical and horizontal disparities, are slightly lower than for dynamic imagery with either horizontal or vertical disparities.
6. There is a significant reduction in permissible disparities when static images are viewed against a homogeneous background, compared with moving images with the same background. However, the tolerances for static imagery with the uniform background are large and, therefore, not critical compared with images viewed against a static real world.
7. Interaction effects due to simultaneous changes in two visual parameters are small, and do not significantly affect binocular disparity tolerances.

SECTION 6

RECOMMENDATION

The effects on binocular disparity tolerances of a dynamic visual real world background against which head-up display images are viewed should be investigated. The results obtained in this manner will provide a more complete basis for head-up display specifications.

SECTION 7

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13. ABSTRACT An experimental study was conducted to determine critical values of the essential optical and electronic design parameters for head-up displays based on the visual requirements of the pilots who will use these displays. This information will provide a basis for future specifications covering this type of display. The investigation covered two areas, size of exit pupil and binocular disparities due to optical distortions. The exit pupil study was conducted in a flight simulator in which a wide field (25 degrees) head-up display with a large aerial exit pupil was installed. Four pilots with military flight experience served as test subjects. The results indicate that the minimum size of exit pupil required is three inches in diameter, for wide-field systems in which the pilot's head position is no more than 10 inches behind the exit pupil. A laboratory telecentric viewing system was developed for the binocular disparity study. This equipment made possible experiments in which disparate, dynamic, head-up display images were presented to subjects who viewed these images against a static view of a real world background. Three test subjects were (Continued)			

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employed in these tests. The results show that binocular disparity tolerances are considerably lower when head-up display images are viewed against a real world background, compared with a homogeneous background of moderate brightness. Maximum disparity levels are one mil for sustained viewing with adequate comfort for vertical disparities and divergent horizontal disparities. Convergent horizontal disparities may be as large as 2.5 mils for the same level of comfort.

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