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Exposure to Stereoscopic
Three-Dimensional Flight
Displays on Real-World
Depth Perception**

**Anthony M. Busquets,
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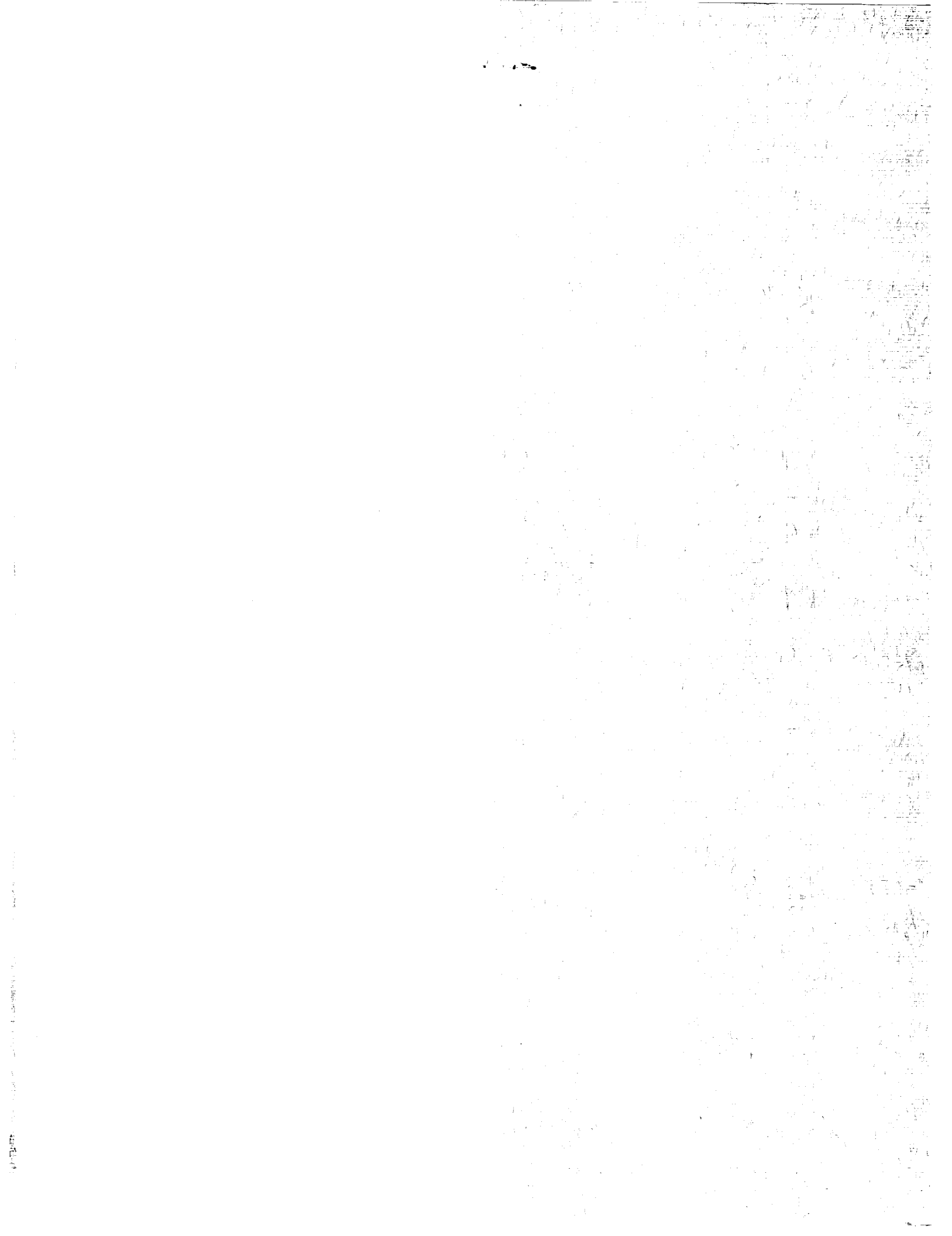
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Summary

High-fidelity color pictorial displays that incorporate depth cues in the display elements are currently available. The intuitively advantageous use of three-dimensional (3-D) display of three-dimensional information, rather than the use of conventional two-dimensional display of such information, is being pursued within the flight display community. These efforts have been particularly intense for helmet-mounted head-up display applications, as the display of stereoptically cued information is readily available with binocular helmet systems. Additional investigations have also been conducted with electronic shutters or polarized filters used in head-down applications (rather than helmet-mounted optics) to present separate left- and right-eye views. The application of depth cuing, through stereopsis, to advanced head-down flight display concepts offers potential enhancements in pilot situational awareness and improved task performance, but little attention has been focused on a fundamental issue involving its use. The goal of this research was to determine whether the use of head-down stereoscopic displays in flight applications would degrade the depth perception of pilots when changing from such displays to a real-world view.

Stereoacuity tests are traditionally used to measure the real-world depth perception of a subject. Stereoacuity is the smallest detectable difference in depth between visual targets. This difference can be determined from measurement of a subject's attempts at placing to the same depth two targets originally positioned at different distances from the subject (Howard-Dolman measurement technique). Eight transport pilots flew repeated simulated landing approaches using both nonstereo and stereo 3-D head-down pathway-in-the-sky displays. At the decision height of each approach, the pilots changed to a stereoacuity test that used real objects.

Statistical analysis of stereoacuity measures (comparison of data for a control condition of no exposure to any electronic flight display with the data for the change from nonstereo displays and from stereo displays) revealed no significant differences for any of the conditions. The mean values of stereoacuity for each condition, averaged over pilots and replicates, are presented. (The data for each individual pilot are also presented.) Tests for statistical significance for the individual data did reveal some differences. In only one instance was stereoacuity degraded from the control condition, and that case was significant only for the change from nonstereo displays. In all other cases there were either no differences or the stereoacuity was improved over that of the control con-

dition. Clearly, changing from short-term exposure to a head-down stereo display has no more effect on real-world depth perception (based on stereoacuity) than changing from a nonstereo display. However, depth perception effects based on size and distance judgments and on long-term exposure remain issues to be investigated.

Introduction

The intuitively advantageous use of three-dimensional (3-D) display of three-dimensional information, rather than the conventional two-dimensional display (with or without perspective) of such information, is being pursued within the flight display community. These efforts have been particularly intense in the area of helmet-mounted head-up display applications, as the display of stereoptically cued information is readily available with binocular helmet systems. Additional investigations have also been conducted in which electronic shutters or polarized filters, rather than helmet optics, were used in head-down display applications, to present separate left- and right-eye views (refs. 1 and 2).

Current electronic display technology can provide high-fidelity color pictorial displays that incorporate depth cues by the use of various stereoptic techniques. The technology has evolved to the point that these displays can be provided in a head-down environment under flicker-free conditions with virtually no operator discomfort (refs. 3 to 5). The application of depth cuing, through stereopsis, to advanced head-down flight display concepts offers potential enhancements to pilot situational awareness and improved task performance (refs. 6 to 11). However, the constraints imposed by the techniques of stereoscopic viewing must be fully understood in order to adequately realize and exploit the depth cuing enhancements. Also, since these techniques do not faithfully reproduce all real-world depth perception cues, there is concern in the flight display research community that depth perception losses may occur when pilots view stereo displays that do not provide *all* the real-world depth cues found in nature or when distortions in particular depth cues are introduced by optical misalignments in the viewing system (ref. 12). A fundamental and important issue involves the determination of whether the use of head-down stereo displays in flight applications will degrade the depth perception of pilots when changing from such displays to the real world.

Stereopsis techniques currently employed in head-down display systems can be controlled to not generate distortions by optical misalignments. (See section entitled "Stereo Visual System Hardware" for

a brief discussion on stereo 3-D display generation with a time-multiplexing technique.) However, the physically interdependent relationships between convergence, accommodation, and binocular disparity cues cannot be maintained (refs. 3 and 13 to 17). The time-multiplexing technique induces a perception of depth by imitating the convergence and binocular disparity cues of the real world. However, the accommodation cue (i.e., focus) remains constant at the display surface, and thus the convergence-accommodation relationship is violated. Studies show that this relationship violation can be tolerated to a certain degree while accurate depth perception is maintained within that environment (ref. 18). The research discussed herein addressed the issue of depth perception effects in a different environment (i.e., the real world) after short-term exposure to stereo 3-D head-down flight displays that violate the normal convergence-accommodation relationship.

While stereoacuity has been a traditional measurement of depth perception abilities, it is a measure of relative depth perception rather than of actual (or absolute) depth perception. In addition to relative depth, absolute depth perception (in terms of judgment of sizes and distances) plays a role in the visual landing task. The effects of the use of stereo displays on absolute depth perception were not addressed directly by this study.

Because stereo depth cues are effective in human vision only out to several hundred feet and because the performance enhancements afforded by stereo presentations are probably needed only for precision aircraft maneuvers, likely initial applications for the use of head-down stereo pictorial displays are for precision approach and landing, takeoff and climbout, air-to-air refueling, and station keeping. Thus, initial applications of stereo displays in the flight environment are likely to have the pilot switching to a stereo display mode for these precision maneuvers. Typically, these maneuvers are performed within a relatively short time duration and constitute a short-term exposure to stereo displays. Thus, it was felt that it was appropriate for this study to address the issue of short-term exposure to stereo displays.

Symbols, Abbreviations, and Definitions

d distance from the viewer to the zero mark (location of rods with no longitudinal displacement) of the Howard-Dolman apparatus, in.

d' Howard-Dolman apparatus rod longitudinal displacement from zero mark, in.
 i interocular distance, in.
 j for asymmetric viewing, the distance between the pupil of the eye that is rotated the most and the extended centerline between both eyes
 S Laplace operator
 x for asymmetric viewing, the lateral distance between the extended centerline between both eyes and the target
 α convergence angle, rad
 δ visual angle, rad
 θ angle generated by an eye's line-of-sight vector and the baseline between both eyes

Abbreviations:

2-D two-dimensional
 3-D three-dimensional
 4-D four-dimensional
 LCD liquid crystal device
 OTW out-the-window
 PFD primary flight display

Definitions:

accommodation "A change in the thickness of the lens of the eye (which changes the eye's focal length) to bring the image of an object into proper focus on the retina." (ref. 19)
 binocular disparity "The difference in the relative horizontal position of the visual images of an object on the left and right retinas due to the lateral separation of the eyes." (ref. 19)
 convergence The rotational movement of the eyes (inward or outward) so that both eye's lines of sight intersect at the depth distance of the object being fixated.

convergence angle	“The angle formed between the lines of sight of the two eyes when the eyes are fixated on a point in space.” (ref. 19)
decision height	“With respect to the operation of aircraft, means the height at which a decision must be made, during an ILS [instrument landing system] or PAR [precision approach radar] instrument approach, to either continue the approach or to execute a missed approach.” (ref. 20) In the context of this experiment, decision height was utilized to establish a baseline height at which the pilot transitions from viewing cockpit instruments to looking out the vehicle windows to obtain ground visual references.
depth cuing (by stereopsis)	The display of information utilizing the depth dimension, introduced by means of lateral disparity.
stereoacuity	“The ability to discriminate depth or distance solely on the basis of lateral retinal image disparity; usually expressed as the smallest detectable difference in depth of two targets (in seconds of arc of visual angle).” (ref. 19)
visual angle	“The angle subtended at the eye by the linear extent of an object in the visual field. It determines linear retinal image size.” (ref. 13)

Participating Pilots and Task

Eight active duty and operationally experienced U.S. Air Force transport pilots participated in this study. Each pilot had extensive experience in EC-135 large-bodied transport aircraft. The pilot's primary task was to fly a four-dimensional (4-D) approach using a pathway-in-the-sky primary flight display (PFD) format and, at decision height, change to an out-the-window (OTW) viewing mode for which

stereoacuity was then measured. (See fig. 1.) This procedure simulated flying an instrumented approach to decision height and the transition to looking out the aircraft windows for the actual landing. It is at the transition point that real-world depth perception is very important, as many real-world visual cues are used in the landing phase (motion parallax, texture gradients, peripheral vision, streaming, etc.). The pilot must make judgments based on perceptions of relative distances (such as touchdown thresholds and runway traffic) and velocities, and all vital pieces of information must remain true and undistorted.

In this experiment, stereoacuity was first measured before the pilots were exposed to any kind of visual display. This set of measures was used as the control condition, representative of the normal, unaffected stereoacuity of the individual. The pilots then performed the primary task repetitiously, in randomized order, for the two primary flight display conditions (stereo and nonstereo). A typical landing approach was performed over the period of 4 minutes, which constituted a short-term exposure to stereopsis for the stereo display condition examined. Four trial repetitions (replicates) were performed in order to obtain an average acuity level for the display condition specified.

Performance Metric and Experimental Design

The performance metric of the study was stereoacuity, and the experiment was designed to examine the variability of the pilot's stereoacuity about the control condition after short-term exposure to the two PFD conditions. The main factor of interest in the experiment was the display condition. The display conditions examined for the landing approach task were the presentation of the information in a pathway-in-the-sky-based PFD in nonstereo (i.e., no depth cues other than those provided by perspective, size, shape, interposition, and motion parallax) and stereo (i.e., additional binocular depth cuing provided by lateral-binocular disparity and convergence).

The experimental procedure was designed so that, after the pilot flew the 4-D approach task for several minutes to the decision height, the PFD would go blank. This would cue the pilot to change views to the real-world stereoacuity measurement device, as if the pilot were looking up from the cockpit instrumentation and out the aircraft windows during the landing phase. At this point a stereoacuity measurement was taken and a subsequent trial initiated. The measurement was verbally reported to the pilot following each trial.

Simulator Description

The simulator was assembled with the following elements: mathematical model, computer implementation, stereo visual system hardware (including stereoacuity measurement device), graphics generation hardware and software, and simulator cockpit (pilot evaluation station).

Mathematical Model

A simplified six-degree-of-freedom mathematical model of an airplane was used in the study. Figures 2 and 3 present block diagrams of the model. The transfer functions and gains were obtained empirically to represent a fixed-wing generic transport airplane. The inertial-axis velocities were obtained by resolving the body-axis velocities of the simplified model through the heading angle. These velocities were then integrated to yield the inertial positions, which are required by the graphics routines.

Turbulence was introduced into the mathematical model through the addition of gust components to the body-axis longitudinal and lateral velocity variables. The level of the turbulence was considered to be moderate to moderately severe by the participating pilots.

Computer Implementation

The mathematical model of the airplane and the simulation hardware drivers were implemented on a VAX 11/780 computer in the Langley Crew Station Systems Research Laboratory (ref. 21). This computer system solved the programmed equations 20 times a second. The average time delay from input to output (1.5 times the sample period) was approximately 75 msec.

Pilot control inputs were transmitted to the VAX 11/780 computer through several differential input analog-to-digital converters. Display drive parameters were output to the flight display host graphics computer via an Ethernet link. (See fig. 4.)

Stereo Visual System Hardware

The stereo visual system hardware operated on the video signals supplied by the graphics generation system. These video signals presented a 60-Hz noninterlaced frame, 1024 × 1280 pixels in resolution, consisting of both the left- and right-eye stereo-pair images. (See fig. 5.) The stereo visual system hardware (fig. 6) separated the left- and right-eye scenes and presented each alternately, at 120 Hz, spread across the entire monitor screen (i.e., time-multiplexed stereo, which results in a loss in vertical

resolution of approximately 50 percent), as shown in figure 7. Liquid crystal device (LCD) glasses were shuttered in synchronization with the stereo pair so that the right eye saw only the right-eye scene and the left eye saw only the left-eye scene, each at 60 Hz, without flicker. The stereo visual system hardware is described in reference 22.

Stereoacuity Measurement Hardware

Test apparatus. Depth perception, based on a stereoacuity measurement, was assessed with a Howard-Dolman test (refs. 13 to 15). The apparatus consisted of a uniformly lighted (approximately 12 footcandles) enclosed wooden box with a small window through which two black rods could be viewed. The rods were of the same diameter (0.39 in.) and, as viewed through the opening, the tops and bottoms could not be seen. Therefore, if the apparatus was placed far enough away from the viewer, all extraneous depth cues (other than lateral disparity) were virtually eliminated. This distance was set at 15 ft.

The depth of the rods could be changed by the viewer pulling strings attached to the rods. (See fig. 8.) The lateral separation of the rods was 3.39 in. When the rods were aligned, they were at the same distance from the viewer or subject. To measure stereoacuity, the viewer attempted to place the rods at the same depth. Stereoacuity was then measured by the accuracy of rod alignment, indicated at the top of the apparatus by rod separation (in longitudinal depth) in centimeters. This measure of stereoacuity based on rod separation was valid only for the particular distance of the apparatus from the viewer. However, expressing stereoacuity in terms of visual angle provided a measurement value independent of depth placement of the measuring device, that is, the Howard-Dolman test apparatus. To provide this independent measure, the conversion of the stereoacuity value, in terms of rod displacement, to visual angle was accomplished through calculation of the convergence angles generated by the setup geometry of the Howard-Dolman test apparatus. This calculation is presented in the next section.

Setup geometry and visual angle conversion. As previously indicated, stereoacuity was given by the longitudinal displacement of the Howard-Dolman rods about a common central point. (The rods were mechanically linked so that as one traveled forward, the other traveled the same distance in the opposite direction.) It can be given in

visual angle terms as the difference between the convergence angles generated by the rods. For the setup, one assumes the rods have no lateral separation. (See fig. 9.) This assumption can be made with less than 1 percent error in convergence-angle calculation if the distance d from the viewer to the point at which the rods are aligned is large enough so that the actual lateral separation of the rods is negligible in terms of convergence-angle calculation. (See appendix for determination of minimum d .)

The simplified symmetrical geometry, as illustrated in figure 9, shows the rod longitudinal displacement d' (and associated alignment point), distance from the viewer d , and the relationship between the generated convergence and visual angles α and δ . Stereoacuity is defined as the difference in convergence angles, $\alpha_2 - \alpha_1$. By simple geometry this is also equal to $2(\theta_1 - \theta_2)$, which is the visual angle δ (in radians). To convert the Howard-Dolman apparatus measurement d' to visual angle, one substitutes for α , where α_1 and α_2 are calculated as follows :

$$\alpha_1 = \arctan[(i/2)/(d + d')]$$

$$\alpha_2 = \arctan[(i/2)/(d - d')]$$

For small convergence angles (less than 10°) the arctangent of the angle is approximately the angle itself, and therefore, by substitution,

$$\delta = \left| \frac{2id'}{d^2 - d'^2} \right|$$

in radians. A simple conversion is then made from radians into the more typical unit of seconds of arc.

Graphics Generation Hardware and Software

The graphics generation software resided within a Silicon Graphics IRIS 4D/70 GT Superworkstation and consisted of the necessary transformation equations and the graphics data bases for the displays. The graphics displays were rendered at an update rate of 20 Hz synchronized to the real-time airplane simulation model. Delay time from simulation computer parameter output (and input to the graphics system) to display update was approximately 125 msec (2.5 simulation frames). Figure 10 illustrates the geometric principle that was employed to produce objects at various depths with the stereo-pair generation software. The heavy horizontal line represents the screen of the display monitor. To present an object that appeared at the depth of the screen, the object was drawn in the same location for

both stereo-pair views. For objects to appear behind the screen, the object was displaced to the left for the left-eye view and to the right for the right-eye view (with the displacement reaching a maximum value to place an object at infinity). For objects to appear in front of the screen, a displacement to the right was used for the left-eye view and to the left for the right-eye view.

To generate this lateral displacement, which is known as lateral disparity, left- and right-eye coordinate systems were transformed from the viewer coordinate system of the visual scene. The nonstereo condition used a lateral disparity of zero, and the stereo condition used disparities resulting from the stereo-pair transformations. Clipping was employed to limit each eye view to the display surface boundaries. Simple perspective division was used to transform the 3-D viewing volumes to 2-D viewports, for which the centers were offset from the center of the display screen by half of the maximum allowed lateral disparity (i.e., that used to represent objects at infinite distance).

Simulator Cockpit

A general-purpose pilot workstation configured as the pilot side of a fixed-wing transport aircraft was used for this study. (See fig. 11.) Pitch and roll inputs were provided by a 2-degree-of-freedom sidarm handcontroller with spring centering. Throttle inputs were provided by a throttle lever that utilized a voltage-referenced potentiometer as the signal source. Typical self-centering rudder pedals provided yaw inputs. No head-down instrumentation other than the display monitor was utilized.

The 19-in. display monitor was mounted approximately 19 in. from the pilot's eye position to yield a total instantaneous field of view of 40° . The display monitor was also tilted to provide a 17° line of sight (from horizontal) over the top of the monitor. This arrangement is typical of over-the-glareshield views in most aircraft and provided a more realistic transition from head-down to OTW viewing when the stereoacuity was measured. The monitor display surface was maintained perpendicular to the pilot's line of sight.

Experimental Results and Discussion

The investigation was designed as a full-factorial, within-subjects experiment, with pilots P , display type D , and replicates R as the main factors of interest for this paper. With the exception of the interaction of pilot and display type ($P \times D$), the higher order terms were pooled a priori with two

other first-order factors not germane to this study (i.e., type of pathway and location of the clipping planes) to increase the error degrees of freedom. Three levels of display type were present: the control condition of no display exposure (the pretest results), transitions after exposure to the nonstereo display, and transitions after exposure to the stereo display.

Analysis of Objective Results

The data collected in the experiment were analyzed with a repeated-measures, univariate analysis of variance for the stereoacuity metric. Table 1 is a summary of the results of this analysis. The results examine each factor, with Newman-Keuls testing (ref. 23) of individual means within the significant factors being performed at appropriate stages in the analysis. (All tests were made at a 1-percent significance level.)

Pilots

The main effect of pilot variability was highly significant for all performance measures. This result is usually expected in a precision task, and the pilot variability was therefore isolated from the rest of the analysis by its inclusion as a main factor in the experiment. Figure 12 presents the mean values of stereoacuity (averaged over all conditions) of each pilot. All the pilots exhibited very good stereoacuity (less than 1 minute of arc), while most of the pilots exhibited excellent stereoacuity (less than 15 seconds of arc).

Display Type

The main effect of display type was not significant. Figure 13 presents the mean values of stereoacuity (averaged over pilots and replicates) for each display type.

Replicates

The replicate factor was not significant. As no learning curve would be expected for tests of stereoacuity, this result was expected.

Interaction of Pilot and Display Type

This second-order interaction effect was highly significant. Figure 14 presents the mean values of stereoacuity for each pilot for each display type. The results of Newman-Keuls testing of the display-type stereoacuity means for each pilot are also shown in the figure. For pilot 2, the stereoacuity for the control condition was significantly less than that for the nonstereo transition condition. The difference between

the control stereoacuity mean and the stereo transition stereoacuity mean is not significant, and neither is the difference between the two transition means (stereo and nonstereo). For pilots 3, 5, and 6, the control-condition stereoacuity mean is significantly greater than the two transition stereoacuity means. The differences between the transition stereoacuity means are not significant.

Inferences From Experimental Results

When the factor of major interest in this study, display type, was statistically analyzed, no significant differences in the overall average stereoacuity measures were found for the comparison of the control condition (no exposure to any electronic flight display) with the transition conditions (nonstereo and stereo displays). Tests for statistical significance of the data of individual pilots did reveal some differences. However, only one instance (pilot 2) was depth perception degraded from the control condition, and that case was significant only for the transition from nonstereo displays. In all other cases, there were either no differences or the stereoacuity was *improved* over the control condition. It was concluded, therefore, that changing from short-term exposure to a head-down stereo display has no more effect on real-world stereoacuity than does changing from a nonstereo display.

The data may also be examined in a manner that allows longer exposures to flight displays of either type to be addressed. Each of the pilots was exposed to the nonstereo and stereo displays in a different randomized order to balance the experimental design, so that issues of continuous exposure for the individual display types cannot be addressed. However, an analysis of variance of the effects of trial number on stereoacuity can at least indicate any possible effects of long-term exposure (approximately 3 hours) to both display types in combination. Table 2 presents a summary of the results of such an analysis for the 10 trials (plus the control condition) of the experiment. The results parallel the previous analysis in that the significant factors were again the pilot and the second-order interaction of the pilot and trial number). No significant differences in stereoacuity were detected for any of the trial numbers (fig. 15). The significance of the second-order interaction, together with the significance of the pilot factor and the insignificance of the trial number factor, indicated that the differences in the stereoacuties of the pilots varied from trial to trial, but that the average stereoacuity for each trial did not vary significantly. Therefore, the analysis revealed no effects on stereoacuity from short-term exposure to flight

displays that alternate randomly between nonstereo and stereo.

Conclusions

A fundamental issue concerning the application of stereoscopic displays in head-down flight applications has been addressed with the determination that stereoacuity is unaffected by the short-term use of stereo three-dimensional (3-D) displays. Indeed, this study determined that there are no more effects on the real-world stereoacuity of individual pilots when changing from short-term exposure to a head-down stereo display than when changing from a nonstereo display. These findings are important in addressing the issue of suitability of stereo displays for future flight applications.

While stereoacuity has been a traditional measurement of depth perception abilities, it is a measure

of relative depth perception rather than of actual (or absolute) depth perception. In addition to relative depth, absolute depth perception (in terms of judgment of sizes and distances) plays a role in the visual landing task. The effects of the use of stereo displays on absolute depth perception were not addressed directly by this study. Further research is required to determine if absolute depth perception, in terms of judgment of sizes and distances, is unaffected. Also, the effects of long-term exposure to the mismatch of convergence-accommodation cues provided by stereo 3-D displays remain an important issue.

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Appendix

Placement of Howard-Dolman Apparatus

The Howard-Dolman stereoacuity measurement apparatus should be placed far enough from the viewer to accomplish the following two objectives: (1) so that all extraneous depth cues other than lateral disparity are eliminated (a distance of 15 ft was selected), and (2) so that the asymmetric convergence viewing case (the actual Howard-Dolman test apparatus viewing condition) may be treated as a symmetric viewing case and therefore allow conversion of stereoacuity measures to distance-independent visual angle measures by simple geometrical calculations. With reference to figure 16, the simplified approximations for calculating convergence angle α for both cases are

Symmetric case:

$$\alpha = i/d \text{ (Approximation error } < 1 \text{ percent for } \alpha < 10^\circ)$$

Asymmetric case:

$$\alpha = 2j/d \text{ (Approximation error} \\ = [(3x^2 + j^2)/3d^2]100)$$

Substituting $i/2$ for j in the asymmetric case generates the symmetric-case convergence-angle approximation. Therefore, if one also substitutes $i/2$ for j in the approximation error equation for the asymmetric case and solves for d , that will generate a 1-percent error. For the Howard-Dolman apparatus, $x = 1.69$ in., with half the average interocular distance (j) of 1.25 in. This results in a minimum depth placement of 1.5 ft, much closer than the 15 ft necessary to eliminate the extraneous depth cues. This proves that the symmetric approximations and geometry can be used in calculation of the convergence angles and, hence, in conversion to visual angle by simple geometry.

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Table 1. Summary of Analysis of Variance for Display Type

Factor	Sum of squares	Degrees of freedom	Mean square	F-test	Significance (a)
Pilot	27 042.73	7	3863.25	67.03	**
Display type	109.92	2	54.96	0.95	-
Replicates	439.99	3	146.66	2.54	-
Interaction of pilot and display type	1 728.37	14	123.46	2.14	**
Pooled error	18 731.11	325	57.63		

^aSignificance:

- Not significant at levels considered.
- * Significant at 5-percent level.
- ** Significant at 1-percent level.

Table 2. Summary of Analysis of Variance for Trial Number

Factor	Sum of squares	Degrees of freedom	Mean square	F-test	Significance (a)
Pilot	27 042.73	7	3863.25	70.22	**
Trial number	406.05	10	40.61	0.74	-
Replicates	397.99	3	132.66	2.41	-
Interaction of pilot and trial number	5 846.07	70	83.52	1.60	**
Pooled error	14 359.21	261	55.02		

^aSignificance:

- Not significant at levels considered.
- * Significant at 5-percent level.
- ** Significant at 1-percent level.

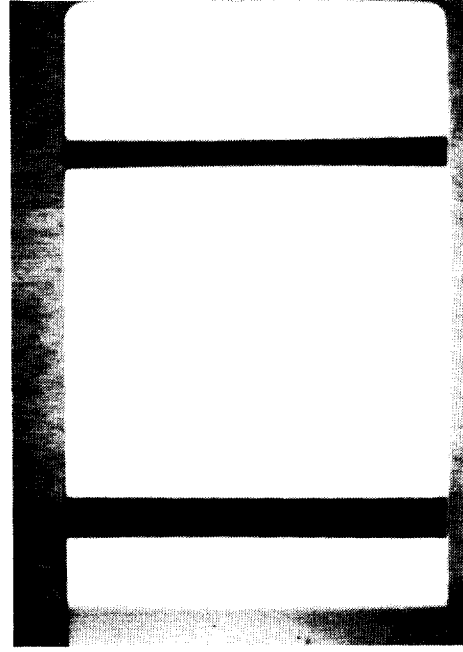
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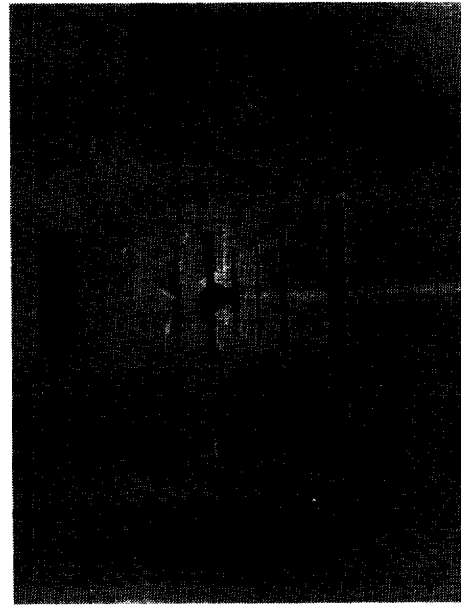
Changing to real world



Flying the landing approach



Howard-Dolman stereo depth test



Pathway-in-the-sky display

L-89-10439

Figure 1. Stereoacuity experiment.

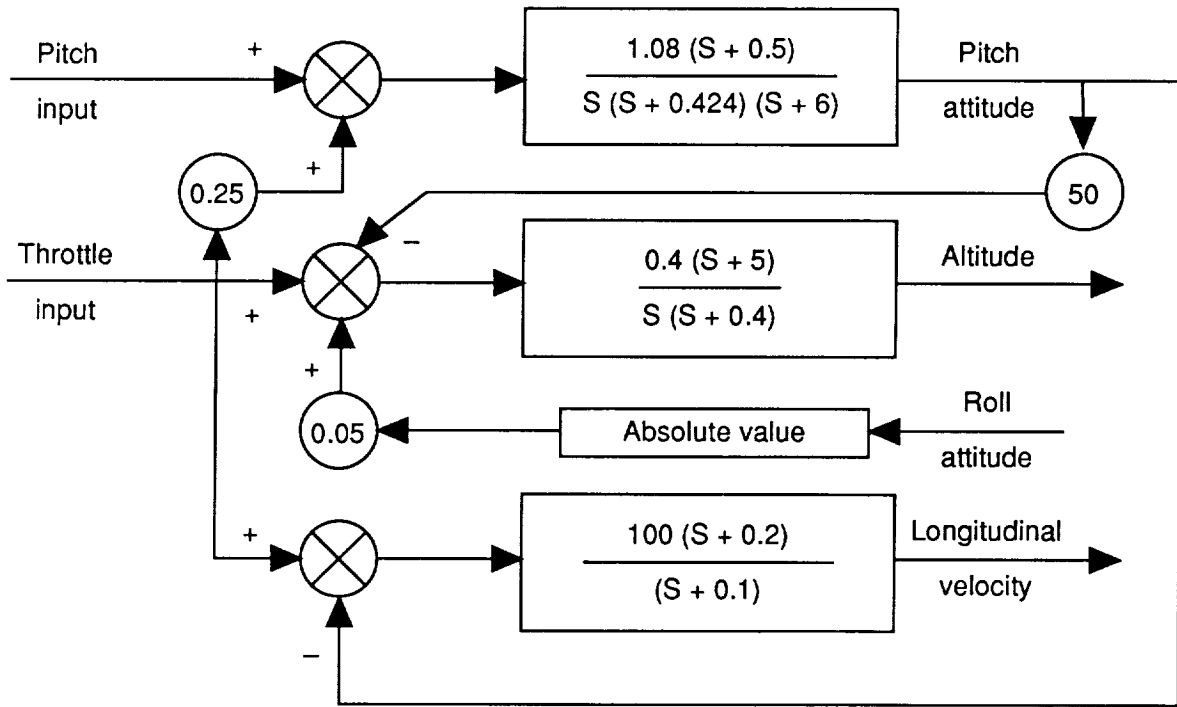


Figure 2. Block diagram of simplified airplane model for longitudinal degrees of freedom. Control inputs are about trimmed condition.

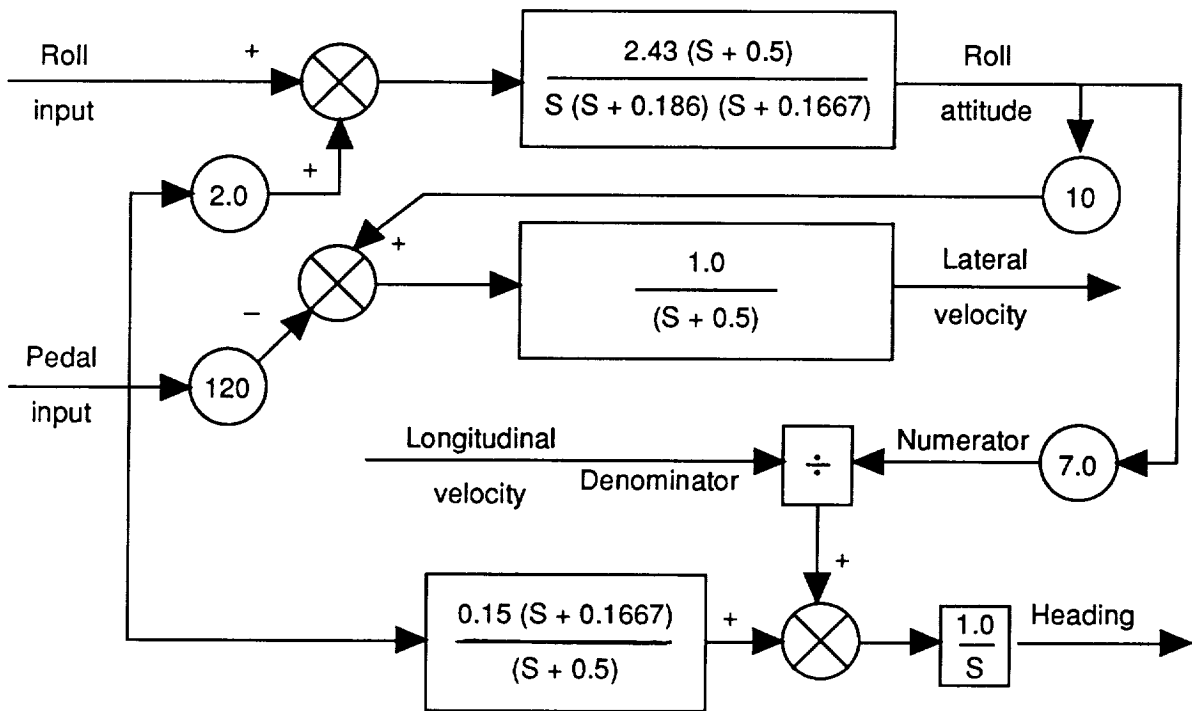


Figure 3. Block diagram of simplified airplane model for lateral degrees of freedom. Control inputs are about trimmed condition.

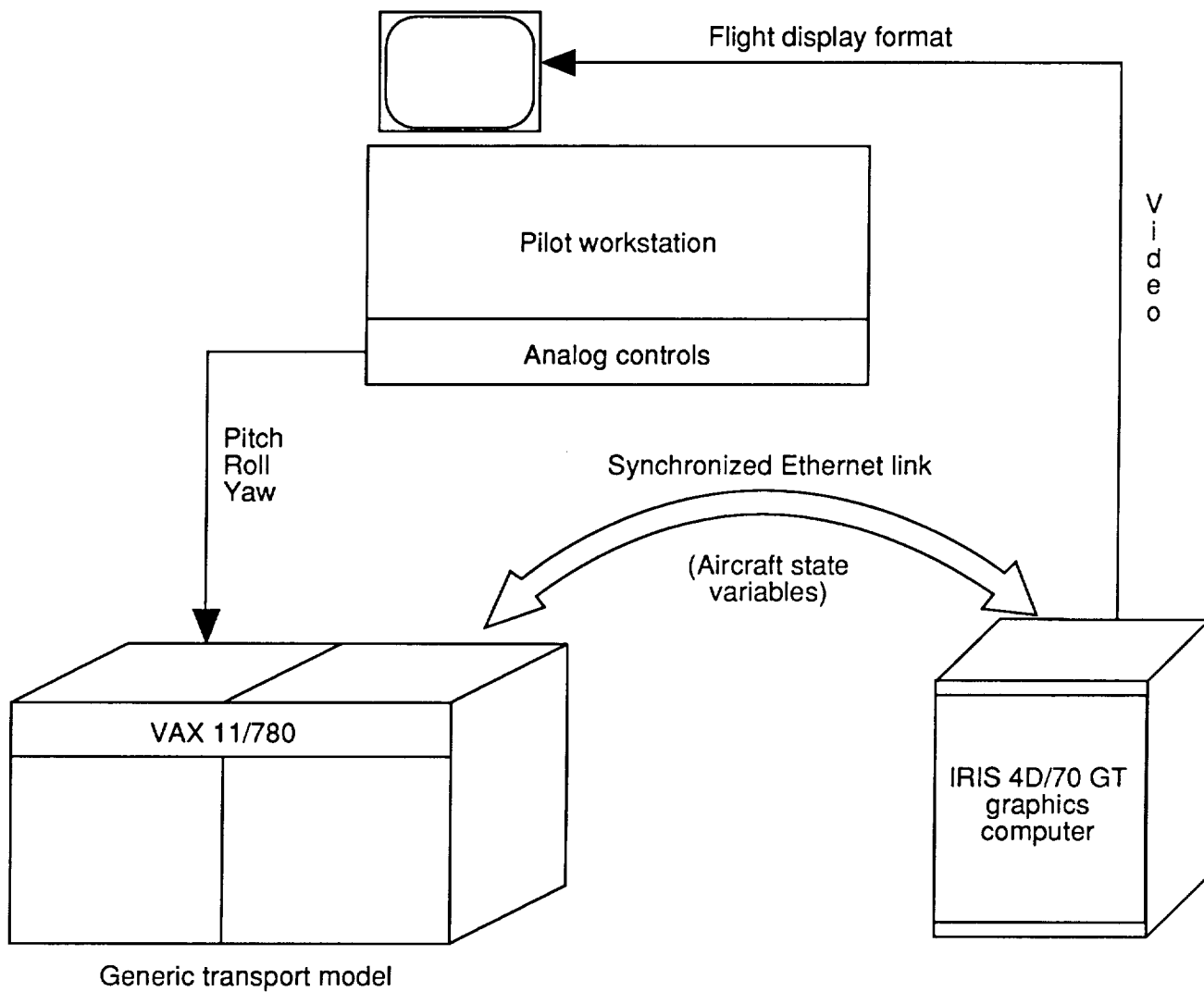
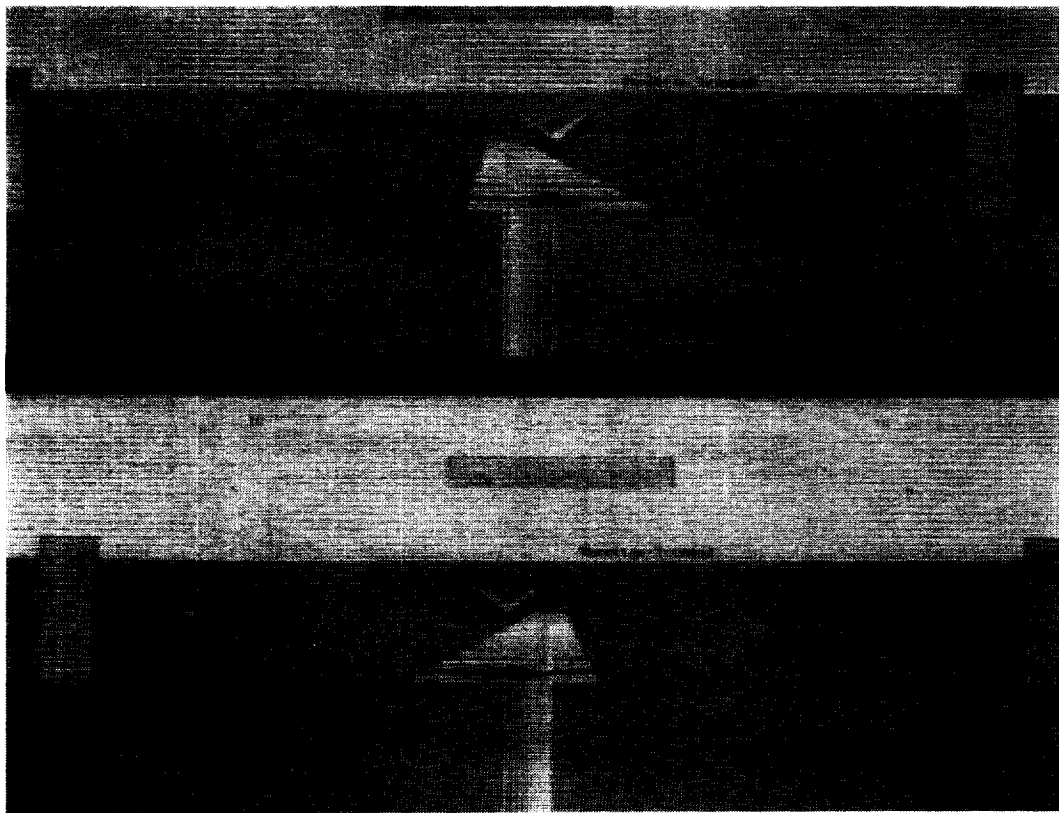
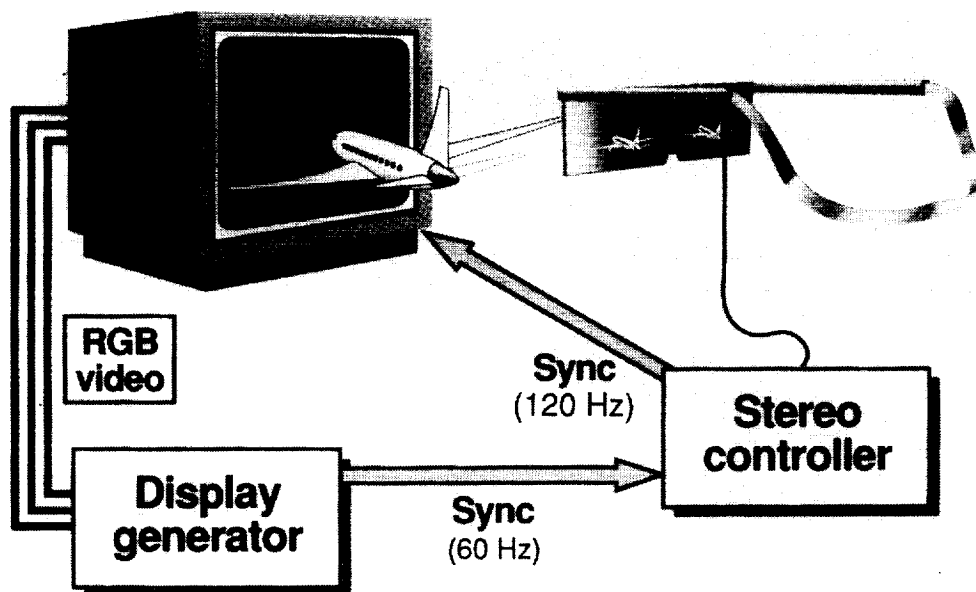


Figure 4. Simulation configuration.



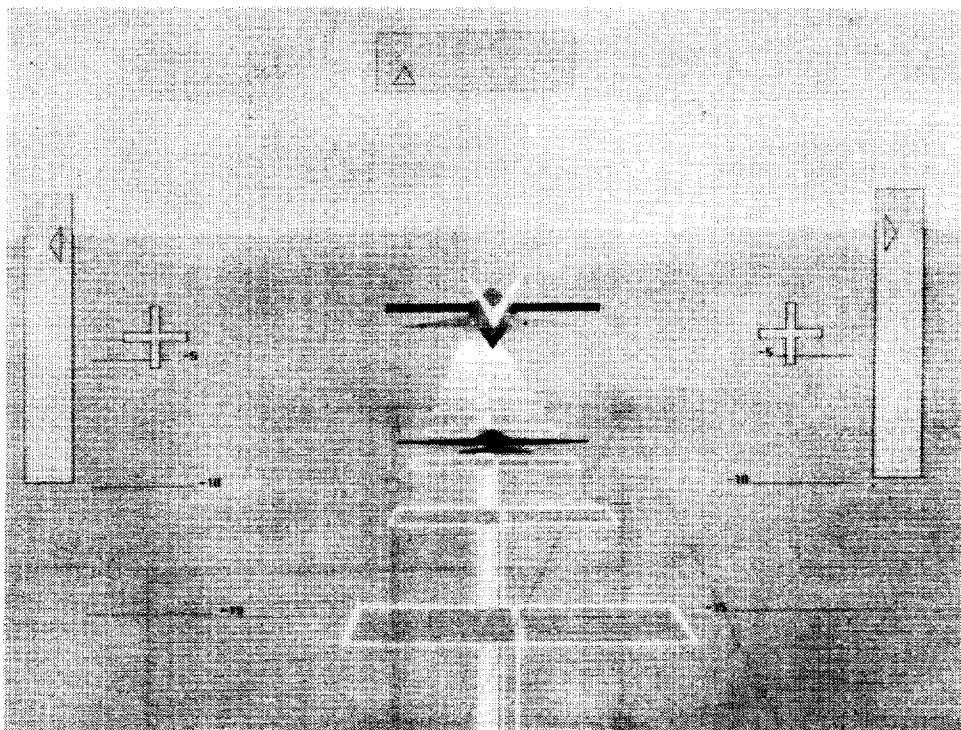
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Figure 5. Left-eye (top) and right-eye (bottom) stereo pair images anamorphically compressed on single display screen.



L-91-61

Figure 6. Stereo 3-D flight display.



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Figure 7. Single-eye view spread over entire display screen and multiplexed in time.



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Figure 8. Pilot attempts rod placement by manipulating attached strings.

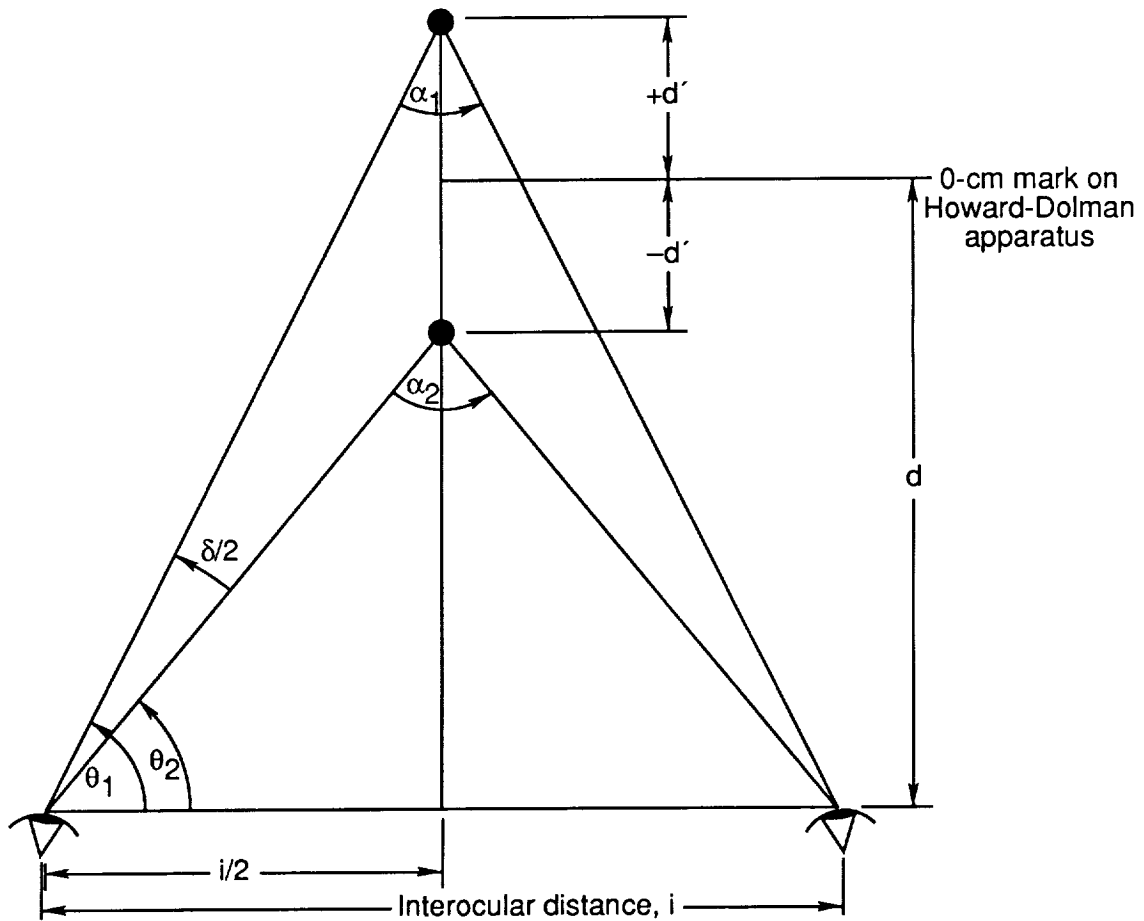


Figure 9. Simplified symmetrical geometry for visual angle conversion.

**Left-right screen positions
for objects located:**

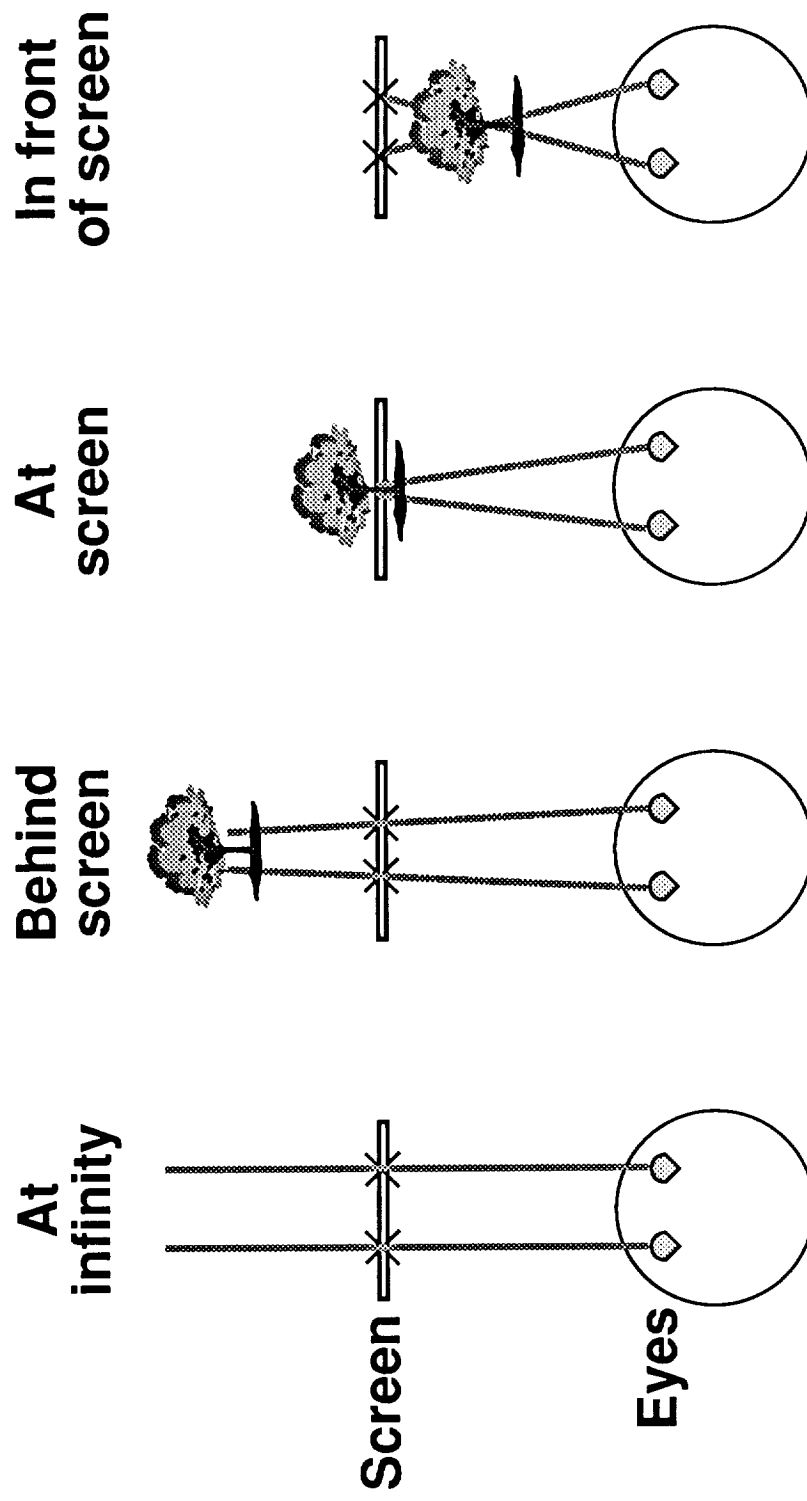


Figure 10. Top view of geometric principle for producing left- and right-eye views.

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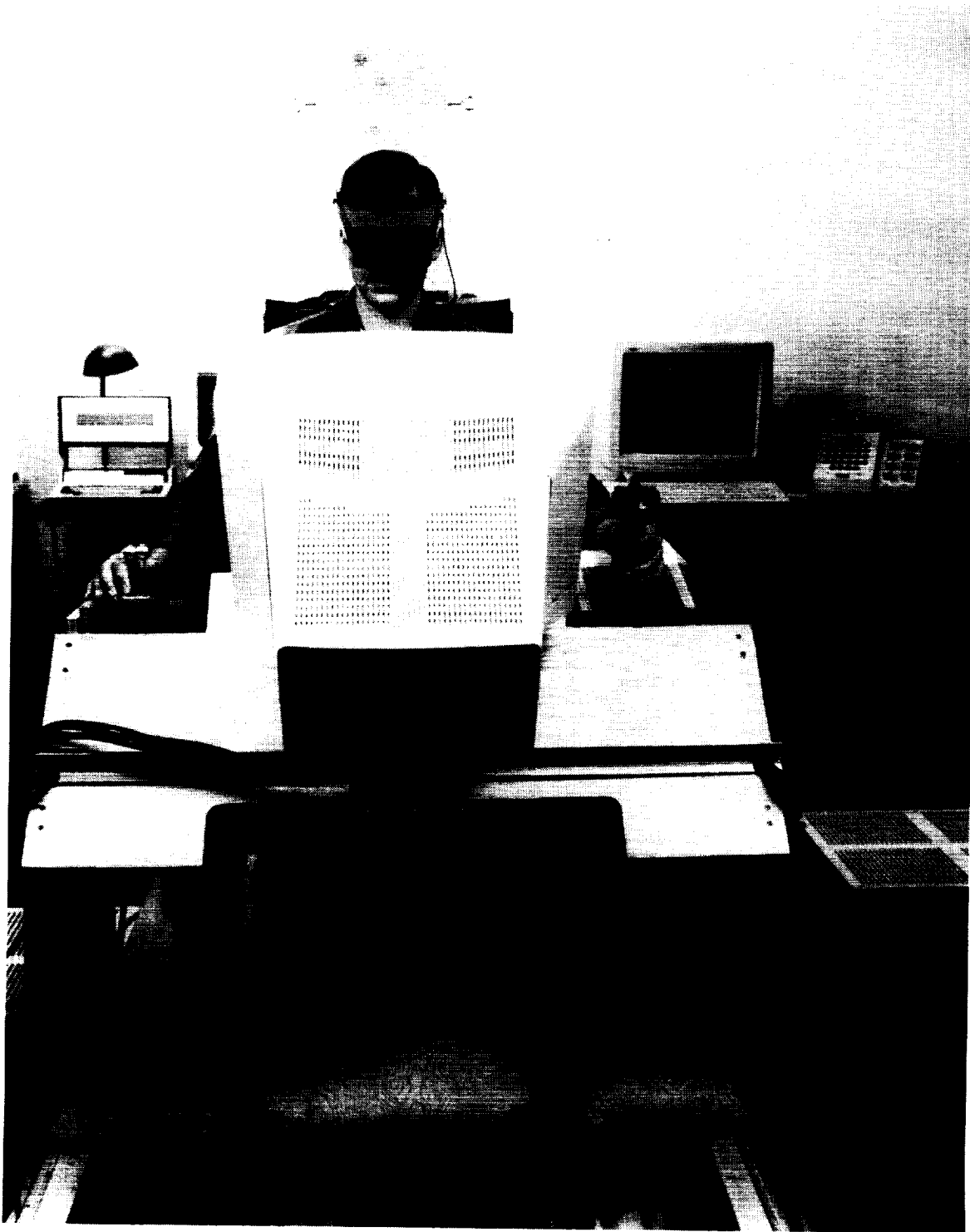


Figure 11. General-purpose pilot workstation.

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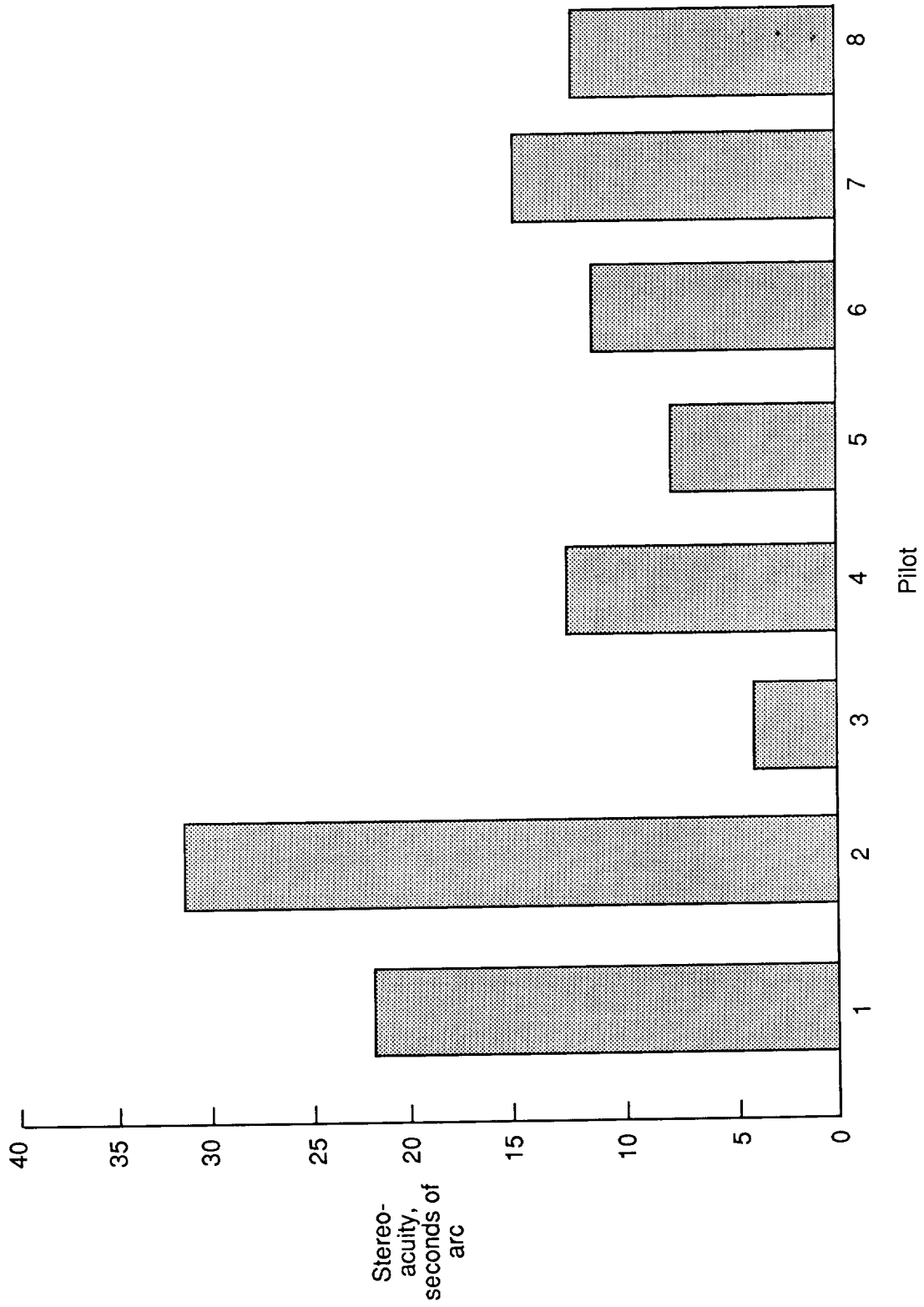


Figure 12. Individual pilot averages of stereoacuity over all conditions.

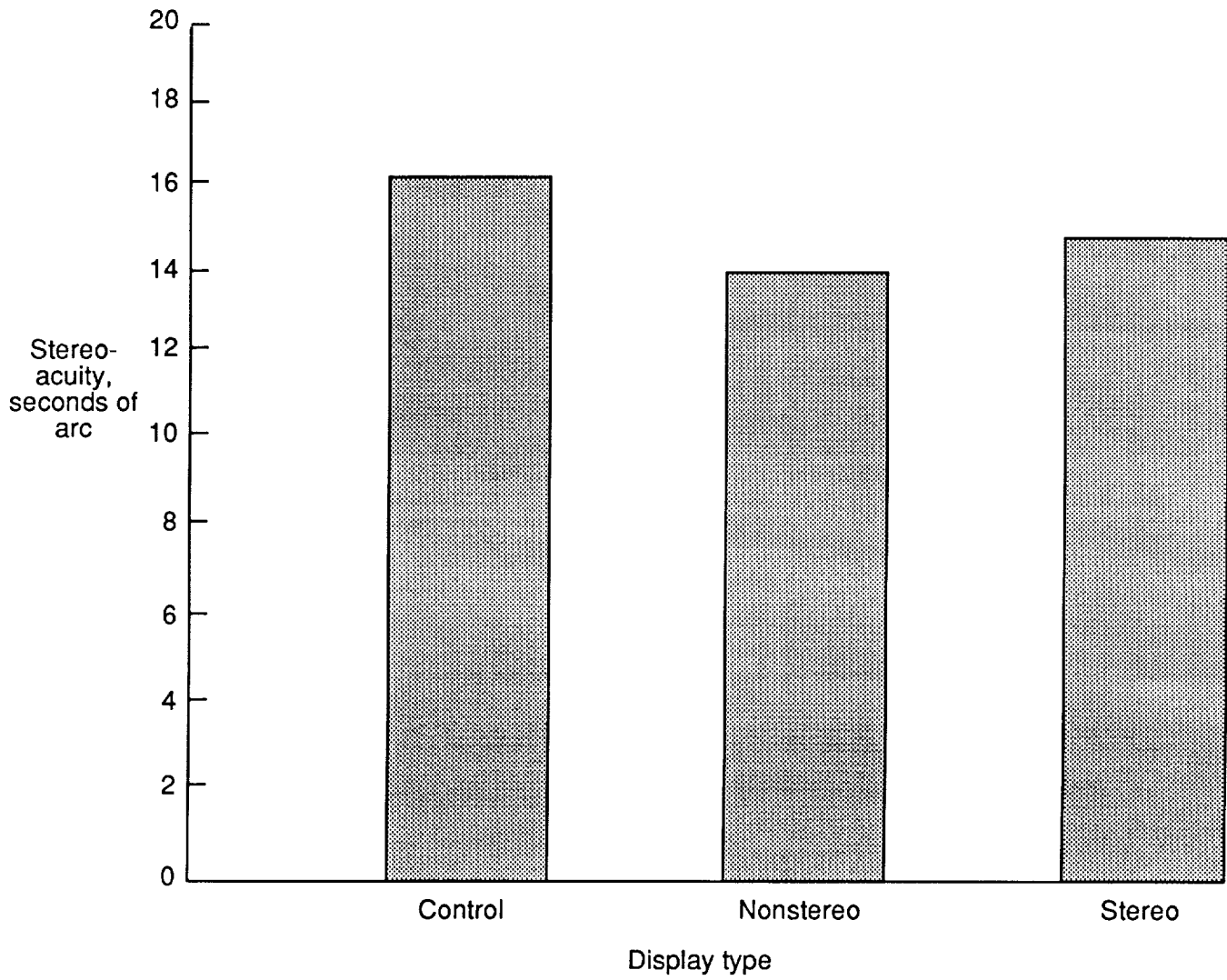


Figure 13. Mean values of stereoacuity for each display type over all eight pilots.

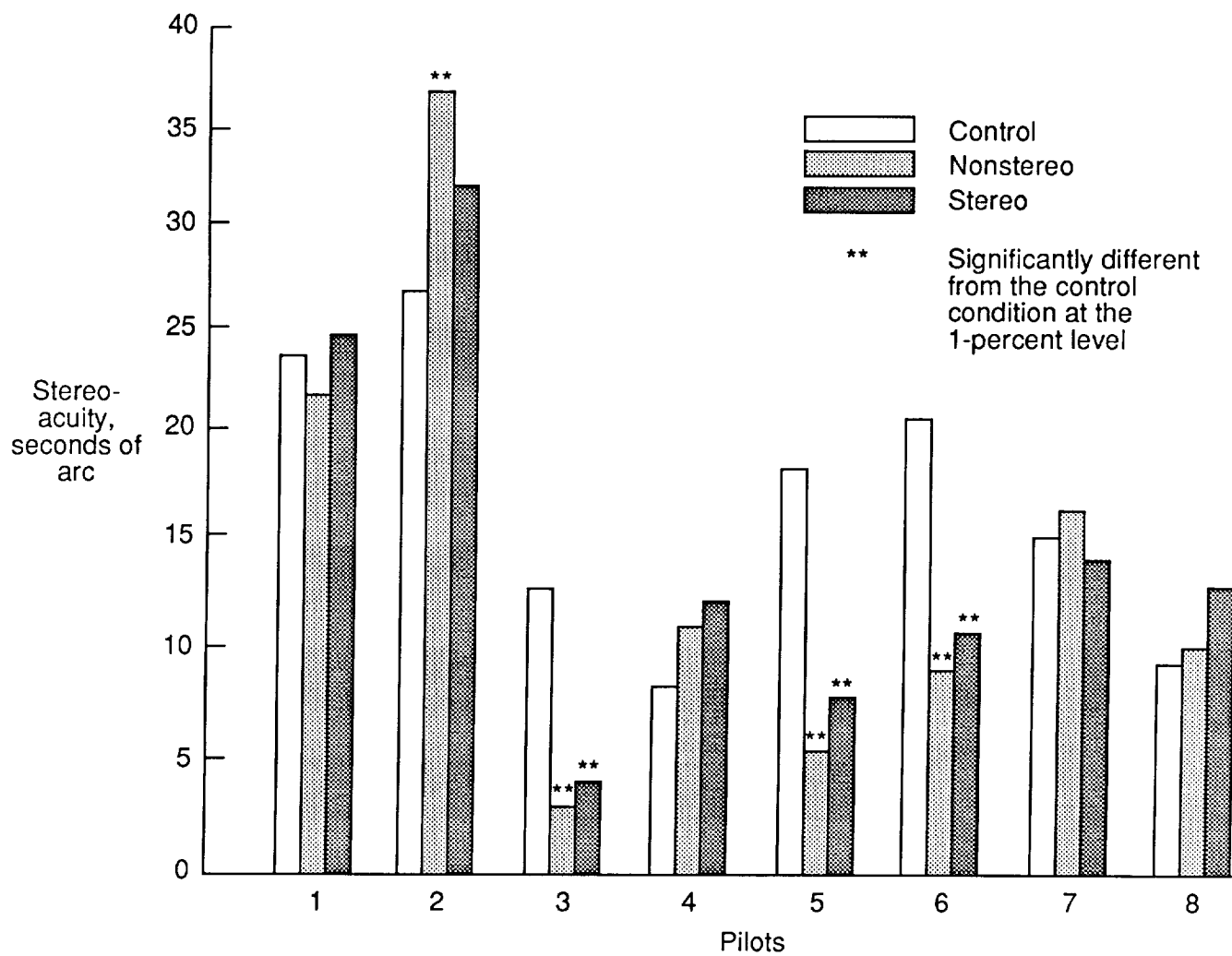


Figure 14. Mean values of stereoacuity for each pilot for each display type.

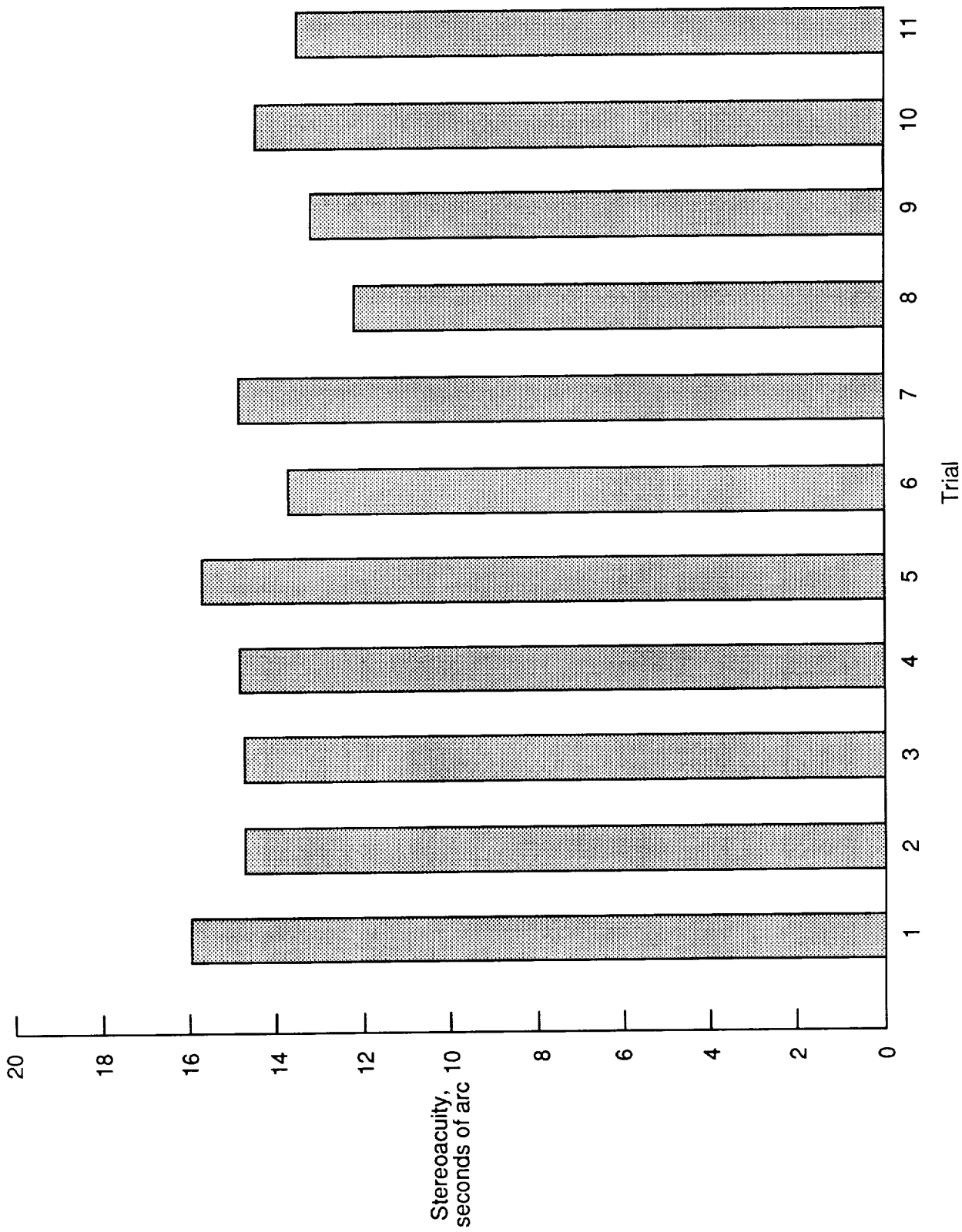


Figure 15. Mean values of stereoacuity by trial number.

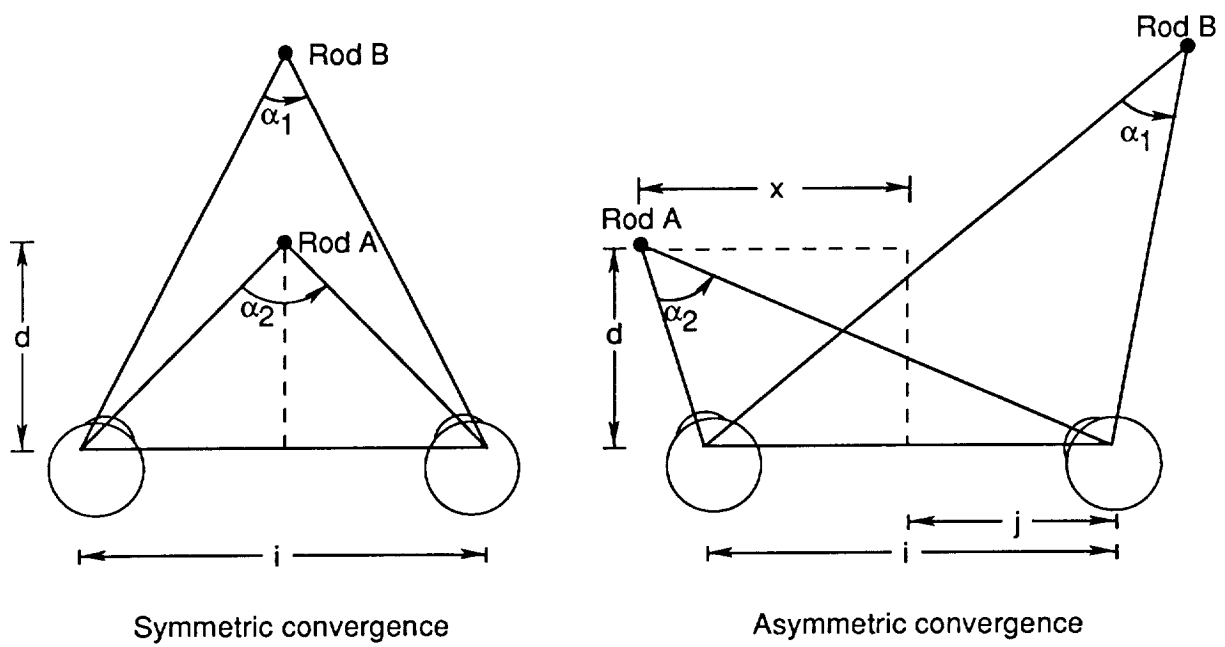


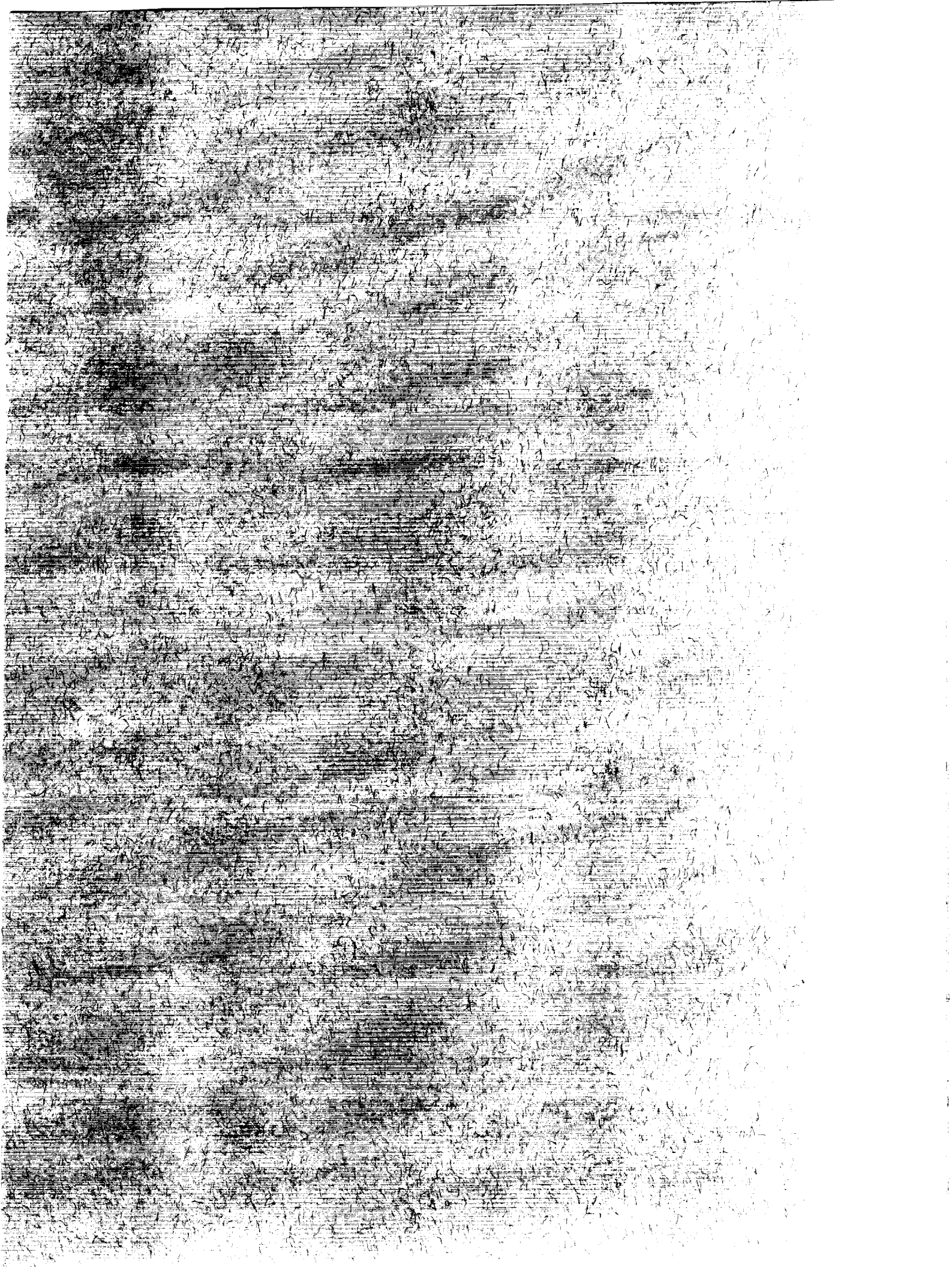
Figure 16. Symmetric and asymmetric geometrical convergence cases.





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16. Abstract High-fidelity color pictorial displays that incorporate depth cues in the display elements are currently available. Depth cuing applied to advanced head-down flight display concepts potentially enhances the pilot's situational awareness and improves task performance. Depth cues provided by stereopsis exhibit constraints that must be fully understood so depth cuing enhancements can be adequately realized and exploited. A fundamental issue (the goal of this investigation) is whether the use of head-down stereoscopic displays in flight applications degrade the real-world depth perception of pilots using such displays. Stereoacuity tests are used in this study as the measure of interest. Eight pilots flew repeated simulated landing approaches using both nonstereo and stereo three-dimensional head-down pathway-in-the-sky displays. At the decision height of each approach (where the pilot changes to an out-the-window view to obtain real-world visual references) the pilots changed to a stereoacuity test that used real objects. Statistical analysis of stereoacuity measures (data for a control condition of no exposure to any electronic flight display compared with data for changes from nonstereo and from stereo displays) reveals no significant differences for any of the conditions. Therefore, changing from short-term exposure to a head-down stereo display has no more effect on real-world relative depth perception than does changing from a nonstereo display. However, depth perception effects based on size and distance judgments and on long-term exposure remain issues to be investigated.					
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