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AIR FORCE HUMAN RESOURCES LABORATORY

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PSYCHOPHYSICAL CRITERIA FOR VISUAL SIMULATION SYSTEMS

By

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This technical report has been reviewed and is approved for publication.

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

This contractual effort studied a prioritized list of psychophysical aspects of visual simulation systems for military flight training simulators. The available literature, operational experiences of simulator commands, current research program data were assembled, organized, reviewed, evaluated and summarized to provide psychophysical criteria for the visual displays subsystem. Areas of insufficient data were identified, and seven experimental designs were suggested for psychophysical investigations to provide some of the missing data.

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SUMMARY

This contractual effort studied a prioritized list of psychophysical aspects of visual simulation systems for military flight training simulators. The available literature, operational experiences of simulator commands and current research program data were assembled, organized, reviewed, evaluated, and summarized to provide psychophysical criteria for the visual displays subsystem. Through this process, some areas of insufficient data were identified, and a selection of those that were amenable to psychophysical investigation was recommended, with suggested experimental designs.

The prioritization of 41 system characteristics as to their relative importance was a product of rank ordering and applying weights assigned to five evaluation factors. The factors were false cues, interaction of characteristics, current prevalence, realism deficiency, and cost of correction. The following characteristics are those discussed in detail within this report.

ALIASING

Defined

In its restricted sense, aliasing refers to the presence of harmonics in the signal leading to an unintended distortion in the information displayed on the cathode-ray tube (CRT). The more current usage of the term aliasing refers to a number of visual anomalies, e.g., shearing, racing, edge walking, angular velocity dependent resolution.

Potential Effects

The possible effects of aliasing include the following: (a) imposes smoothing requirements that reduce display resolution, (b) allows incidental learned effects that are not useful in real flight, (c) provides distractions that use up available time thereby adding to the pilot's work load, (d) imposes changes of visual search patterns, and (e) decreases pilot acceptance of visual simulation.

Method of Minimization

The general solution is to minimize effect by "smoothing" of edge gradient by software routines, using 60 Hz update and refresh rates, and using lower contrasts in the scene. One promising anti-aliasing technique that is a feasible alternative to pre-filtering is to oversample the data, apply a digital low-pass filter, and then down-sample the data to the resolution of the display.

MAGNIFICATION

Defined

Three types of magnification are related to perceptual effects in a visual simulation system. These are (a) uniform magnification within the optical system with image size which subtends the correct visual angle for the object size and distance portrayed, (b) uniform magnification of a scene to an image size (visual angle subtense) larger than that dictated by the size-distance relationship, (c) non-uniform magnification, in which objects in some areas of a display are magnified more than objects in other areas.

Potential Effects

For type (b), the danger is in a "flattening" effect produced by the differential ratio of magnification of near and far objects, causing misperception of distance and approach angle relative to the terrain surface. Type (c), uneven magnification will produce distortions, and uneven relative magnification of the images presented to each eye will impose general discomfort, eye strain, and changes in flight performance.

Limits and Recommendations

The runway plane distortion is perhaps the most serious case resulting from optical magnification. No definitive data were found to establish detection thresholds; therefore, this is one area where a psychophysical study was recommended. Differential size magnification between the images presented to each eye should not exceed 1.0%, to avoid discomfort and possible lower flight performance.

SCENE OVERLAYS AND INSERTS

Defined

Scene overlays are used in simulators such as those employed for combat training where another aircraft must be presented against a "fixed" background of earth and sky. Scene inserts differ in that they replace a portion of the background scene rather than being superposed on it. Since the overlay technique has a very restricted application and has obvious drawbacks (one image projected over another projected image) the discussion in this section concentrates on computer generated imagery (CGI). The discussion includes methods of slaving the insert to head or eye position, horizontal versus vertical resolution, orientation of raster lines, raster line density, and effects of vibration.

Potential Effects

Scene overlays which may be identified by any display characteristic other than the presence of the target reduces the "search time" in target acquisition. Acquisition times are generally much longer than "recognition times." To properly simulate air-to-air or air-to-ground target acquisition, recognition and weapon delivery require high resolution scenes, wide fields of view, and if inserts are used, non-recognizable inserts or multiple "placebo-inserts."

Required Information

The just-not-noticeable thresholds for edge matches, raster alignments, image rotations, contrast differences in CGI scenes, or velocity variations need to be established.

BINOCULAR DEVIATIONS AND IMAGE SIZE DIFFERENCES

Defined

Binocular deviations and image size differences (aniseikonia) encompass a variety of visual display problems in which the images to the two eyes differ. These disparities are categorized as horizontal/vertical, magnification, and distortion/astigmatism.

Potential Effects

A large quantity of data has been obtained from a number of sources and includes recommended tolerance limits for lateral and vertical misalignment of binocular images. Recent studies show the effects of differential distortion of right and left eye images on pilot performance in the approach and landing maneuver. A combination of vertical and lateral displacements is treated in the discussion of binocular image rotation. The topic of unequal magnification (aniseikonia), which has been the subject of much research, is discussed not only in psychophysical and clinical terms but reference is also made to direct effects on performance in flying simulators. Optical effects such as collimation error and astigmatism are discussed from the standpoint of geometrical optics and in terms of their perceptual effects.

Suggested Tolerances:

Horizontal and Vertical Disparities

Average Binocular Deviation < 9 arc minutes

Localized Lateral Disparities from < 6 arc seconds to < 100 arc minutes depending on scene and task.

Localized Vertical Disparities < 15 arc minutes

Vertical Displacements of R and L Images < 7.5 arc minutes

Rotational Tolerances with 20° field of view or larger, comfort and minimal effect upon approach angle estimates $< 1°$ (should be studied).

Image Size Differences (aniseikonia) $< 1\%$.

Binocular Image Distortion and Astigmatism. There is need for experimentally determining thresholds for this area with CGI imagery.

LATERAL VERGENCE/COLLIMATION/IMAGE DISTANCE ERROR

Defined

Vertical and lateral vergences are defined and discussed. The confusion between display divergence and convergence, being opposite visual divergence and convergence, is treated. The rough equivalence of tolerance limits for vertical and lateral divergence is contrasted with the larger tolerance for lateral convergence. This is related to display collimation error limits. The collimation error assessments of two infinity displays of widely different fields of view are presented.

Potential Effects

Vertical Vergence

Within Panum's areas, and with the standard deviation of repeated settings of vertical alignment by trained observers of < 7 arc minutes of vertical separation, misalignment less than this would be associated with no discomfort and good visual performance. At > 34 arc minutes, discomfort occurs and doubling of images is frequently reported.

Lateral Vergence

Should be less than 26 arc minute range for no discomfort and good visual performance.

Chromatic Aberration

Chromatic aberration (as imposed by the optical aspects of display systems) resulting in color fringing is discussed. Lack of convergence of the red, green, and blue electron beams in color CRTs, although similar in appearance and effect, is shown to have generally much larger magnitude of error. The effect of either source of color fringes decreases system resolution and legibility.

Holes in the Data Base

Seven areas were designated wherein the data were inadequate or incomplete and in which good quantification should be expected from psychophysical experiments. The specific functional relationships needing quantification were the following:

1. The effect of Horizontal Aniseikonia on Target Detection and Motion Recognition

2. The effect of Aliasing on Visual Search

3. The Effect of Optical Magnification on Perception of Runway Plane

4. The Effects of Accommodation/Convergence Errors Interacting With Quality of Displayed Images

5. The Masking of Scene Inserts as a Function of Insert Area and Transition Technique

6. The Effects of Scene Complexity and Separation on the Detection of Scene Misalignment

7. Absolute Brightness Levels in Simulators

PREFACE

This report was prepared by the Crew Systems and Simulation organization, Data Processing Technology, of the Boeing Aerospace Company, Seattle, Washington. The work was done under contract F33615-78-C-0012 for the ASM Branch of Human Resources Laboratory at WPAFB, Ohio.

The authors are appreciative of Dr. Doug Anderson's support as monitor of this contract. At the submittal of the second draft of Phase I, the monitorship changed hands, and we are especially appreciative of Dr. Ken Boff's interest in this program and his help in seeing it through to completion.

Special thanks are also due Helen von Tobel for her work on the illustrations, editing and manuscript preparation.

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INTRODUCTION

Visual systems for flight simulators have become a major portion of the large simulator budget of the United States Air Force (USAF), especially as computer-generated image (CGI) systems have demonstrated their feasibility and flexibility. The USAF is currently engaged in procurement of a number of such systems for flight simulators, almost all of which will have an out-of-the-window scene which may be designed for specific training tasks, such as the terrain-following training needed for the A-10 or the high-altitude air-to-air combat training for the F-15. The more accurately the effects of, various design concepts are predicted, the more cost-effective the procurement cycle will become.

These and other visual systems should have design features that are based on requirements of the human visual system. This modality provides users with most of their sensory input, with the peripheral retina answering the "where" question and the central, foveal area the "what" of pattern vision. The visual displays normally provide the pilots with the type of information they conventionally use in performing flight maneuvers, in sensing unexpected deviations from the flight path and to warn of intrusions by friend or foe. However, today's technology still has its limits and cannot duplicate the real world in this external scene, but this is not necessary for most training purposes. Some studies seem to imply that including only the needed information in a purposively simplified image may provide improved performance and transfer of training (Ritchie, 1976; Roscoe, 1977).

The visual perception literature can provide much of the information for some aspects of the display system design. However, out-of-the-window scenes with their requirements for large fields of view, special optics, real-time dynamics, complete feedback, and special effects impose trades and restraints not found in the classical literature. The task of this program then was to define the display design characteristics which may affect perceptual or physiological responses, to establish the relative importance of the corresponding visual and physiological effects, to understand their relationship with the physical continua of the displays, to determine those areas for which insufficient definitive data are available, and to develop experimental designs for possible Phase II investigations in these areas. The following discussion shows the diversity and magnitude of some of the problems that have been encountered in some methods of generating dynamic external scenes.

One of the earliest visual simulation systems used motion picture films as an image source and anamorphic lenses in the display to simulate visual scene dynamics needed in approach and landing training. The visual display features that were inadequately handled by this system included a limited visual envelope, such that the pilot could not fly patterns without creating gross distortions or complete break-up of the scene. The anamorphic lenses distorted the picture to depict off-track flight, and tall buildings in the scene appeared to lie flat on the terrain when the simulated aircraft was off the flightpath and to stand up when the aircraft was on the same path as in original filming. Thus, the apparent distortions could be used as an aid to navigation, a cue that does not exist in the real world. In addition, scratches, as seen in the display, provided a "vertical" reference and their thickness an "off-track" reference. Absolute luminance level, or brightness, was quite low in this system due to the 22 lens elements involved in creating the dynamic distortion.

Closed circuit television (CCTV) systems that move across a fixed model of terrain can be displayed through a number of systems. In one, a "flat screen" display, a light valve system projects the moving scene on a tilted screen about 12 feet (3.66m) from the pilot's eye reference point. This means that the corresponding visual accommodative distance (visual focus) is also at 12 feet, requiring 0.27 diopter of accommodation. The incompatibility between the visual focus at 12 feet and the scene, most of which is normally at a far distance (infinity focus), may cause errors in the pilot's perception of the size, distance to, or perspective of objects in the scene. Another current display is a virtual image system where the projected image is displayed on a translucent screen and viewed from the back side in a large collimating mirror. This system provides a very large exit pupil (or viewing volume), the design of which usually does not permit as high a display resolution overall as the narrower exit-pupil systems. The light-valve projector and translucent screen are other sources of resolution loss. Yet another type of display uses a beam-splitter and spherical mirror, and this display adds a bit of magnification and a small amount of distortion, but only a little attenuation of resolution to that of the generating system. Visual accommodation is generally maximum at 0.1 diopter as most of these systems are designed to be collimated at or beyond 10 meters.

Inappropriate accommodation distances and resolution limits are even more serious in cathode-ray tube (CRT) displays that have been used at windscreen distance in some moving-belt displays. Twenty-inch-wide CRTs viewed at 28 inches provide a 36-degree horizontal field of view, potentially 5.0+ arc minutes of line-pair resolution, and visual accommodation of 1.4 diopters. Magnification of the scene by the optical elements of a display that employs line scan excitation of a phosphor as an image source generally is provided at the expense of resolution. Some beam-splitter and mirror displays use a 1:1 ratio displayed scene size to real-world size, some a 1.2:1.0 ratio. In one system with a 25-inch (diagonal) CRT, the relationship provides a 40-degree display field, while in another system, the 1.2:1.0 ratio is used with a 48 degree display field. With the image generator producing an element length of .023 inch, the 1:1 system viewed from 28 inches would result in a visual angle resolution for the smallest element of 2.82 arc minutes and the 1.2:1 system would provide 3.39 arc minutes resolution.

The design for the Advanced Simulator for Pilot Training (ASPT), Flying Training Division of the Air Force Human Resources Laboratory at Williams AFB, opted for a wide field of view, 158 degrees vertically and 300 degrees horizontally, requiring seven pentagon-shaped optical windows to achieve some magnification. To keep the resolution within a reasonable range, a 1000-line raster display was a necessary part of that design. The wide field of view may be an important design variable, with experimental results indicating that field of view is linearly and negatively correlated with bombing error if both variables are plotted as log functions (Cyrus, 1978). It is not known whether such a relationship would have been found if a 525-line system had been used to reduce cost.

The resolution of the current visual scene generators and their display devices in terms of line pairs falls between 5 arc minutes and 19+ arc minutes on the retina of the eye. These resolutions are, as yet, far from matching the visual acuity of the average pilot, which must at least meet the clinical norm of 1 arc minute (20/20 Snellen), nor do they reach the average acuity performance of pilots as measured experimentally. For one sample using Landolt "Cs," the average acuity was 40 arc seconds (Kraft, Booth, & Boucek, 1972) and with another sample, the performance of 24 pilots (18 civilian and six USAF), on optometric examinations with Snellen letters, 51.7 arc seconds was the average (Kraft, Farrell, Boucek, Anderson, & Holland, 1973). It is not yet known which of the flying tasks, other than air-to-ground target acquisition, require scan-line spatial frequencies approximating the resolution capability of the eye. On the other hand, some scene generators and displays are of such low resolution that cities cannot be differentiated from countryside. However, at least some effective and efficient flight training is being accomplished with these scenes. The relevant question is whether the scene itself has adequate training value. It may be that a very good syllabus with excellent instructors is contributing most of the training that transfers to the aircraft. Before conducting training effectiveness studies of these factors, however, it is appropriate to establish the perceptual and physiological relationships involved.

As a class, CCTV and fixed-model, image-generation systems have a difficult display problem. The probe must come very close to the model and sample the image along the length of the model. This imposes a need for a very small aperture to gain as much depth of field as possible. The visual requirement is very severe because, in vision from the aircraft with clear atmospheric conditions, almost all items within hundreds of miles are in sharp focus. In the CCTV/fixed model system, the depth-of-field limitation is such that all of a 10,000 foot long runway cannot be in focus at one time. One solution to this problem is the addition of a software management scheme to shift the hyperfocal distance to different portions of the runway as the final approach, flare, and touchdown phases of landing are completed. The Scheimpflug modification was designed and developed as an optical solution to this problem. The short depth of field with the Scheimpflug modification is vertical instead of horizontal. This can provide for a complete runway in focus, but the transition of the landing aircraft into this clear image zone provides a visible cue as to altitude, a cue only present in the simulator.

Some less well known aspects of visual displays may be of similar or greater importance for training. Interocular differences, for example, may be a source of distortion that affects physiological comfort and psychophysical performance. This effort attempted to treat both the familiar and lesser known aspects of displays in terms of their established influence on the visual performance of cockpit crews. If the relationships between display characteristics and performance are not quantitatively established, there was an attempt to identify these areas and suggest methods (experimental designs) for acquiring the critical data.

VISUAL SIMULATION CONCEPTS STUDY

RATIONALE FOR SELECTION OF VISUAL SIMULATION SYSTEM CHARACTERISTICS

The primary purposes of the Visual Simulation Concepts Study were: (a) to establish those visual simulation characteristics which could significantly affect the perception of the displayed scene by the cockpit crew or induce physiological reactions such as fatigue, kinetosis, stress or strain and (b) to rank order the characteristics as to their relative importance for subsequent study by the contractor. The procedure followed included first the development of the rationale for the selection of characteristics, based upon ground rules provided by the Statement of Work (SOW) for this contract:

A. The areas of particular interest included:

   1. Simulation system characteristics which degrade the realism of the displayed imagery and impart cues of "simulation" rather than "reality" to the crew.

   2. Characteristics which provide artificial or false visual cues, which are used to accomplish a specific task in the simulator, but which are not available in the real world.

   3. Characteristics which may produce physiological, or visuo-physiological reactions such as fatigue, eye strain, or motion sickness.

B. Areas <u>not</u> to be addressed in this effort included scene content requirements, stereoscopic systems, and the effects of the characteristics on simulator training effectiveness.

In addition to these general requirements, the SOW also listed a minimum set of characteristics to be considered, such as collimation errors, distortion, and image sharpness. The initial attempt to develop a comprehensive list of characteristics, however, immediately demonstrated the need for additional rationale or ground rules for the derivation of the list. Since many of the "types" of characteristics listed in the SOW could be broken out into a number of more discrete factors, and these in turn into even finer elements, it was necessary to establish a ground rule for the consistent derivation of "characteristics." It was recognized that various sub-factors, or even elements, might differ significantly in their contribution to a given perceptual effect and therefore perhaps should be treated individually.

On the other hand, it was also recognized that the utility of this overall effort would be enhanced if the characteristics were meaningful to behavioral scientists, pilots, managers, etc., as well as to electronic and optical engineers. For example, while beam intensity and diameter, point spread function, voltage, phosphor characteristics, halation, and bandwidth are terms an electronics engineer would be comfortable with, a diverse user group might stay "tuned in" only if the next level, more generic term "spot size" were used.

Finally, it was desirable that the characteristics be easily and adequately related to perceptual effects, and integrated into the other contractual tasks such as the analysis of literature data and the development of experimental designs. Thus, the terminology (level of definition) used was consistent with that most frequently found in available experimental reports concerning the relationship among, for example, spot size, visual acuity and legibility. In following this ground rule for the selection of levels of definition for the visual simulation system characteristics, two levels of description were used: one being a general category descriptor and the other consisting of component sub-factors.

Another ground rule involved the origin of the characteristic under consideration. A particular distortion, for example, might originate in the image generation equipment or material. However, this distortion might be increased or eliminated by the design of the image transmission equipment and therefore be considerably modulated at the image display surface. Relating perceptual effects to the original distortion would thus involve consideration of a potentially complex interaction with other system elements. To avoid such difficulties, and yet recognizing that they will still exist for the system designer, it was decided to consider the characteristics as existing at the image display surface. Thus, displayed image resolution would be a valid "characteristic," while image generator resolution would not.

Appendix A contains a list of visual simulation system characteristics which were determined to have potential for significant perceptual or visuo-physiological effects in current simulation system designs. Also provided in this appendix is a preliminary list of the types of perceptual effects associated with each characteristic. While the attempt was made to derive as complete a list of characteristics as possible, it is not claimed to be exhaustive.

RANKING OF DISPLAY CHARACTERISTICS

Rationale

The purpose in ranking the list of visual simulation characteristics was to establish their relative importance for further study. It was recognized that all of the characteristics could not be comprehensively treated within a contractual effort of this size, and that it was probably not desirable to treat each characteristic equally. This dictated that the relative importance of the characteristics be determined, and the contractor selected the method of pseudo-ordinal ranking based upon the scoring of each characteristic against a weighted set of "importance" criteria as evaluation factors.

Evaluation Factors for Ranking Characteristics

The selection of evaluation factors or criteria to use in ranking the characteristics was not an easy task. Since these factors, by their nature and function, largely influence the order of ranked characteristics, they were "flagships" for the direction the contractual effort would follow for the remainder of the study effort.

This contract was not designed to consider questions of transfer of training from simulator to flight performance as it is affected by false visual cues or lack of realism or by fatigue, stress, strain, etc. However, it was recognized that such questions are ultimately the most important ones to answer in establishing design criteria and specifications for visual simulation systems. In the meantime, it is important to determine the relationship between false visual cues, lack of realism, etc. (perceptual effects) and the characteristics in the system which cause these effects. The evaluation factors for ranking these characteristics did provide, however, a mechanism for relating the importance of the characteristics and their associated perceptual effects to their impact on training, flight performance, fatigue, equipment design, etc.

The evaluation factors themselves were ranked as to their relative emphasis or weight in the evaluation of each characteristic. The weights of 6 to 10 were selected rather than 1 to 5, 0 to 4, or any of the other alternatives in order to provide some differentiation of relative importance, but at the same time, to keep the difference between the lowest and highest weights to less than twice the lowest weight, since it was felt that the highest weighted factor was probably not more than twice as important than the lowest weighted factor. The following five evaluation factors, along with their weights, were developed by the contractor with guidance by the Air Force Human Resources Laboratory (AFHRL) project engineer:

1. FALSE CUES

   (Wt = 10) - The potential of the characteristic to produce false visual cues which may (a) have negative transfer of training effects, (b) interfere with, or increase the cost of, simulator training, or (c) affect flight safety.

2. INTERACTION OF CHARACTERISTICS

   (Wt = 9) - The potential for interaction of the characteristic with other visual or system factors to produce eye stress, strain, or fatigue; visuo-physiological reactions; or generalized image degradation.

3. CURRENT PREVALENCE

   (Wt = 8) - The prevalence of the characteristic in current visual simulation systems.

4. REALISM DEFICIENCY

(Wt = 7) - The extent to which the characteristic degrades the realism of the displayed visual scene, independent of the effects upon training.

5. CORRECTION COST

(Wt = 6) - The potential impact of the characteristic, if its effect is to be eliminated or minimized, upon the design, construction, operation, and maintenance costs of the visual simulation system.

Matrix of Characteristic Rankings

Each characteristic was scored on a scale of 1 to 5 against each of the five evaluation factors. This score was then multiplied by the weight of the evaluation factor to derive a "weighted score." Finally, the weighted scores on all evaluation factors for a particular characteristic were added together for a "total score." These total scores were then used to rank the characteristics as to their relative importance for subsequent study.

Appendix B presents the matrix of characteristics by evaluation factors with both initial and weighted scores as well as total scores. Also indicated is a category mean score ("AVE"), which is the average of the total scores in a particular category. Table 1 lists the characteristics in order of their resulting total scores.

REVIEW OF VISUAL SIMULATION CONCEPTS STUDY

The results of the Visual Simulation Concepts Study were documented in a Detailed Research Plan and submitted to the Air Force for review and approval. As a result of this review, some revisions in the evaluation scheme and consolidation of some of the characteristics in the rank ordered list were made. The primary revisions involved exchanging weightings between two of the evaluation factors and the establishment of the weighting values of 6 to 10. These changes were accommodated in the description of the evaluation factors presented earlier.

In several instances it appeared that two or more individual visual system characteristics could be grouped together without jeopardizing their uniqueness, but at the same time producing a more comprehensive analysis and compilation of data. Therefore, in consideration of the interactive nature of some of these characteristics, several consolidations were made in deriving a "most important" list of characteristics for subsequent study. Among those so combined were "binocular deviation" with "binocular image size differences" and with "dipvergence," "visual system lags" with "update rate," and "lateral vergence" with "collimation/image distance error" and with "image distance variability."

The review, and subsequent revisions, resulted in the following list of visual simulation system characteristics considered to be of prime importance for subsequent study:

Table 1. Rank Order of Visual Simulation System Characteristics

Rank Order	Visual System Characteristics	Total Score
1	Aliasing	146
2	Scene Overlays and Inserts	138
3	Field of View	138
4	Temporal Intensity Fluctuations	138
5	Binocular Deviation	137
6	Visual System Lag	137
7	Magnification	136
8	Scene Misalignment	136
9	Update Rate	134
10	Hue Range (Wavelength Distribution)	134
11	Active Lines per Visual Angle	134
12	Picture Elements	134
13	Exit Pupil	133
14	Type of Scan or Formatting	132
15	Color Saturation and Contrast	132
16	Color Differences	130
17	Luminosity Function	129
18	Image Distance and Variability	128
19	Reflections, Glare, Ghosting, Etc.	128
20	Gaps in FOV	127
21	Luminance Range	126
22	Geometric Perspective	125
23	Lateral Vergence	124
24	Eye Relief Envelope	123
25	Displayed Depth of Field	119
26	Luminance Differences	119
27	Temporal Changes in Color Balance	118
28	Dipvergence	116
29	Frame Rate	110
30	Collimation/Image Distance Error	110
31	Contrast	108
32	Binocular Image Size Differences	100
33	Color Registration	92
34	Quantization	87
35	Spot Size/Shape/Spread	86
36	Uneven Line Resolution	86
37	Luminance Variation	84
38	Phosphor Decay Time	80
39	Color Fringes	80
40	Color Variation Within Display	76
41	Vibration	75

Aliasing

Magnification

Scene Overlays and Inserts

Binocular Deviation/Binocular Image Size Differences/Dipvergence

Visual System Lag/Update Rate

Color Differences

Scene Misalignment

Temporal Intensity Fluctuations

Lateral Vergence/Image Distance and Variability/ Collimation/Image Distance Error

This list formed the basis for the literature search and data evaluation tasks. The results of these tasks, in turn, led to the development of experimental designs for those system characteristics for which data were found to be inadequate or insufficient to use as a basis for recommending definitive visual simulation system design criteria.

LITERATURE SEARCH AND EVALUATION

LITERATURE SEARCH DEVELOPMENT

The literature search was initiated with a computer-based search through the services of the Boeing Aerospace Technical Library. Over 100 information data bases were accessible through the library's contractual tie-ins with System Development Corporation, Lockheed Information Systems, Defense Documentation Center, National Aeronautics and Space Administration, and the New York Times Information Bank. Using as "key words" the visual system characteristics developed in the concept study, and adding some combinations of general descriptors such as visual simulation, visual systems, visual distortions, and flight simulation, the computer-based search assessed something over 2000 titles. The abstracts, printed out for most of these reports in the computer search, were reviewed and those appearing relevant to the study were ordered. Over 350 reports were initially requested, with supplemental requests for nearly 200 additional reports being made as a result of the examination of reference lists of acquired reports, or from the other aspects of the literature search.

The second aspect of the literature search was to review analytical and experimental work, which had been conducted by the contractor either under contract or with in-house research and development funds and which was relevant to the visual simulation design problem. This included psychophysical studies of various aspects of vision, such as visual acuity, stereo acuity, target acquisition, chromostereopsis, cyclophoria, photointerpretation, and related performance tasks such as aircraft approach and landing under a variety of conditions, including night/dark field, sloping surrounds, distortion windshields, etc.

In addition, extensive experience has been gained over the past several years by principal members of this contract team in direct support of investigations of visual simulation systems leading up to selection of the system for the contractor's Flight Crew Training simulators. This is an ongoing support effort, with evaluations currently being conducted for near future visual simulation requirements.

The third aspect of the literature search was to gather data not available in the published literature. This was done through visits and personal communications with other investigators conducting relevant analytical, developmental, and experimental efforts. Early in the contract period, a trip was made to eight visual flight simulation facilities around the country. This visit served to establish a broader link with researchers and simulation facilities of varied types and also to increase familiarization with the unique capabilities and limitations of the different visual simulation system concepts and equipment employed in these facilities.

LITERATURE DATA EVALUATION

The literature search task involved not only the acquisition of reports, but the evaluation of these data as to their validity, reliability, and relevance. It was recognized that this task was important in developing design guidelines that could be used with confidence by the Air Force for selecting design specifications for, or evaluating designs of, future visual simulation systems. Where there was an abundance of relevant data, the most comprehensive and relevant reports were selected for summarization.

In approaching the literature, the procedure was to compile work lists of all available references which might be relevant to each characteristic. From reviewing the abstracts, the studies employing the appropriate type and range of independent and dependent variables were selected for detailed evaluation of the complete report. The following list contains the evaluation criteria used to establish a level of confidence and utility for the data in each report.

Evaluation Criteria:

1. Were the levels of independent and dependent variables used directly applicable?
2. How sound was the basic experimental design?
3. Were intervening or extraneous variables adequately controlled?
4. Did the type and number of observers or subjects used make the results generalizable?
5. Were the basic assumptions of the experimental design met?
6. Were the statistical analyses used appropriate and comprehensive?
7. How sound was the interpretation of the data and statistical analyses?
8. Were the conclusions warranted?
9. What was the power of the test and reliability of the measurements?
10. Has the study been replicated?
11. If so, are the corresponding data and conclusions in agreement?

LITERATURE SEARCH LIMITATIONS

Any literature search, no matter how intensively pursued, will almost certainly fail to pick up all relevant reports, especially when dealing with as broad a topic as the present one on psychophysical criteria for visual simulation systems.

One reason for this is that some published reports are not accessible under the keywords chosen to maximize relevant information retrieval. If the major interest of the author is peripheral to the literature searcher's category of interest, the keyword list provided by the author of the report may not include some words which would lead to its discovery by the literature searcher.

Another problem is the time factor. Work schedules force the searcher to review that which is available on a timely basis. Finally, the allocation of time to the literature search task may require a less than thorough examination of the material in an area where there is an overabundance, while an area where there is a paucity of information may require much digging to find the rare article of significance to the research goals.

Every serious researcher knows that the seeking of relevant information from the literature can be a never ending task but that practical considerations require that a cutoff point be established, however arbitrary this may seem from the standpoint of thoroughness in a technical sense.

EVALUATION OF RESEARCH DATA

INTRODUCTION

Phase I of this contractual effort was organized around four tasks. The first two, visual simulation concepts study and the literature search, have already been discussed. The following sections deal with the evaluation of research data. The fourth task resulted in the design of seven experiments for Phase II (Appendixes C to I).

The following sections of the report discuss the evaluation of research data and are organized about the nine major sets of characteristics of the USAF approved prime list. The order of their appearance is common to the scaling of importance. One deviation from this order is the appearance of a section on Update Rate which is under the main heading of Aliasing, instead of being a portion of Visual System Lag. This choice was arbitrary, as from a visual standpoint it fits within the concept of Aliasing. Whatever the effect of the interaction of samplings and digitizing, the observed effects are also a product of a partial system lag.

In each section, an attempt has been made to assemble and summarize the critical information from the technical, experimental, and developmental literature. To illustrate the advantages and disadvantages of specific design criteria for the improvement of the display and utilization of information, an attempt has been made to translate into designer and operational uses, the terms and criteria that come from diverse professional sources. In the pursuit of completeness, an attempt has been made to assess which data are missing and which portions need analytical research or operational data for the design of new displays or the retrofit of current ones.

ALIASING

INTRODUCTION

The general problem called "aliasing" by engineers covers a multitude of visual effects which visual specialists would classify as "anomalies" and which are due to quantizing and sampling at various stages during the generation, processing and display of television images.

The instructors and pilots undergoing training with flight simulators fitted with visual systems have some very descriptive names for these visual anomalies seen in CCTV displays with computer generated images (CGIs). Examples of such descriptors are shearing, tearing, flickering, creeping, sparkling, streaking, bouncing, oscillating, racing, jumping, skipping, edge walking, and reversing.

The Potential Effects of Aliasing

The influence of these visual phenomena that are specific to the line scan and digital quantizing of the displays has not been quantified. These phenomena are, at the least, annoying and create distractions which may interfere with pilot performance by causing frequent short interval delays. Potentially, they can impose incorrect perceptions of speed when they take the form of slowdowns or movement reversals. They may also provide navigational and spatial orientation cues where there are no real-world equivalents and thereby lead to "interference effects in transferring to the real world situations." Such interference effects are probably the greatest danger imposed by these visual anomalies, especially if the artificial cues are learned without awareness of such learning by the pilots or flight instructors.

An example of a potential source of a negative transfer of training would be present for a day scene with a CGI display with a line scan system. For an approach and landing task, the runway would be depicted as being ahead of the approaching aircraft, and in this hypothetical scene, the data base has a contrasting color (or luminous intensity) field in the distance beyond this runway. This field covers a very short extent beyond the runway's length but is quite wide (horizontally). It is trigonometrically possible that the frontal extent of this field could cover only one raster line when the approaching aircraft is on the proper glideslope. If the pilots undergoing training keep this field in view, they may learn by comparing this aspect of the scene with the glideslope indication on their Attitude Direction Indicator (ADI) that (a) the field disappears when they are below glideslope, and (b) it flickers (oscillating between two raster lines) when they are above glideslope. They now have a "head-up display" or an optical lever they can use to maintain a proper descent path with less frequent reference to their ADI. They may change the visual scan among the instruments without thinking that they are using the visibility of that particular field as a check on their proximity to the glideslope. The instructor, without realizing that the pupil is using this "aid," rates that student's proficiency too high. The pilot, subsequent to training, will not perform as well on the "check ride," since this visual cue will not exist in the real world and at least this part of the training will not have positive transfer to operational flying.

In addition to the aliasing cue, there is another complementary cue that pilots might learn that provides an excellent azimuth alignment visual level on a CGI display that uses raster lines. The Federal Aviation Agency (FAA) specification for the markings on a runway include a centerline and two runway edge lines. The edge lines are solid white lines that go the full length of the runway and are near the right- and left-hand edges of the hardened surface. When the aircraft is represented as being 5 miles out, and on a 3 degree glideslope, the representation of the runway is relatively small. The "level of detail" input from the software is operating on the first or second of eight possible levels of increasing complexity. The edge lines appear to be described by a series of short segments, each made up of two or three raster lines. Each of these elements is written at a different time due to the digital inputs from the computer. These small temporal differences in writing times gives the pilot the impression that the runway edge lines are relatively dynamic. They appear to scintillate, moving away or toward the airplane or flicker without changing position. It may soon be learned by the pilot that the aircraft position controls the type and direction of the apparent motion. If the aircraft is to the left of the runway centerline extension, the left-hand edge of the runway appears to be moving from a distance toward the aircraft and the right-hand edge line appears to be moving from the aircraft toward the horizon. If the pilot changes the relative position, bringing the airplane closer to the extension of the centerline, the rates of differential apparent movement begin to slow. The apparent motion stops when the aircraft's position is centered on the extension of the runway centerline. If the pilot overshoots the centerline extension, ending up to the right of this reference, the relative apparent motion of the runway edge lines shifts direction. Then the right-hand edge line appears to move toward the aircraft and the left-hand edge line appears to be moving away from the aircraft toward the horizon. Therefore, at a great distance from the runway, the pilot can get azimuth alignment cues by watching this relative motion of runway edges. This visual anomaly is useful in the simulator as a pilot aid, but the transfer of the skill of using this in the real world is zero or negative. The visual cue is also specific to visual systems that utilize digital inputs coupled with raster line displays.

EXAMPLES OF ALIASING ERRORS

Edges With Apparent Steps

The CGI daylight systems until 1973 were producing surfaces whose sloping edges appeared as a series of steps or "jaggies" (Schumacker & Rougelot, 1977). Figure 1 depicts this relationship. Each pixel was assigned a supra-threshold luminous chromaticity that was based on a single sample of the scene spatially located at the center of the pixel.

If the horizontal length of each pixel is greater than the resolution threshold of the eye, then the appearance will be of a step-wise edge, as shown in Figure 1. In a computer generated scene depicting the distant horizon as a straight line traversing the width of the display, the horizon will be a straight line following a single raster

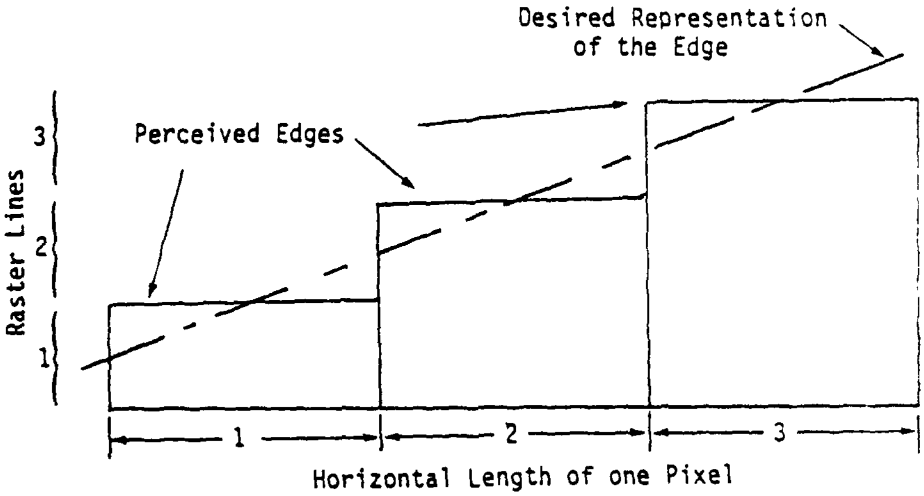


Figure 1. Schematic representation of a jagged edge.
(Schumacker & Rougelot, 1977)

line. However, as the aircraft is banked and the horizon dips on the left side and rises on the right, the horizon crosses many raster lines and its appearance changes. The line appears as a series of steps progressing upward from left to right. This description holds only for a steady state of right wing down. The dynamic changes in roll produce the perception of a phenomenal movement. The sawtooth-like edges seem to step in time such that they shear from the left to the right, a non-real but apparent motion known as the phi phenomenon. This apparent motion is due to a differential writing rate interacting with the different raster line spatial position.

For any given raster line, each pixel is written from the left to the right in an ordered sequence, so the "sawtooth" on the left side of the display is written first, and the "sawtooth" on the right edge of the display is written last. The individual steps in the sawtooth appear then to be written in a moving fashion from left to right, and the perception is that the steps are moving from left to right.

A Theoretical but Impractical Solution

One solution for this problem would be to have sufficient raster lines and elements so that the pixel size would be less than the resolution of the eye. The vernier threshold at 6 foot-lamberts and more than 40 percent contrast is .04 arc minute. In a beam-splitter-mirror display with a viewing distance of 47 inches, this solution would require 27,512 raster lines and 36,684 elements per line. This would also require a 38.5 times reduction of the spatial extent of the triad in the current 1000-line, 25-inch CRT. This is an impractical solution for today's technology. The alternative solutions include reducing the overall contrast of the scene, or reducing the sharpness of the gradient of luminosity across the edge, or a combination of these factors.

Smoothing as a Solution for Jagged Edges

Reducing the edge gradient in combined hue and luminosity transitions in the CGI image displays is called "smoothing." This is an effective solution obtained by displaying each pixel which is cut by an edge as a blend of the colors on either side of that edge. If two pixels are cut, the mixtures would be 33/67 and 67/33 blends. Sampling across three pixels would make the transition as 25/75, 50/50, and 75/25 proportions from one color to the next. For a long horizontal edge, the smoothing may be a near-linear transition over a number of pixels. Since horizontal elements of a raster line may have no interval between them, "horizontal" smoothing is perceptually different from "vertical" smoothing as the space between lines is generally visible and near-vertical edges may involve only one element smoothing.

Interactive Effect of Smoothing on Resolution

Smoothing has an interactive effect on display resolution. The distribution of an edge over more than one element length decreases the resolving power of the display as shown in Figure 2. A system whose element length subtends 2.3 arc minutes on the human retina and has a

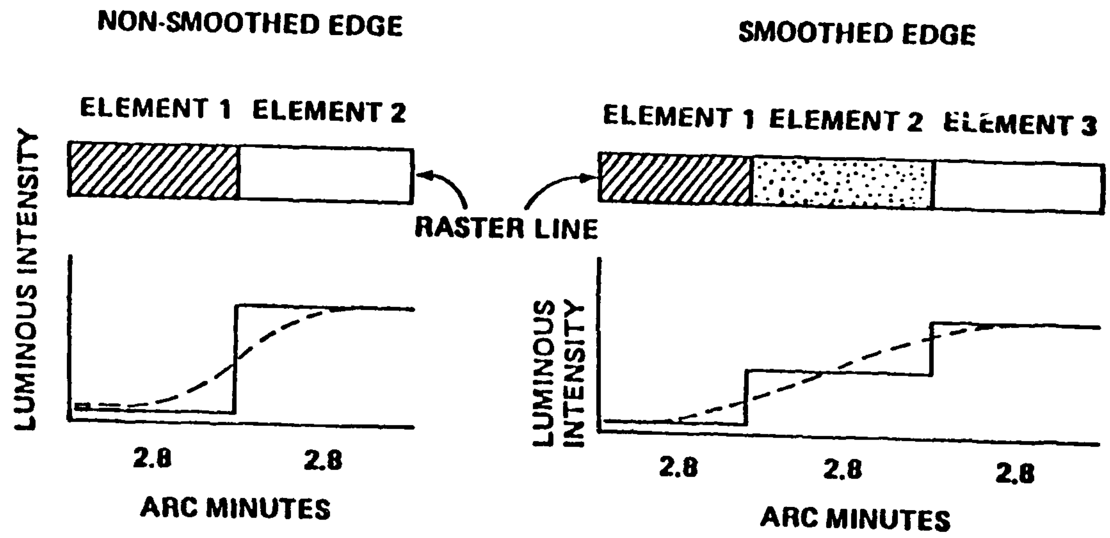


Figure 2. The effect of smoothing on the resolution of edges. (Kraft & Shaffer, 1978)

single sampling at the middle of the element will display an edge as drawn on the left of Figure 2. If the apparent edge is at 50-percent luminous intensity, then a single element will appear to have the right and left edges 2.3 arc minutes apart. If the transition is smoothed across three elements, then the smallest displayed distance between two edges becomes 5.6 arc minutes, and for a four-element smoothing, the minimum two-edge distance is 8.4 arc minutes. Therefore, system resolution specifications should take into account the effect of the electronic smoothing technique and the sampling frequency per pixel (Kraft & Shaffer, 1978).

Interactive Effect of Contrast and Smoothing

The jagged appearance of an edge will be maximized by high contrast and decrease with lowered contrast. Apparent sharpness of an edge increases with the steepness of the ogive curve describing the luminous intensity change as a function of spatial separation of the minima and maxima in luminosities. Holding the spatial distribution constant and reducing the range of intensities produces a reduction in contrast and in the apparent sharpness of the edge. Therefore, in a scene composed of small contrast differences, edge smoothing will affect the perception of the steps, making them either less noticeable or not discernible at all.

The Interactive Effect of Update Rate and Scene Content

If a line scan, digital computer generated system has refresh and update rates of 60 Hz the phenomena described in the following discussion are minimized; however if the update rate is 30 Hz, these phenomena will be observed. If the scene being drawn contains lines that are parallel to the flightpath of the airplane, the edges of these lines will appear to be quite smooth if the airplane is proceeding on a straight line. However, when the airplane begins to change heading at a sufficient rate and the angular velocity reaches a specific amount, the appearance of a smooth vertical line now appears as a jagged line on its right and left edges. The paradigm is like the image is made up of two combs with every other tooth being represented by a different comb. When one comb is moved to the left and the other to the right, the tips of each of the individual spines no longer form a straight line. This would describe the appearance of the left and right edges. The slippage in space is dynamic, a direct function of the angular visual velocity generated by the movement of the aircraft relative to the scene. The nearer the object in the scene is to the pilot, the greater the angular velocity for any common rate of turn. Two differential resolutions exist within the scene until the turning movement returns to zero.

A different perception occurs when the aircraft remains on the same heading and the pitch is changed. When the rate of change in pitch becomes sufficient, the steady transition changes to a step-wise progression. This is most noticeable when looking at horizontal elements. The vertical lines are not affected by this direction of movement. The interaction between the slower update rate and the depiction of small objects in the scene is represented by a phenomenal change. First, the width of the small object increases, then it appears as two elements instead of one. An example is when the scene depicts a runway and the dynamic movements are those of a takeoff. As the aircraft gains speed, the runway edge lights will, at some point, begin to stretch and then break apart, and then become two lights. The space between the two representations will increase as a function of the angular velocity. At a 30 Hz update rate and a 29 foot eye height, an aircraft speed of about 116 knots will produce double images of runway lights 150 feet to the right or left of the cockpit. The double images are located in the lower right and left portions of a 30 by 40 degree field of view. The pilots may incidentally learn the relationship between V1 speed and the appearance of doubling of the lights and they could use this as a cue for when to rotate the aircraft without reference to the airspeed indicator.

The doubling of the runway edge lights will also occur during a taxiing maneuver when the aircraft turns from the runway onto an adjacent taxiway. This is true if the turn is a 90 degree turn and the taxiing velocity is about 9 knots. Pilots could learn to associate the amount of separation in the images of a single light with the angular velocity of the turn and use it to their advantage.

The perception of edge breakup and doubling of small objects is directly related to the angular velocity in the scene. High aircraft speeds, rates of turn, roll rates, etc. may occur without the pilot's seeing this visual phenomenon. That is, for the same rates of turn, near objects may appear to double, intermediately distant targets will appear to blur on the left and right borders, and distant objects will appear unaltered (Table 2).

It is not known whether these phenomena have a negative effect on transfer of training. Update rates are task dependent, particularly in the military situation. Angular velocities represented in the visual scene will be much higher for tasks like those assigned to the A-10 in low level, high speed flight, in contrast to the approach and landing rates of military air transport. Even more extreme, high angular velocities will occur in air-to-air combat. The advantage of using a faster update rate will be that the simulator and its visual scene can be used for more tasks. However, the disadvantage is that the amount of computer capability will have to be increased to gain a 60 Hz update rate.

Table 2. The influence of a 30 Hz update rate on the appearance of lights and small objects (≤ 3 arc min) in 1000-raster line displays (values in table are in degrees)

Aircraft Speed in Knots	Distance From Pilot's Eye to Small Object in Scene				
	50'	100'	150'	1000'	10,000'
100	6.42	3.22	2.14	.322	.032
150	9.58	4.82	3.22	.48[illegible]	.048
200	12.68	6.42	4.29	.644	.064
	*		**	***	

* Will appear as two objects instead of one.

** Width of object will appear too large.

*** Object will appear unaltered by speed.

MAGNIFICATION

INTRODUCTION

Magnification of a CGI remains a point of discussion among specialists in vision and equipment designers. The goal is to provide a CGI image with a specific display that permits the greatest amount of transfer of training from simulators to the real world. The design of a certain field of view for a display system may be achieved by magnifying the CRT image to fill the angle subtended by the display. Whether the resulting magnification of the image is acceptable for training may depend more on the representation of relative sizes of objects and their interrelationships imposed by the dynamics of motion in real time, than on the absolute image size. This section discusses some of the possible implications of magnification in display design.

The three aspects of magnification to be considered here may produce perceptual effects in a visual simulation system: (a) Uniform magnification within the optical system with image size correct for the object size and distance portrayed, (b) Uniform magnification of a scene to an image size larger or smaller than that dictated by the size/distance relationship, (c) Non-uniform magnification, in which objects in some areas of a display are magnified more than objects in other areas (i.e., distortion).

Optical Magnification

The first type to be described has been termed "optical" or "instrumental" magnification (Bartley, 1951; Miller & Bartley, 1954; and Lumsden, 1977) and may be found in visual simulation systems when a "too small" scene is magnified by the transmission optics (usually in the interest of expanding the field of view of the display). Under this condition, it is assumed that there are no specific distortions of the image; i.e, the image has "geometric equivalence" to the "real" scene. The optical magnification problem is relevant to systems which use films or physical models, such as model boards, for the original scene construction and may or may not be a problem in CGI systems.

The perceptual effect found with optical magnification is a "flattening" of the third dimension of the scene, i.e., a compression of perceived depth in the scene with resulting apparent distortions of three-dimensional objects in the image. This effect occurs whether the scene is real or a two-dimensional representation, such as a film. The cause of this reduction in the perceived third dimension is that magnifying the image proportionately enlarges all portions of the scene and objects within the scene. Thus, if a 2x magnification is used, both "near" and "far" objects are doubled in size in their two-dimensional representation. In the real world, the equivalent of magnification would be to move closer to the scene, and in the process, "near" and "far" objects do not increase in size (visual angle) in the same proportion since the reductions in distance are, respectively, different ratios.

The apparent distortion in objects such as buildings consists also of a compression of depth which appears to alter the angular or geometrical relationships of intersecting planes or edges. This perceived distortion can also be found in two-dimensional shapes which have a Z-axis component, such as a runway outline viewed on final approach in a simulator. In this situation, the compression of depth translates into a tilting or slant of the runway plane, with the far end tilted up (closer to the observer). Figure 3 depicts this relationship, with the upper figure showing the plane both as viewed naturally at full distance and as viewed with optical magnification, and with the lower figure showing the plane viewed naturally at a closer distance. A comparison of the angular relationships of planes AB, YX, and A_1, B_1, show the perceived distortion in the slant of the optically magnified plane.

The runway plane distortion is perhaps the most serious case resulting from optical magnification, and while this effect has been known for some time (Bartley, 1951), no definitive data have been found to establish detection thresholds. However, there are some representative data on the threshold for the detection of slant under unaided viewing conditions. In a study of "geographical" versus "optical" slant, Gibson and Cornsweet (1952) reported standard deviations for the judgments of slant to be about 10 degrees and 6 degrees respectively. To provide more definitive data, an experimental design for a psychophysical study has been developed and is included in Appendix E.

Since the effects of optical magnification do not include distortions or degrading of image quality in the usual sense, it is anticipated that there will be no attendant visual strain, fatigue, or visual tolerance levels. There may, however, be visual disorientation or confusion with extreme cases of magnification.

Size Magnification

The second type of magnification of concern in visual simulation system design is that involving uniform magnification of the overall scene such that the visual angle subtended by depicted objects is greater than the angle dictated by the size/distance relationship represented. Such magnification may result from poorly controlled design features, such as improper eye-to-display distance or improper object-to-magnifier distance. Figure 4 (from Ganzler, 1971) depicts the relationship between eye-to-lens distance and image size for various object-to-lens distances. The perceptual effects of such magnification are linked to size constancy and perceptual size-distance relationships. Consequently, no general detection or tolerance criteria can be established; the perceived effects can be described only in the context of the specific viewing conditions and scene constructs such as level of detail or texture; and even with such specificity, individual differences in perception make attempts at the establishment of detection thresholds etc. a very tenuous proposition. Nevertheless, this subject is discussed in more detail in the section on Lateral Vergence/Collimation/ Image Distance.

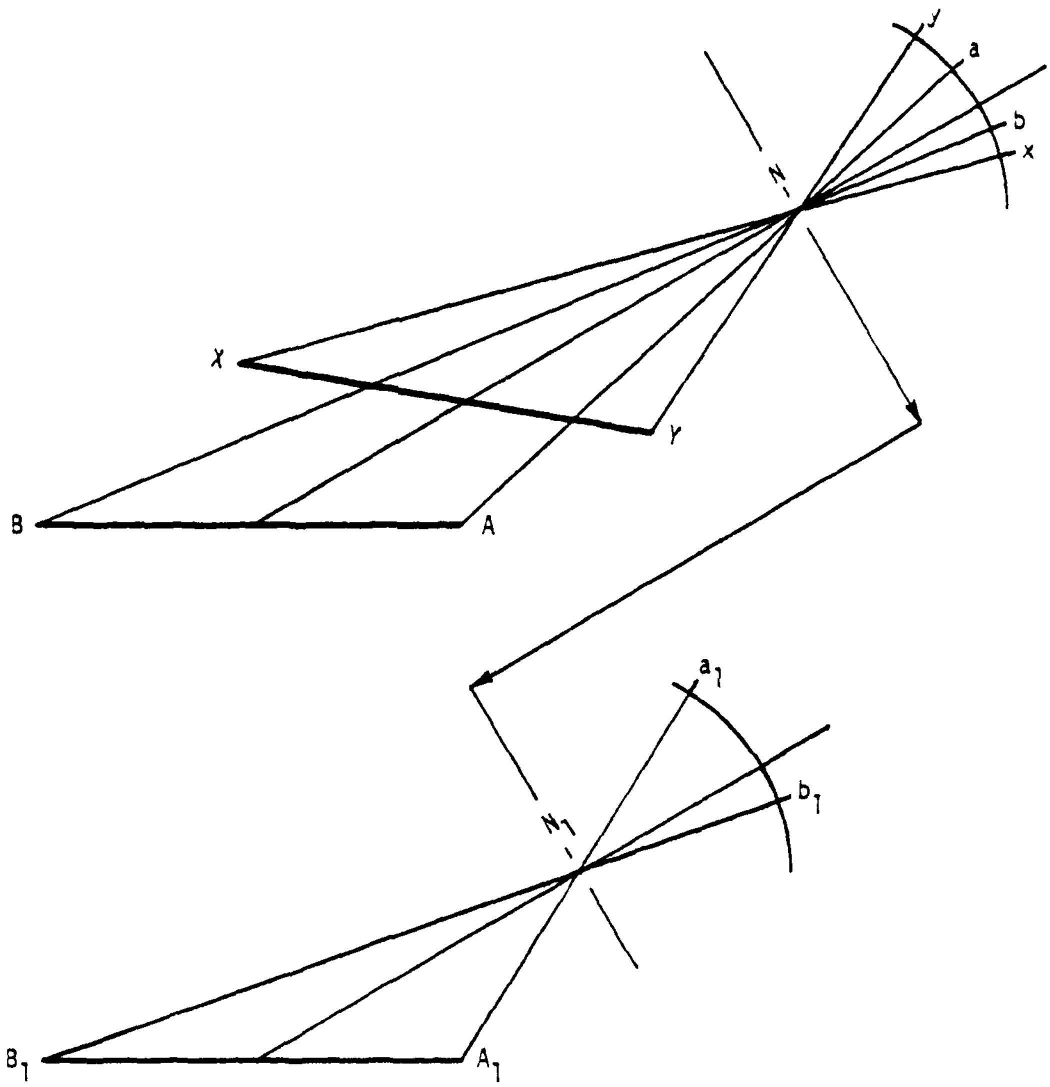


Figure 3. The upper figure shows a runway plane as viewed naturally (abNAB) and under instrumental magnification (yxNYX), compared with the runway viewed naturally but at a closer distance ($a_1b_1N_1A_1B_1$), as in the lower figure. (Redrawn from Bartley, 1951.)

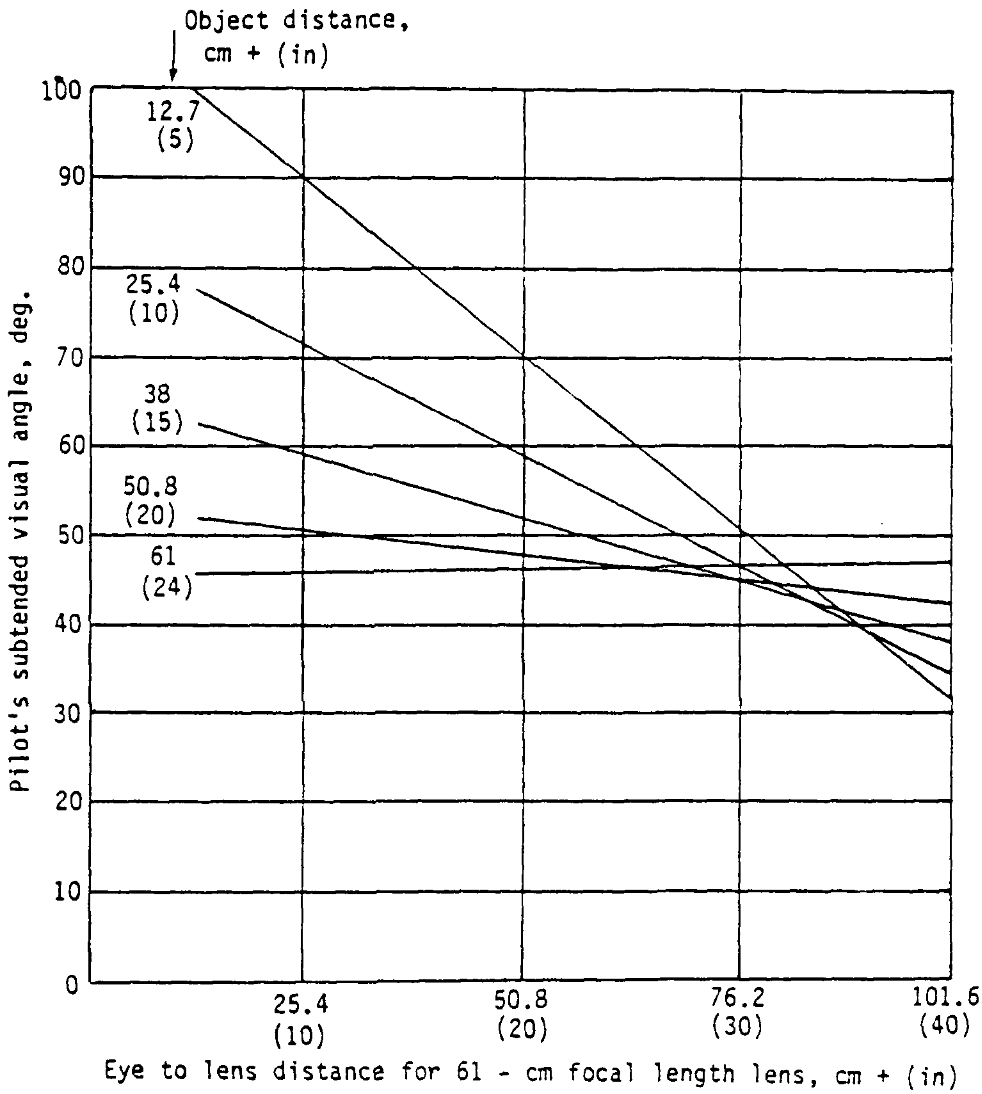


Figure 4. Relationship between pilot's subtended visual angle, object distance, and eye-to-lens distance for a 61-cm focal length lens (Ganzler, 1971).

Non-Uniform Magnification

The third type of magnification of interest here involves distortion of the image, in which some portions of the image are magnified more than other portions. Generally, this results from residual distortions of the barrel or pincushion type, although symmetrical meridional aniseikonia also can be at fault. In most cases these distortions appear unequal to the two eyes due to the differing off-axis positions. For these cases, the criteria developed in the section on Image Size Differences are most applicable.

SCENE OVERLAPS AND INSERTS

INTRODUCTION

The extensive maneuvering required of military aircraft in air-to-air engagement requires a much larger field of view than that for approach and landing. The F-15 and "aggressor" squadron pilots training in the maneuvering range have found that the first visual acquisition of the "foe" is almost essential for survival. Radar may assist the pilot in narrowing the field of search, but visual acquisition is necessary to gain early position and attitude information. Once acquired, vision remains the main source of information about the other aircraft's speed, direction of movement, and attitudinal changes that are the precursors of each maneuver. The "friendly" and "aggressor" fighter pilots are emphatic about their need for "the largest possible" field of view for aerial combat.

The AFHRL Flying Training Division at Williams AFB has provided quantitative measurement of the relationship between fields of view and pilot performance in terms of circular error in bombing (Cyrus, 1978). It was found that the larger the field of view, the smaller the circular error. The trend in flight simulators designed for the training of fighter pilots is toward incorporating visual displays of very large fields of view and accepting lower general resolution (with the exception of inserts of the "other" aircraft) as a necessity imposed by the current state of the art.

Requirements for simulators of large aircraft, bomber, cargo, tanker, command post, airborne early warning, and air-to-surface patrol types include an out-of-the-window visual simulation capability with large fields of view. Refueling of these aircraft is one task that has the face validity of requiring a large field of view. Air safety along heavily travelled routes and in air terminal areas with high density traffic may also be improved by the larger fields of view.

Field of View and Resolution

To generate images for wider fields of view with special television or CGI techniques generally reduces the line width x element resolution as illustrated in Table 3 and Figure 5 (Kraft & Shaffer 1978). However, air-to-air and air-to-ground visual tasks of aerial combat, reconnaissance, and attack all require high resolution systems. The technique of providing "area of interest" inserts in displays becomes a logical mode for solving the tradeoff between field of view and resolution. This is fostered by the theoretically unlimited number of channels that might be generated in CGI systems to cover the large field. To also incorporate very high resolution simultaneously in all areas of the display is not cost effective, considering the computer storage and display requirements to have all the "edges" or "polygons" necessary for high resolution and great detail througnout a 200 degree x 360 degree field of view.

Table 3. Interrelationship of visual resolution and field of view for a 1000 line visual system. (Kraft & Schaffer, 1978)

Field of View (in degrees)			Visual Resolution (in arc minutes) per line pair		
Vertical	x	Horizontal	Vertical	x	Horizontal
10	x	15	0.8	x	1.0
15	x	20	1.2	x	1.4
30	x	40	2.5	x	2.8
36	x	48	3.0	x	3.3
60	x	80	4.9	x	5.5

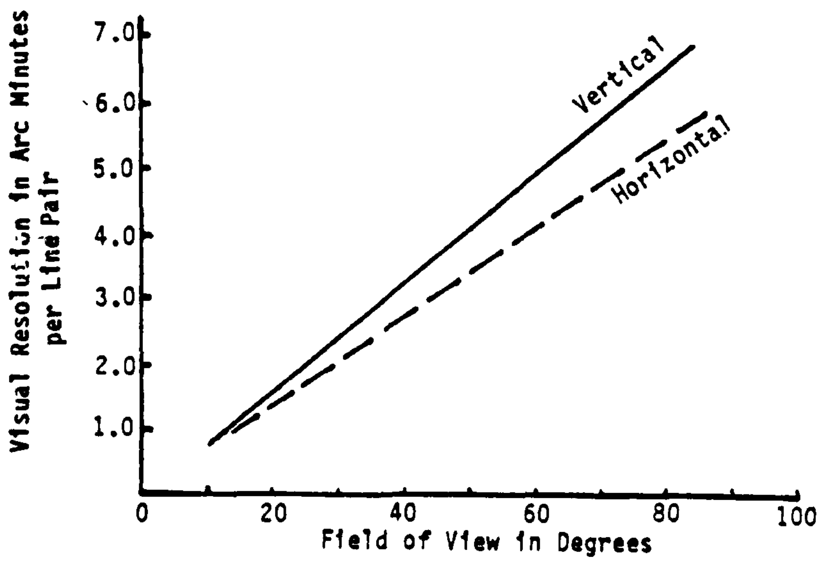


Figure 5. Interrelationship of visual resolution and field of view for a 1000 line visual system.

THE GENERAL PROBLEM OF INSERTS

The degree of attainable realism in a CGI scene is nearly limitless theoretically. However, practical limitations, primarily in computer capacity, force the purchaser/user to settle for something less than the near perfect simulation. The compromise may be to concentrate the high level of detail in certain areas of specific interest while allowing other areas to be shown in lower resolution. In an air-to-ground target acquisition task, for example, it is wasteful to assign as much computer work to the sky as to the ground area. Further refinements on this general approach and some attendant problems are discussed in the following paragraphs.

The problem becomes one of producing a display system which can take full advantage of CGI signals, provide adequate luminous intensity, realistic scene movement and velocities, large field of view, and an area of interest with high resolution. Then the major problem shifts toward placing, stabilizing, and matching this area of interest to the pilot's line of sight, maintaining in real time the high resolution image on and around the fovea and phenomenal macula. Inserts successfully slaved to the line of sight would be an ideal solution for all visual tasks. The concept of slaving the area of interest to ground targets is theoretically easier to achieve; however, the area of high resolution would be easily recognized by the pilot. The main disadvantage of target slaved areas of interest becomes evident, in that easily discriminated patches of high quality images would provide excellent cues for where to search for a target of opportunity. Thus, the most difficult and time-consuming aspect of target acquisition is artificially aided to the point that target acquisition becomes a target recognition task.

Insert Slaved to Head Position

The present state of the art permits slaving the insert to head position. Remaining problems include system lags wherein the final phases of positioning the image after a head motion (approximately 10 degrees or more) are visible. The saccadic eye movement made to track this final scene movement overshoots the final position and comes to rest beyond the final stop position of the scene. Then a new reverse saccade centers the fovea on the now stationary point of interest.

Head and Eye Tracking Combined to Drive Insert

Incorporating eye-tracking devices within a helmet, to add eye tracking to that of head tracking, is currently not within the state of the art. Although this would represent the ideal control of a high quality insert, there are a number of major limitations that must be overcome before this solution becomes practical. For example fighter pilots who pull high Gs in combat maneuvering avoid any additional weight or structure on their helmets. Their search patterns are slowed and the canopy is scratched by existing helmet attachments during the gross head motions used in the fast wide field scanning that are part of air-to-air engagements staged at the maneuvering range. Also, current eye trackers which are capable of the necessary accuracy and speed are laboratory tools, mounted on rigid platforms, and requiring hours to set up and calibrate for each observer. The systems are not adaptable to all individuals because pupil size, corneal curvature, etc. are not always compatible with the equipment's capabilities.

Some Specification Information on Inserts

An insert that is rotated from vertical or horizontal without any reference as to vertical or horizontal in the peripheral area surrounding the insert still must be within 1 degree of vertical. Alluisi & Muller (1956) have shown that the vertical and horizontal orientation of a line can be used as an error-free coding category within the limit of 1 degree. The error-free zones of inclination as a coding category become larger out to 45 degrees, then decrease in a similar manner until 90 degree rotation (horizontal) is reached. Visual acuity data also illustrate a greater discrimination in the horizontal and vertical meridians than are to be found along the oblique meridians.

Ogle (1962) indicates that the directional values of the retina indicate a "pincushion" type of discrepancy. If the insert has strong horizontal or vertical elements within the scene, those off the central locus will not seem horizontal or vertical as do the other elements. Thus, the horizontal elements in the lower half of the scene will appear rotated slightly counterclockwise in the lower right quadrant and clockwise in the lower left quadrant. The upper quadrants will be mirror images of this apparent rotation, i.e., as though they are hinged at the horizon.

Raster Lines and Inserts

Raster lines that have a horizontal orientation will provide easily discriminated cues of angular misalignment of inserts. That is, an insert presented in a homogeneous field must be within 1 degree of horizontal to be discriminated as horizontal. When the surrounding field is also made up of horizontal raster lines, the discrimination of matching horizontalness of insert with field becomes a vernier acuity discrimination sampled at both vertical edges of the insert. Mismatched edges of raster lines of high contrast may be discriminated at less than 0.05 arc minute when the luminance level is between 1 and 10 foot Lamberts (Farrell & Booth, 1975).

Differences in density of raster lines will be discriminated as contrast differences when the individual lines are of a width and separation that approximate the visual threshold of resolution. The lines will be judged as visible near a modulation of 0.013 when the luminance is near 10 foot Lamberts. Adjacent gratings comprising two different raster densities will be discriminated as insert vs. field when the contrast difference is greater than 2.5 percent.

Vertical vibration that is perpendicular to the raster lines will reduce the visibility of a high contrast grating. An insert of high quality (1.5 arc min. resolution) that matches the field in apparent contrast will become visible as an insert of a different contrast if it vibrates with a peak-to-peak amplitude of 1.0 to 1.75 Hz for frequencies of 20 to 120 Hz. These just discriminable contrasts would apply to still scenes should become less visible with moving scenes because the image quality of both field and insert become less as the phosphor smear increases due to motion.

BINOCULAR DEVIATIONS AND IMAGE SIZE DIFFERENCES

INTRODUCTION

Distortions or deviations in the ray bundles transmitted from a single scene to the two eyes of the observer (biocular systems) may produce perceptual effects which are unique and/or either more or less severe than those produced when the two eyes receive separate image packages. Visual systems such as helmet-mounted or stereoscopic displays often present basically different images to the two eyes, thus requiring both physiological and central integration of the separate images. Although the subject of stereoscopic displays or imagery was, by intent, not a part of this effort, it was felt that some characteristics of these types of displays were legitimate areas of concern in this analysis of binocular effects. In fact, the monoscopic, biocular systems of most concern to us are "stereoscopic" to the extent that different images (via system distortions) are presented to the two eyes. Therefore, visual system characteristics of such systems, except those which are primarily associated with stereopsis or with image depth effects, are included in this section.

Among those binocular visual system characteristics which may produce noticeable or bothersome effects are the following:

1. Horizontal and vertical disparities.
2. Image size differences (differential magnification).
3. Binocular image distortion and astigmatism differences.

The perceptual or visuo-physiological effects which may be experienced by the simulator display user are described in the following sections, along with the presentation and evaluation of applicable data derived from the literature. Each binocular characteristic or effect elicits unique or significantly different perceptions or reactions from the observers.

HORIZONTAL AND VERTICAL DISPARITIES

Distortions in optical systems which produce severe binocular deviations or aniseikonic effects are found infrequently in modern technology systems; although, they occasionally result as a side effect of design features requiring compromise in the quality of the image. An analogous example is found in the design of some recent aircraft windshields, in which the requirements for bird-strike protection and complex curvatures result in aniseikonic and astigmatic binocular images, as well as in more random ray deviations. The question of whether the visual simulation system designed for flight training for this aircraft should reproduce these anomalies, through scene or optical system degradation, is an important one but not within the scope of this contract.

A more relevant example would be the refractive doublet virtual image systems (shown schematically in Figure 6 from Kahlbaum, 1977) in which aberrations, particularly chromatic, can be a major design problem and where binocular differences in magnification, astigmatism, disparity, and apparent image distance may affect perception.

In distortions categorized as binocular deviations, all corresponding parts of the two (left and right) images do not fall on corresponding points on the retina as is basically needed for single or fused vision. However, precise points of correspondence are not necessary, since locations falling within a small area ("Panum's area") surrounding the corresponding point also result in a single binocular image. Although there is some controversy about whether these areas represent true physiological relationships or are artifacts of resolution limits (LeGrand, 1967), the effect is to facilitate single binocular vision. The extent of these areas (sometimes referred to as the disparity threshold for diplopia or DTD), as measured in the horizontal meridian, was found by Panum to average 15 to 20 minutes of arc (Borish, 1970). Carter found the size of the area to vary from 6 to 15 minutes of arc at the fovea to 30 to 40 minutes of arc at a distance of 10 to 15 degrees off the fixation point (Borish, 1970). Also, Shepherd found the size of the areas to vary from 5 to 26 minutes of arc horizontally to 3 to 4 minutes vertically (Borish, 1954). A spatial representation of the binocular single vision region for data reported by Ogle (1962) is shown in Figure 7 . An increase in the extent of Panum's fusional areas with peripheral visual angle is shown in Figure 8.

Optical distortions which result in binocular deviations exceeding the above limits may produce perceptual effects including double imaging, retinal rivalry, accommodation changes, blurring, and changes in apparent depth or distance of scene elments. The double imaging or localized diplopia may be suppressed for many observers by the influence of the dominant eye, in which only the disparate image to that eye is perceived. In cases where the disparity is less than the diameter of the scene element involved, blurring of the element may result if there is incomplete suppression of one of the elements. One of the most interesting of the perceptual phenomena resulting from localized binocular deviations and/or distortion or accommodation differences is discussed in a later section of this report,, and involves a binocular montage in which a "good" fused image is extracted from two degraded images.

Only limited data have been found on comfort, visual fatigue, or other decrements in visual performance as a result of binocular deviations which involve a relatively small portion of the displayed scene. Some recent data indicate that localized, binocular deviations can affect pilot performance in a flight simulator (Kraft, Elworth & Anderson, 1978). Vertical and horizontal components of binocular displacements in the image were determined utilizing measurements of the elements in a resolution target photographed through a simulated windscreen panel. Binocular deviations were measured for four levels of image quality panels which were placed in the windscreen frame in a 727-200 flight simulator. The two groups of pilots (eight in one study, six in the other) flew straight-in visual approaches while viewing the CGI visual runway through the distortion panels. Figure 9 shows that a high

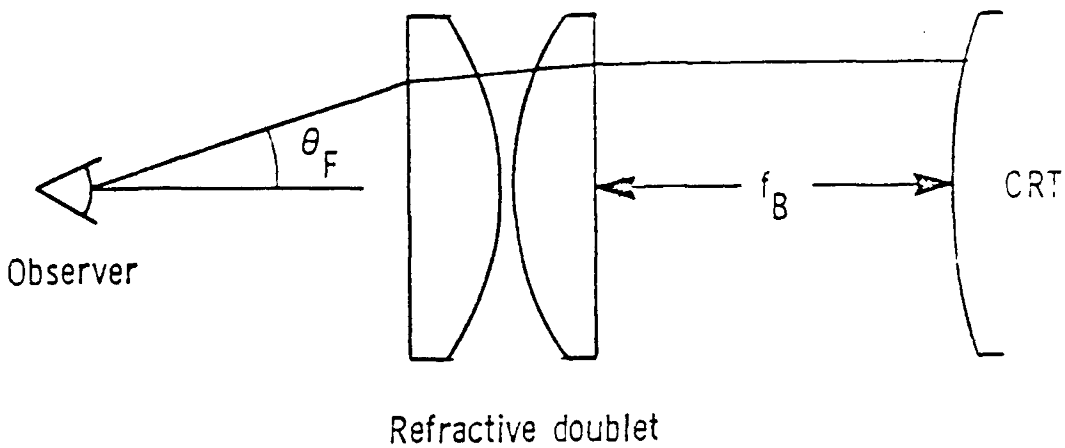


Figure 6. Virtual image systems.
(Kahlbaum, 1977)

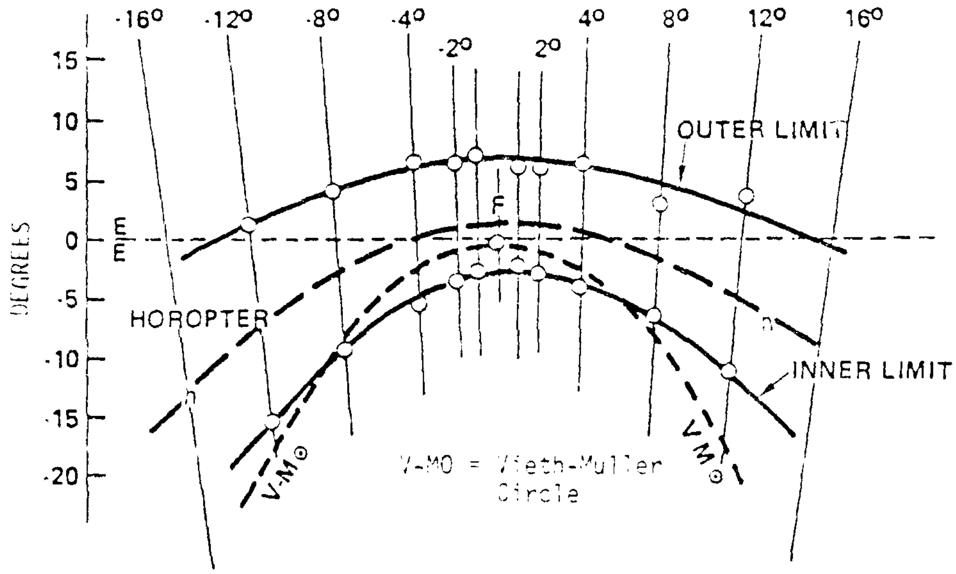


Figure 7. Spatial representation of experimental results showing region of binocular single vision. The observation distance to the fixation point, F, from the eyes was 40-cm. Ordinates are magnified twofold. (Ogle, 1962)

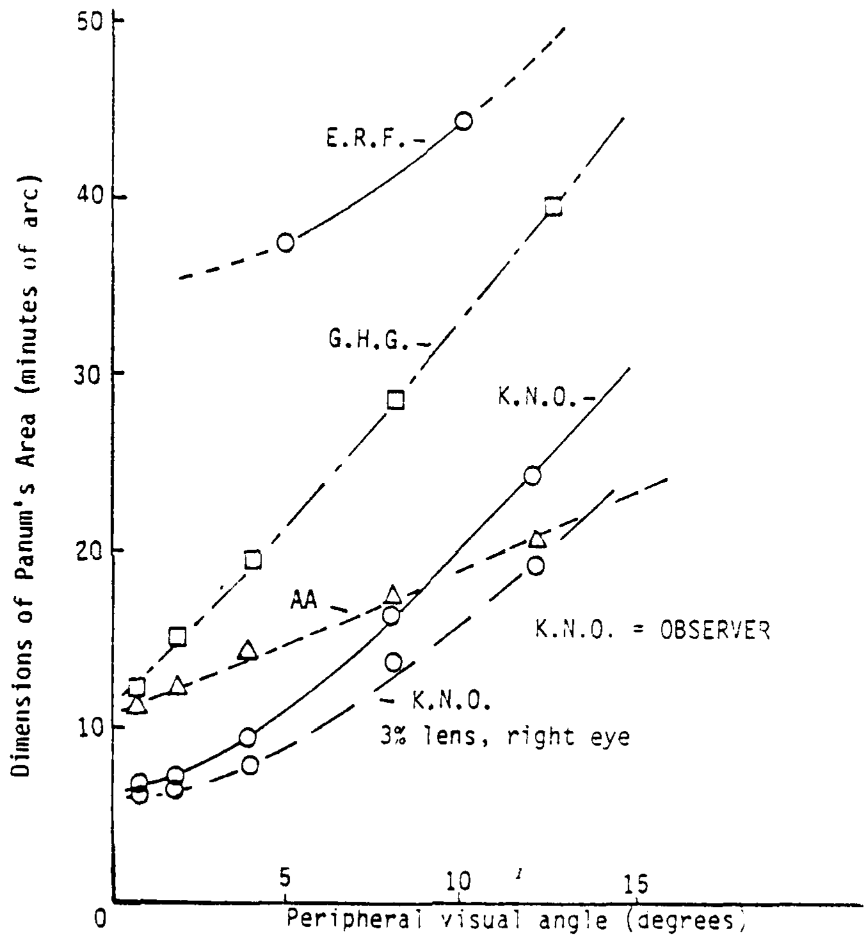


Figure 8. Relationship of magnitude of transverse extent of Panum's fusional areas with peripheral angle for several observers. (Ogle, 1950)

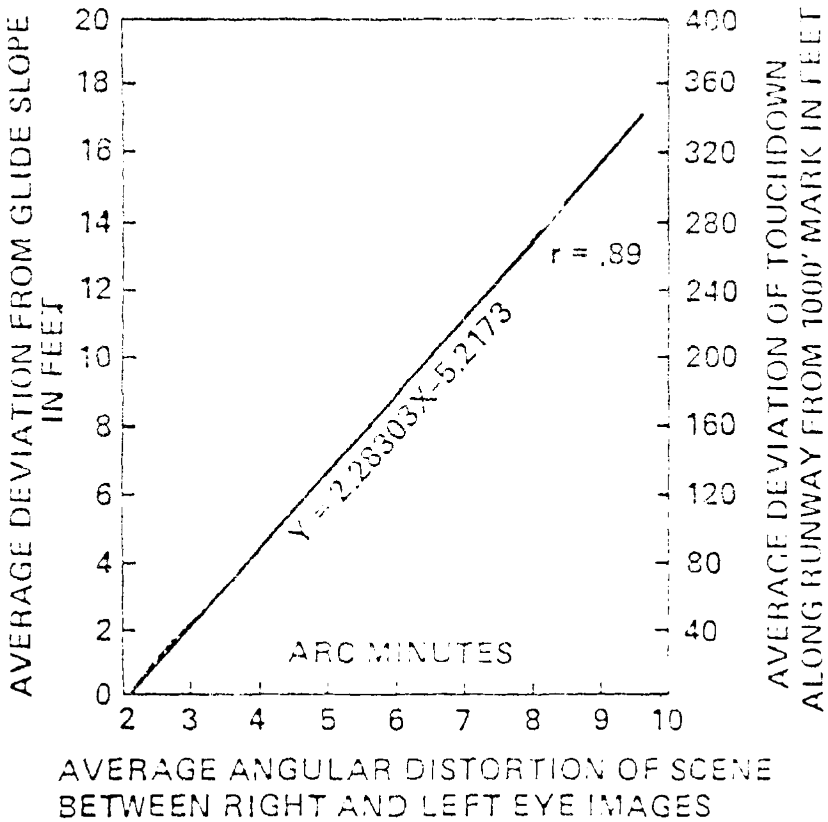


Figure 9. Prediction of pilot performance from a [illegible] measure of optical quality of windshields [illegible] [illegible]worth & Anderson, [illegible]

correlation (.8[illegible]) was found between the average angular binocular distortion [illegible] deviation from the glideslope at touchdown, which is [illegible] with longitudinal deviation from the touchdown mark. The range of average binocular deviations that were found ([illegible] to [illegible] minutes of arc) also tended to correlate with pilot responses on questions of discomfort, image quality, and willingness to fly with the level of distortion in the simulated windscreen. In other studies, involving heads-up display design (Gold & Hyman, 1970; Gold, 1971), a reduction in visual comfort was found to vary widely among subjects. Limits of 3.4 arc minutes diverging disparity and 8.6 arc minutes converging disparity in a binocular reticle were recommended for heads-up display design.

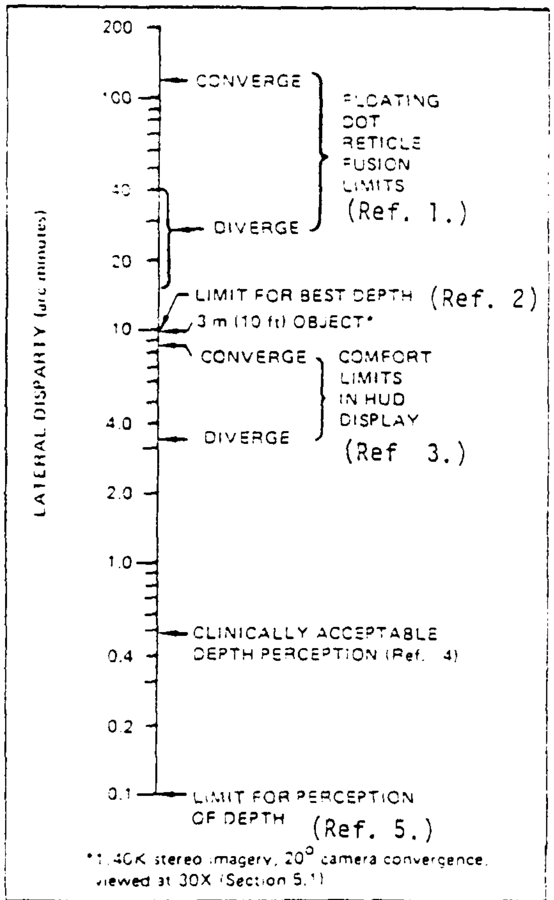
Localized Lateral Disparity

Ogle (1962) reported that as early as 1868, Hering had discovered that stereoscopic depth could be acquired with incomplete binocular fusion. Ogle (1952) also found under some conditions that the retinal disparity could be so large the images would be seen as slightly double, yet stereoscopic depth was still experienced. It should be noted here that horizontal (lateral) disparity is precisely the necessary and sufficient condition for stereopsis; so localized horizontal disparities within [illegible] scene elements that are not constrained by scene continuity, are often seen as displacements in depth. Since the sensitivity to horizontal disparity is 5 seconds of arc or less, small deviations can cause significant errors in perceived depth in images with limited textural continuity. This condition has recently been utilized in the development of a sensitive test of stereoscopic acuity (Farrell & Booth, 1975). As will be seen in a later section (Image Size Differences), more generalized horizontal disparities resulting from lateral magnification differences also produce depth distortion effects characterized by rotation of the fronto-parallel plane about a vertical axis running through the fixation point. These 'stereoscopic' effects can be significant even in a 'non-stereo' display system.

Figure 10 (from Farrell & Booth, 1975) summarizes data from several sources (Farrell, 1975; Ogle, 1952a and 1952b; Gold, 1971; Riccardi, 19[illegible]; Graham, 1965) on the range of lateral disparities that can be utilized for various purposes. These show a detection of 5 seconds of arc for the perception of depth to a fusional tolerance level of around [illegible] arc minutes. Thus, the limits for localized lateral disparities [illegible] upon the complexity or continuity of the scene and upon the [illegible] effects of variations in perceived distance of disparate scene [illegible] elements.

Localized Vertical Disparity

The [illegible] influence of localized vertical disparities can be [illegible] their effect on the ability to discriminate depth. Ogle (19[illegible]) [illegible] a small study (only two subjects were used) in which vertical [illegible] minutes [illegible] the [illegible] Figure 11 [illegible] However, [illegible]



REFERENCES

1. Farrell, 1975
2. Ogle, 1952
3. Gold, 1971
4. Ricciardi, 1966
5. Graham, 1965

Figure 10. Effects of specific lateral disparities.
(Farrell & Booth, 1975)

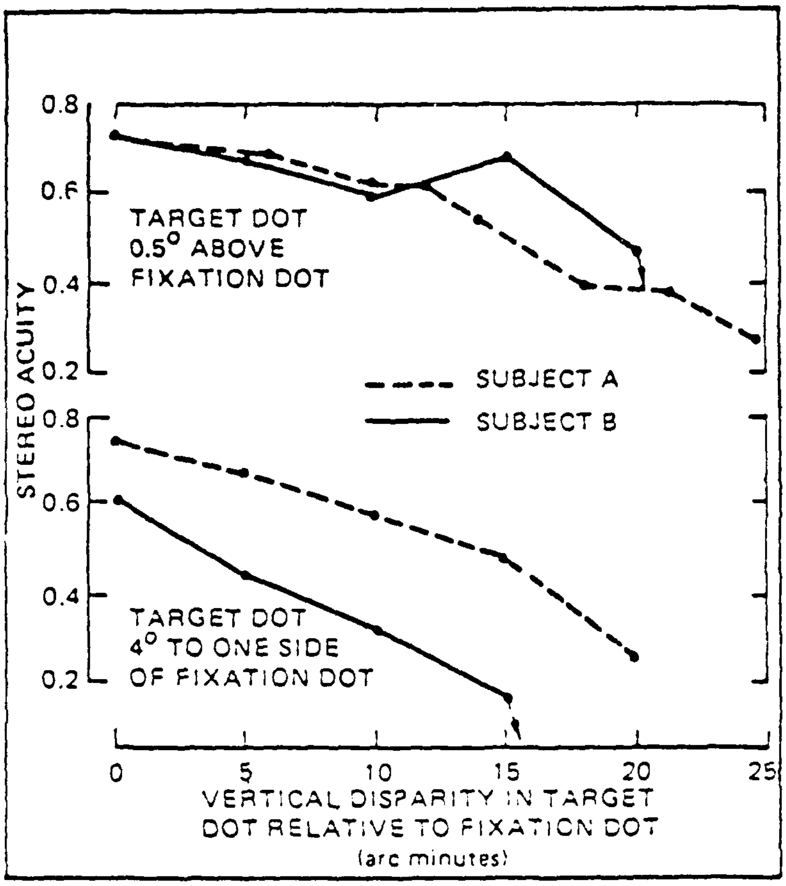


Figure 11. Ability to discriminate depth
(Farrell & Booth, 1975)

recommends a limit for vertical disparity of 17 arc minutes, and Shenker (1972) recommended a tolerance level of 15 arc minutes.

In evaluating the effects of vertical disparities, it is important to note that in normal, natural vision, objects seen at relatively close distances present vertical disparities for all points above or below the visual plane, except those falling in the median plane (Ogle, 1962). That these off-axis disparities do not normally produce bothersome rivalry or diplopia can be attributed, at least partially, to the fact that visual acuity decreases rapidly, and Panum's areas increase with increasing distance of the object point from the fixation point. In Ogle's study of vertical disparities and depth perception, it was observed that the stereoscopic depth perception was maintained even when the disparities were large enough to cause a doubling of the images. Figure 12 (from Farrell & Booth, 1975) presents data from four different experimenters that were summarized by Mitchell (1966). As can be seen, there is considerable variance in the findings for the vertical disparity limits of single vision and in the rate of increase as a function of distance from the fixation point.

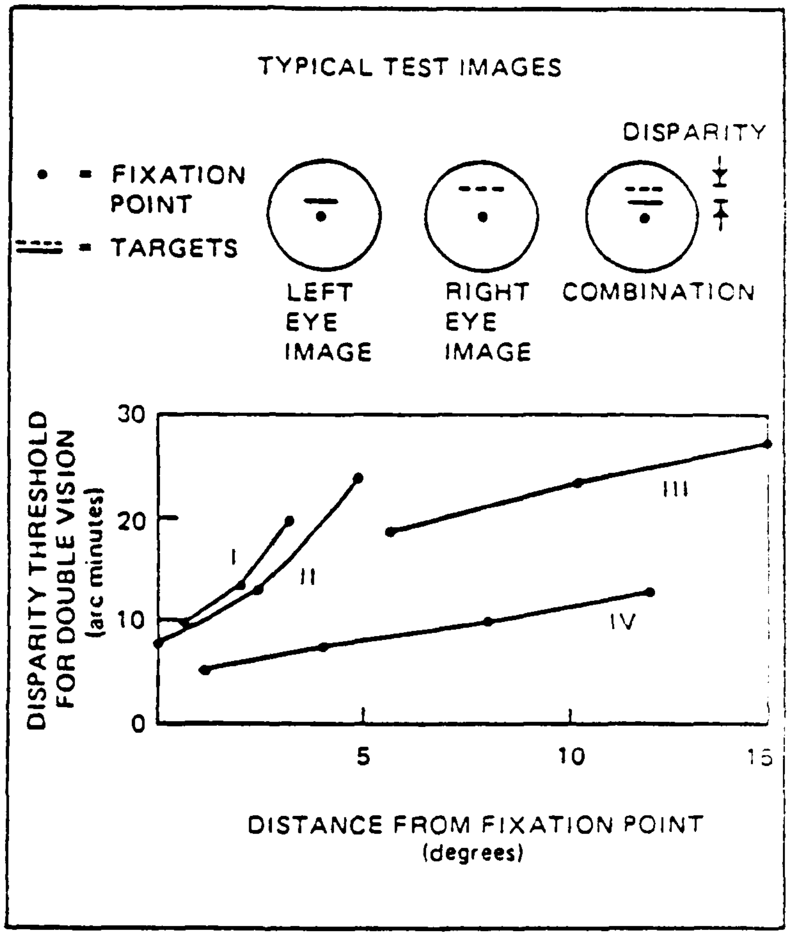
Except for the previously discussed questionnaire data on discomfort with vertical and lateral disparities gathered by Kraft, et al., (1978), Gold (1972) reported the only other data found on comfort levels with vertical disparities. As with diverging lateral disparities, a recommended limit of 3.4 arc minutes was designated for vertical disparities.

Vertical Misalignment

In visual simulator designs, such as the refractive doublet virtual image system, distortions are less likely to produce bothersome disparities in localized areas as they are a more generalized shift in binocular disparity or vergences as the head is displaced horizontally off the primary axis. Using the geometric relationship depicted in Figure 13, Kahlbaum (1977) calculated generalized horizontal and vertical disparities for different lateral head displacements and for various field angles for the refractive doublet and also for a refractive triplet system (Figure 14). The data on lateral disparity will be discussed under the topic "Lateral Vergence/Collimation/Image Distance Error." Kahlbaum's calculated data for overall vertical disparity (Figure 15) indicate increasing disparity with increasing head displacement or with increasing field angle. The maximum head displacement utilized was 3 cm, which resulted in calculated vertical disparities of about 7.5 arc minutes.

For two optimized designs for a wide-angle, multiviewer (viewing volume of 5 x 3 x 1.5 feet) infinity display system for flight simulators, Rhinehart (1977) reported vertical disparity values ranging between ± .23 degree. From the rear corners of the viewing volume, this range increased to ± .32 degree.

The determination of detection thresholds and tolerance levels for vertical misalignment of the images to the two eyes is an unpredictable proposition. This is due, in part, to the fact that in natural viewing



Note: As the results obtained by the four different experimenters, I, II, III, and IV illustrate, there is much disagreement on the rate of increase.

Figure 12. Variation in disparity tolerance with retinal location (Farrell & Booth, 1975)

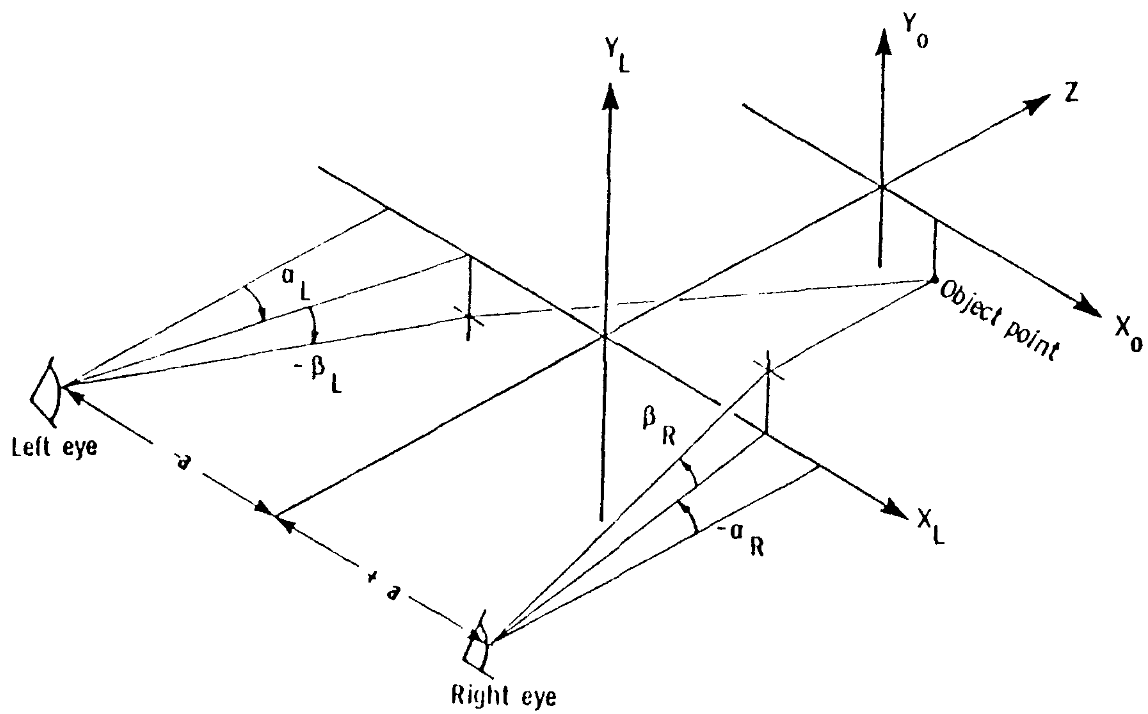


Figure 13. Geometry for measurement of binocular disparity (Kahlbaum, 1977)

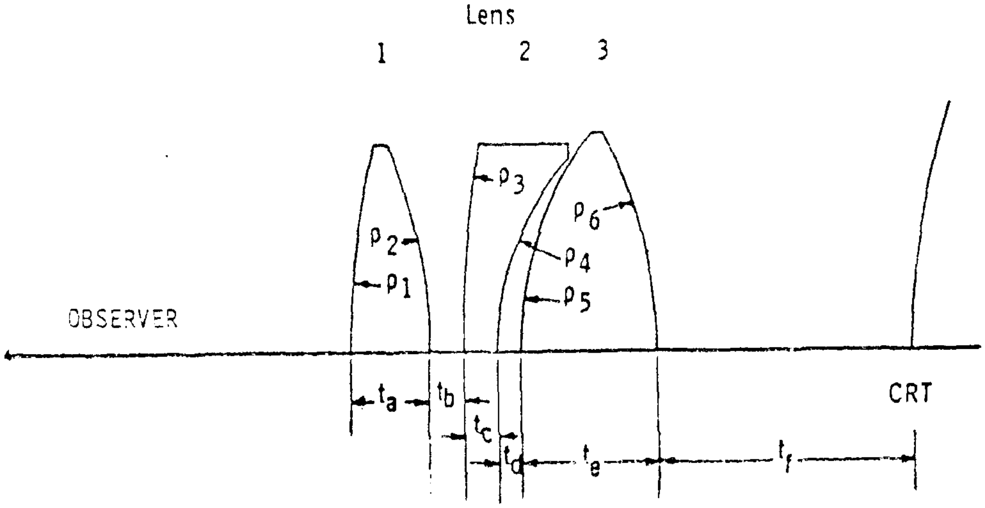


Figure 11. Basic triplet layout.
(Kahlbaum, 1977)

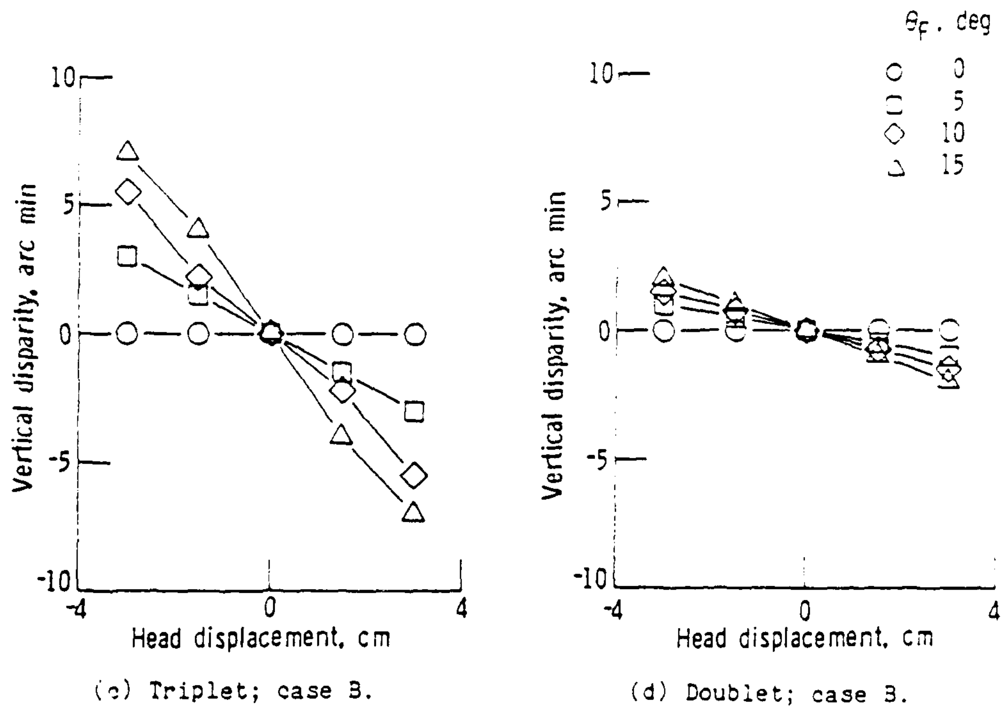


Figure 15. Vertical binocular disparity. (Kahlbaum, 1977)

situations, there normally is no vertical misalignment of the overall images, as compared to the small and variable disparities induced in off-axis portions of the image. It would be predicted, therefore, that the observer would be more sensitive to vertical misalignment than to horizontal misalignments where the convergence/divergence mechanism of the eyes is more or less constantly making adjustments in the interest of fusion and where horizontal disparities are accepted as representing displacements in depth. Support for this proposition is found in the vertical versus horizontal extents of Panum's fusional areas (3 to 4 arc minutes vertical vs. 5 to 6 arc minutes horizontal, as reported in Borish, 1954). Similar data were found by Farrell and Booth (1975) in a preliminary study of the variability in the vertical alignment of a stereo pair of images by six observers. Although absolute alignment errors were not available, individual standard deviations ranging from 3.2 to 7.3 arc minutes were found with an average of 6.0 arc minutes.

Tolerances to vertical misalignment, on the other hand, may be more than an order of magnitude larger than these "detection" thresholds. Crook, Anderson, Bishop, Hanson & Raben (1962) reported that with long adaptation periods and dedicated observers, satisfactory fusion could be maintained with up to 3 degrees of vertical misalignment. Harker and Henderson (1956) reported an unsubstantiated finding of satisfactory vision with up to 1 degree of vertical misalignment. In reports from cases in a refraction clinic (Bureau of Visual Science, 1950), it was reported that blurring or doubling of the image typically occurred in the 34 to 102 arc minute range of dipvergence. It should be noted, however, that in the clinic situation, visual discomfort was often experienced with vertical misalignment values below these levels.

The effect of vertical misalignment on a visual task, in this case a simple relative distance stereo test, was also examined in the study by Harker and Henderson (1956). Figure 16 depicts the relative response time and relative error rate for three levels of vertical misalignment; 0, 17, and 34 minutes of arc. Detrimental effects are shown on both dependent measures for both 17 and 34 arc minutes of vertical misalignment.

It should be noted that vertical misalignment of images is partially compensated for by fusional movements of the eyes (dipvergence) which serve to reduce the misalignment to within fixation disparity limits. The amplitude of fusional movements is dependent upon several factors, among them the complexity of the stimuli, observation time, individual variability, the amount of image misalignment, and the visual field location of the disparate stimuli. The effects of the latter two factors are shown in Figure 17 (from Alpern, 1962). While these fusional movements may tend to reduce the effects of image misalignment on visual performance (acuity, stereo, target detection, etc.), they will increase the probability of observer discomfort, eye strain and fatigue.

<u>Image Rotation Differences</u>

In addition to image misalignment in the horizontal and vertical meridians, it is possible that a combination of these two misalignments may exist that can be described as a rotational misalignment or differ-

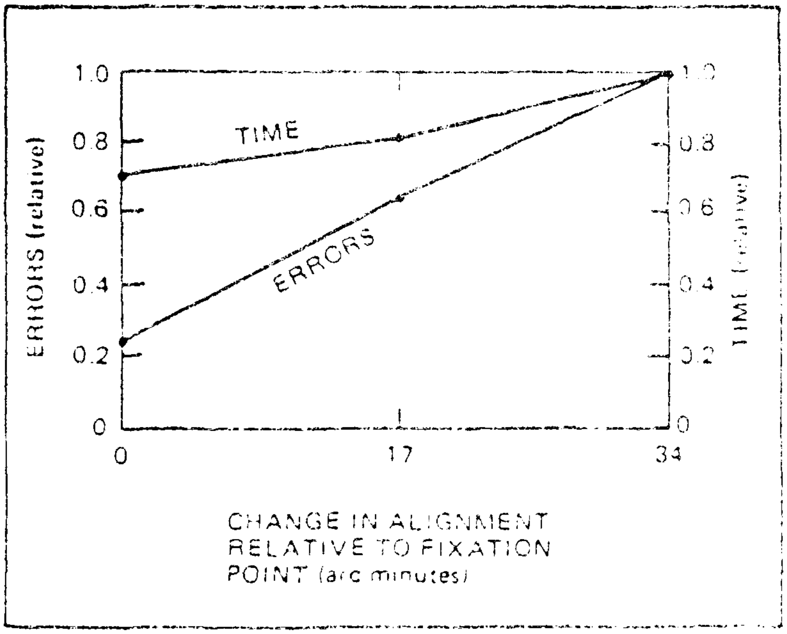


Figure 16. Reduction in vision with alternations in vertical alignment. (Farrell & Booth 1975)

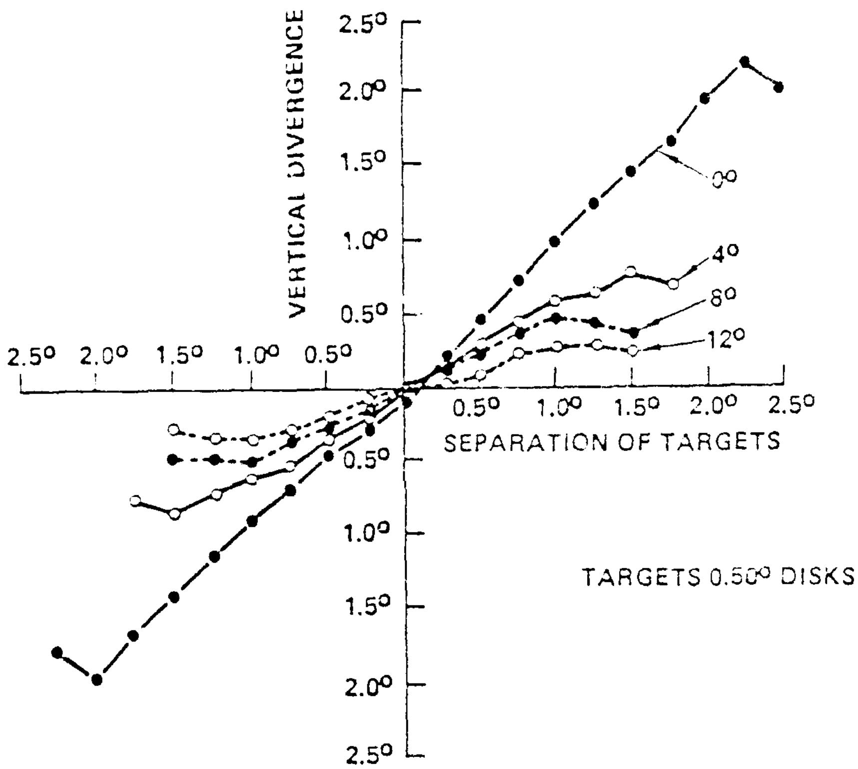


Figure 17. The amplitude of vertical fusional divergence for different amounts of eccentric localized fusional targets according to the measurements of Ellerbrock (1949). On each curve is indicated the elevation of the fixed target above the fixation point. (Alpern, 1962)

ence between the images to the two eyes. Such a rotational difference is not likely to be large enough to be significant in monoscopic, biocular displays, but may occur in binocular systems such as helmet-mounted display systems.

Since rotational misalignment can be broken down into vertical and horizontal components, it is not unreasonable to consider the detection thresholds and tolerance limits for these components to be applicable to rotational misalignment. From this standpoint, and since vertical misalignment is generally more critical in terms of effects on performance, discomfort, and eye strain, it is reasonable to use these values as tentative rotational thresholds and tolerances.

The horizontal component of rotational misalignment should be given special consideration, however, because of a unique relationship not seen in cases of simple vertical or horizontal misalignment. Opposite rotation of the two images about a central fixation point produces horizontal disparities along the vertical meridian in which those displacements above the fixation point are opposite in direction (and in perceived depth) to those below the fixation point. For example, if a thin, vertical bar is rotated clockwise for the right eye and counterclockwise in the image to the left eye, the integrated, fused perception is of a single bar rotated in the third dimension around a horizontal axis through the fixation point or center of rotation, with the top of the bar tilted away and the bottom tilted toward the observer. Figure 18 (from Ellerbrock, 1954) depicts this situation. This tilting of the fronto-parallel plane is most prevalent with a vertical stimulus such as a line or bar and least for a complex scene or series of horizontal bars. For the latter case, the induced disparity is mostly vertical and consequently the eyes tend to cyclorotate in the interest of maintaining fusion. The data depicted in Figure 19 (from Ogle & Ellerbrock, 1946) illustrate the effects of increasing the number of horizontal contours (and therefore vertical disparities) upon the cyclofusional movements of the eyes when an oblique cross is utilized as a stabilizing stimulus. Ogle and Ellerbrock found that under some stimulus conditions, subjects could make very precise cyclofusional "corrections," with standard deviations of less than 5 minutes of arc.

In a study by Kertesz (1973), tolerances to image cyclorotation were measured for a single line versus 50 horizontal lines, and for display field radii from 1 to 5 degrees. The results are depicted in Figure 20 (Study I) along with those (Study II) from an investigation by Kraft (1968). In this second study, observers were asked to eliminate rotational differences in stereo pairs of a depth perception test. The 5th to 95th percentile error range (1.0 to 2.2 degrees) is depicted in the figure. Although the stimuli were considerably different in these two studies, the results can be taken as illustrative of the differences in detection thresholds versus tolerance levels for rotational errors in displayed imagery. In a recent study of the effect of cyclophoria on the pilot's perception of the runway plane (Kraft et al. 1979), it was found that ± 2 degrees of image cyclorotation produced significant changes both in the perceived depth relationship of vertically adjacent disc stimuli and in the estimated approach angle to the runway plane ("above" or "below" glideslope).

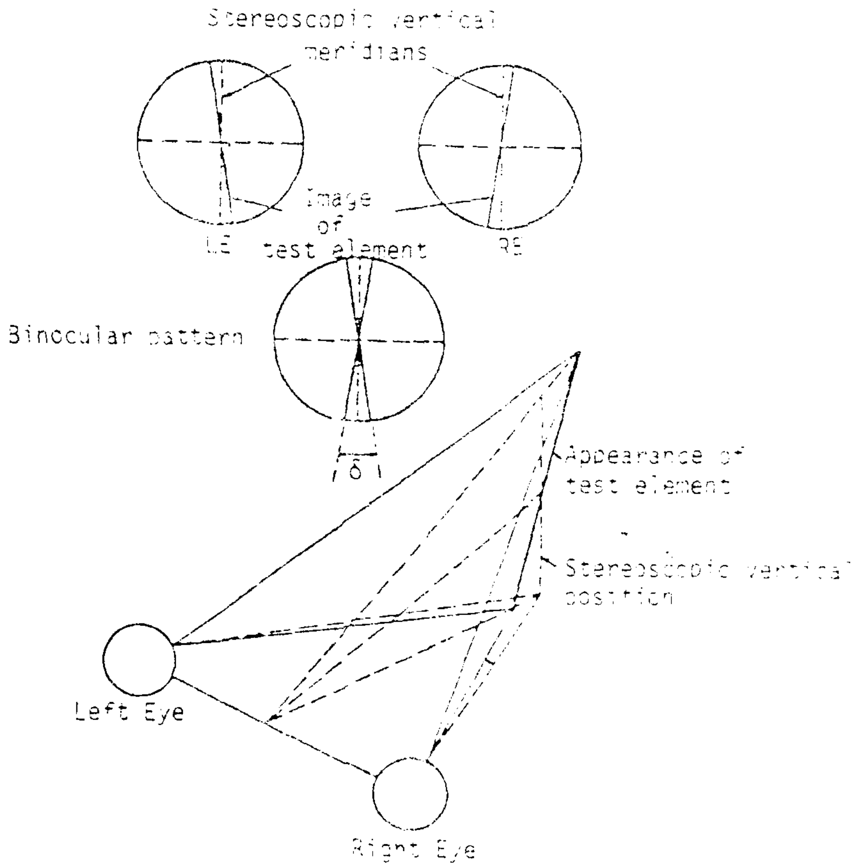


Figure 13. Top: The images of the test element are rotated from the stereoscopic vertical meridians. Bottom: The binocular spatial localization of the test element. (Ellerbrock, 1954)

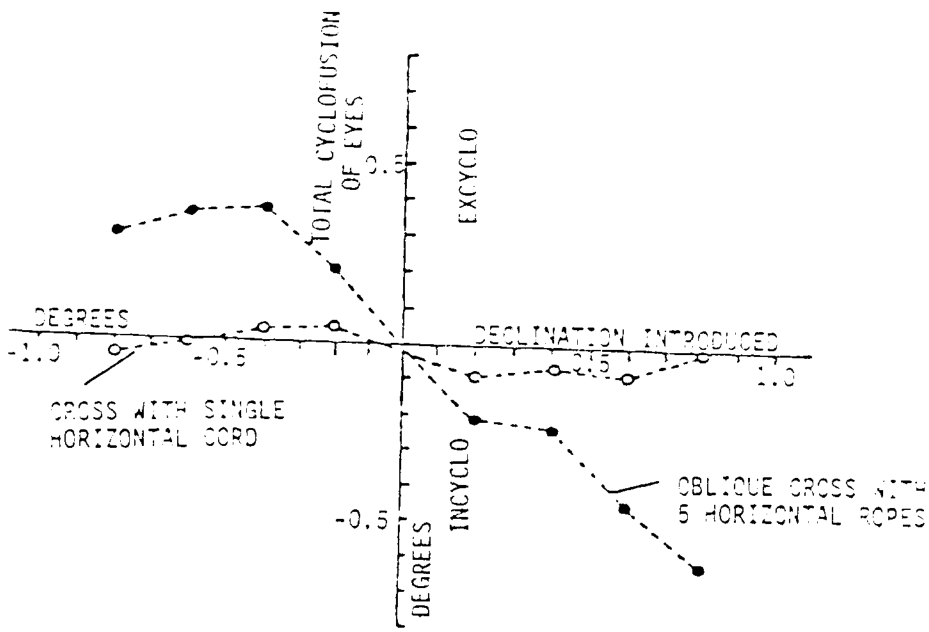
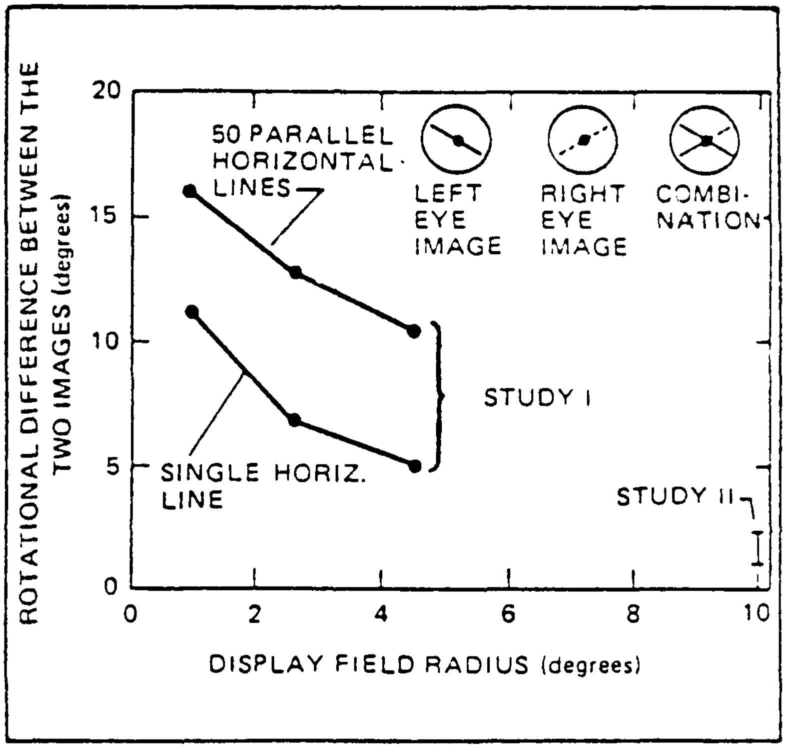


Figure 19. Results which show that only when the number of horizontal contours is increased will the compulsion for a cyclo-fusional movement offset the stabilizing effect of an oblique cross. (Ogle & Ellerbrock, 1946)



Study I: Kertesz, 1973
Study II: Kraft, 1968

Figure 20. Tolerance for image rotation
(Farrell & Booth, 1975)

[illegible] DIFFERENCES (DIFFERENTIAL MAGNIFICATION)

[illegible]seikonia

[illegible] refractive virtual image systems, image size differences between [illegible] may result from geometrical distortions having the basic [illegible]istic depicted in Figure 21 (Kahlbaum, 1977). Of course, [illegible] image size differences (aniseikonia) may also result from a [illegible] difference in the refractive power between the two eyes of the [illegible], but these anomalies are less frequently found in pilot popula- [illegible] due to the visual screening process. This analysis will be con- [illegible] to image size differences and other aniseikonic effects origina- [illegible] the visual simulation system optics, but may also be applicable [illegible] observers with natural aniseikonia or with refractive correction [illegible]es.

Figure 22 presents the findings of Ogle (1950) from a survey of 230 [illegible] and instructor pilots, along with the results reported by Ewalt [illegible] on 100 consecutive patients. Remarkably similar data are shown [illegible] Figure 23 for findings by Burian (1943) on two similar populations. [illegible] data can be compared with those of others: Burian (cited by Duke- [illegible], 1949) found that 33 percent of a student body exhibited measu- [illegible] amounts of aniseikonia with 70 percent of these having up to 1 [illegible] size differences, 23 percent with 1 to 2 percent, and 7 percent [illegible] these having more than 2 percent size differences; Duke-Elder, him- self, estimated that 20 to 30 percent of the population wearing glasses [illegible] a measurable degree of aniseikonia (Borish, 1970). At the [illegible], Alaimo (1954) reported an 85 percent incidence of measurable [illegible]seikonia in 327 cases.

In Kahlbaum's analysis of the refractive triplet, he found as much [illegible] percent magnification differences with 3 cm of lateral head dis- [illegible] and with a horizontal field angle of 15 degrees. The data for [illegible] the doublet and triplet, with both vertical and horizontal field [illegible], are shown in Figure 24. Observations through the refractive [illegible] resulted in no noticeable loss in binocular fusion. Kahlbaum had [illegible]anation for the apparent lack of fusional disturbance as might be [illegible] by the recommended tolerance limit of a 2 percent size differ- [illegible] given in MIL-HDBK-141. It should be noted however, that size [illegible]ences exceeding 5 percent were found only in the case with horizon- [illegible] field angles of 15 degrees.

[illegible]e detection threshold for image size differences has been re- [illegible] by several investigators. LeGrand (1967) indicates that a dis- [illegible] of .25 percent can be appreciated by some observers. A detection [illegible] of about .25 percent was also reported by several others: von [illegible] (1909), Fischer (1924), Tschermak (1924), Herzau (1929), and Ames, [illegible] and Ogle (1932).

[illegible]e-Elder and Abrams (1970) report that a size difference of one [illegible] generally caused visual problems in the refraction clinic, and [illegible] considered as the level where significant symptoms or effects [illegible] At least two design handbooks, MIL-HDBK-141 (1962) and Specifi-

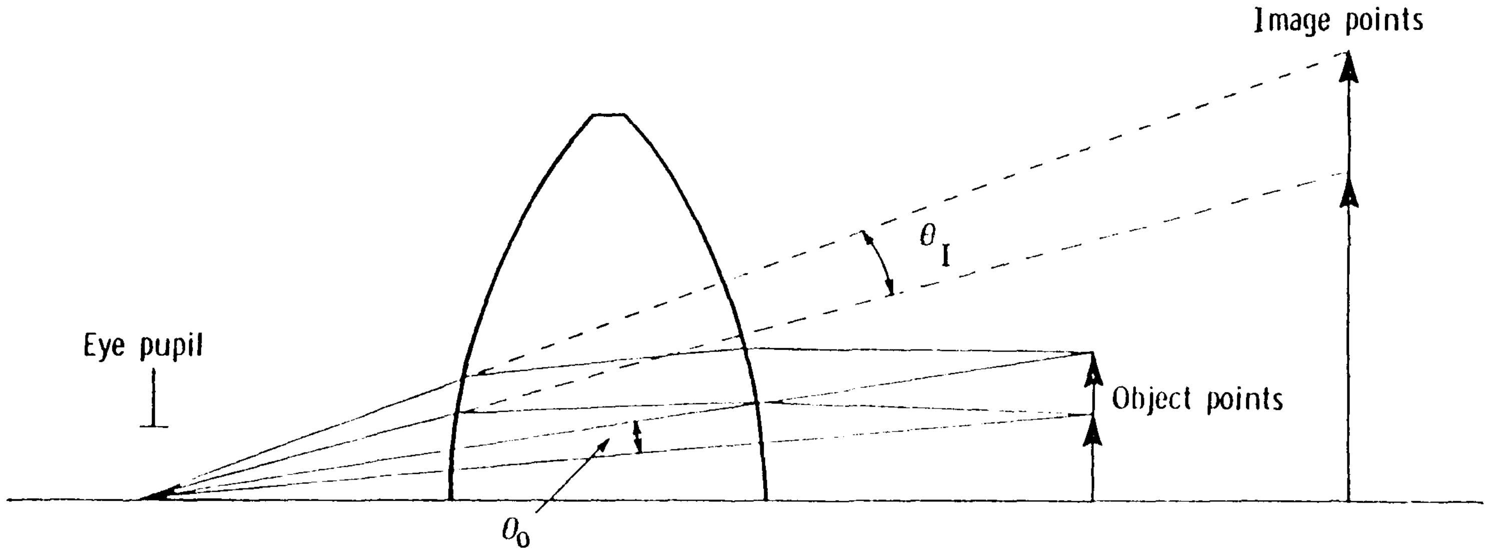


Figure 21. Geometrical definition of angular magnification (Kahlbaum, 1977)

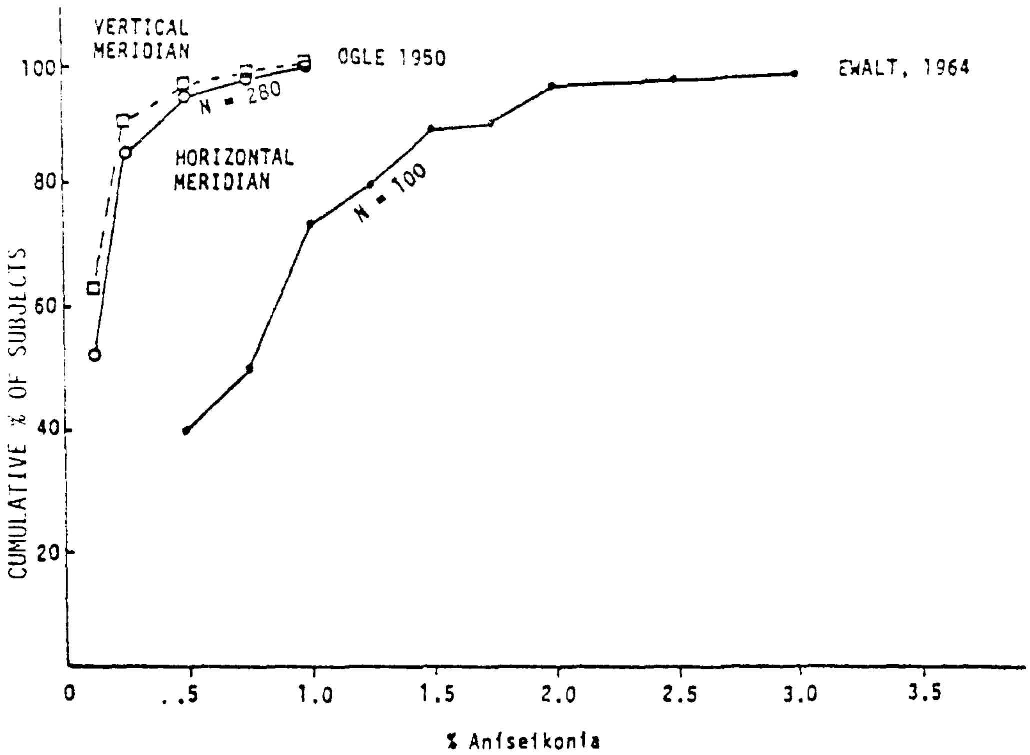


Figure 22. Image size differences.
(Ogle, 1950)

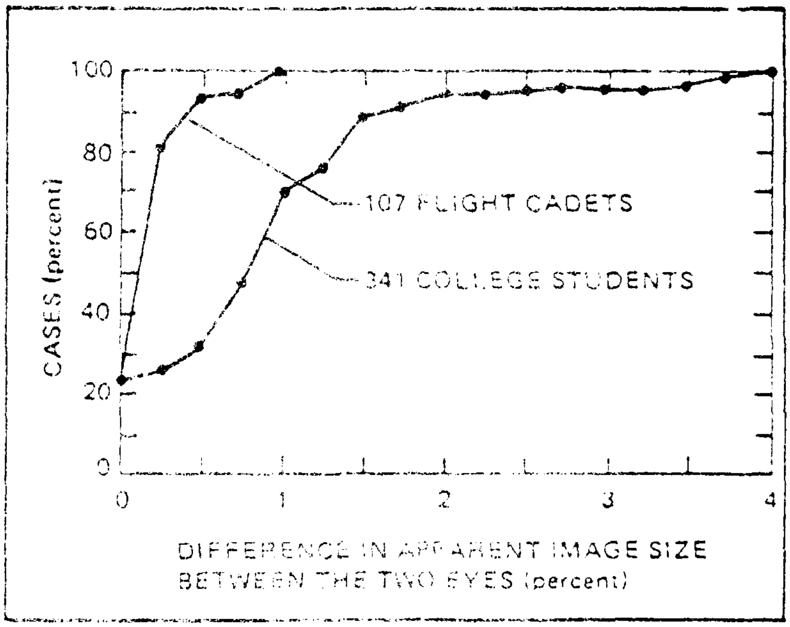


Figure 23. Normally occurring image size differences.
(Farrell & Booth, 1975)

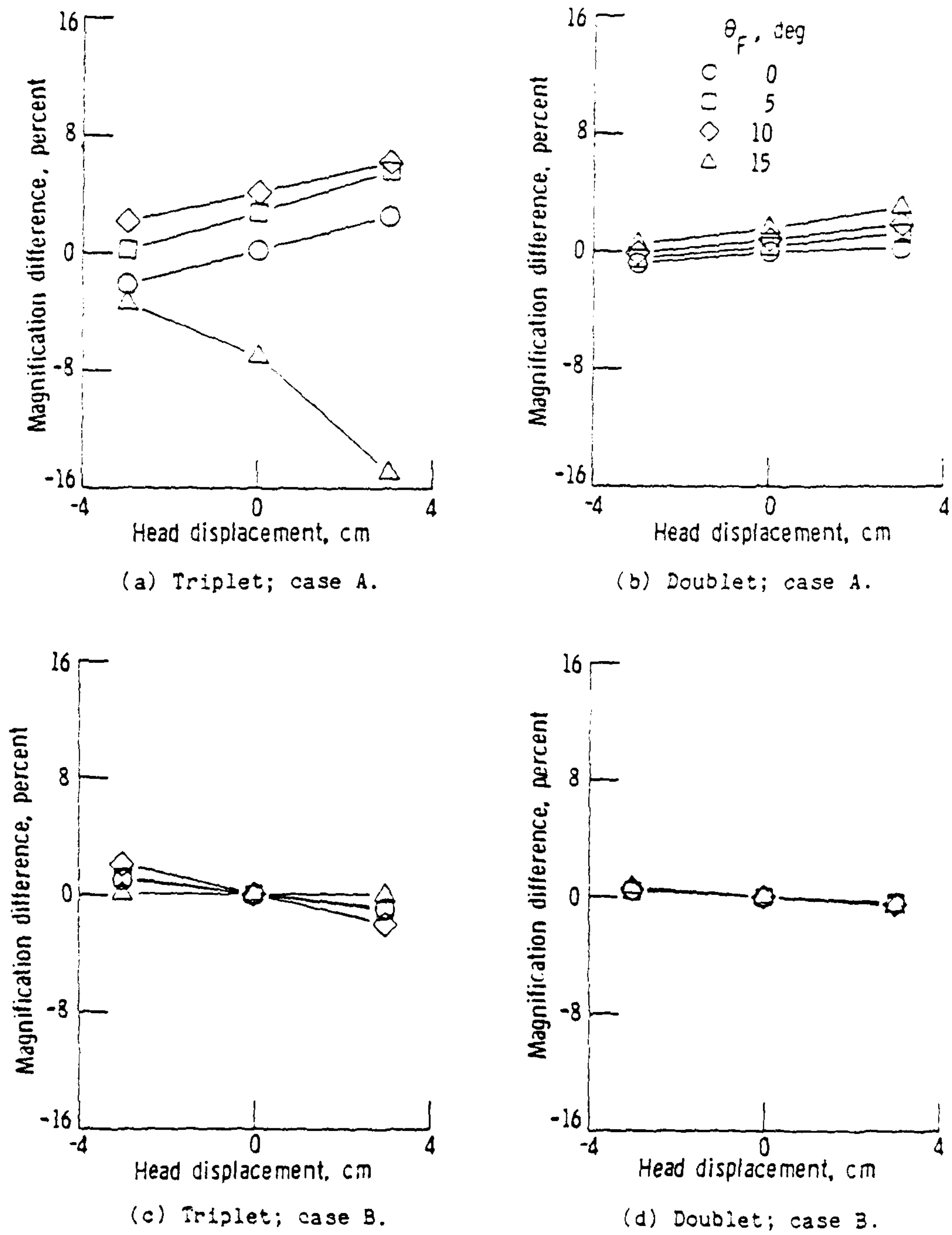


Figure 24. Binocular magnification differences (Kahlbaum, 1977)

cations for Mirror Stereoscopes by S. A. Hempenius (1962) also recommend a limit of 1 to 2 percent image size difference for various optical instruments.

Image size differences smaller than 1 percent may cause discomfort and affect performance. Enoch (1975) reported that levels of .25 to .50 percent caused visual discomfort and constant variable errors in a contour mapping task performed by photogrammetrists, although Richards (1962) reported consistent visual strain likely only at levels exceeding 1 to 2 percent. Puig (1973) recommended a tolerance limit of two percent after reviewing some of the above mentioned reports.

With the space eikonometer developed by Ames (1945), Ogle and Ellerbrock (1945) report sensitivities (standard deviations) to image size differences of .05 percent for the horizontal meridian and .07 percent for the vertical meridian.

Tolerance levels for magnification differences can be related to the limitations on vertical misalignment as developed earlier. Figure 25 (from Farrell & Booth, 1975) provides the transformation of 5, 10, and 20 arc minutes of vertical misalignment (My) to image size differences as a function of the image field size around the fixation point. It can be seen that a vertical misalignment tolerance of 10 arc minutes and a critical field size (radius) of 20 degrees would translate into a size difference of about .8 percent.

Anamorphic Magnification

When differential magnification is primarily in the horizontal meridian (anamorphic magnification), a distortion of the fronto-parallel plane is observed in which the plane is perceived as rotated around a vertical axis which runs through the fixation point. Figure 26 (from Duke-Elder & Abrams, 1970) illustrates this rotational distortion for a right-eye image size larger than that of the left eye (the geometric relationships have been condensed by illustrating simply two different image plane extents, AB and A'B'). For the relative horizontal magnification in the right eye (as diagrammed), the right-hand portion of the image plane is seen as displaced farther away and enlarged, and the left-hand portion as displaced nearer and relatively smaller. The geometric explanation for this perception is shown by the image points "C" and "D" which represent the object points in space necessary to produce these visual angle relationships for the two eyes under normal, non-aniseikonic conditions. The plane "CD" therefore represents the perceived image plane under horizontal aniseikonia.

It is known that this type of meridional distortion attenuates stereo acuity performance (Kraft, 1972 & Kraft, Anderson, Elworth & Larry, 1977). It would seem reasonable to hypothesize that target detection and motion detection thresholds would also be affected; but the rationale is less certain, as the effect on stereo acuity may be partially due to the rotation of the perceived image plane rather than to non-correspondence of image contours. However, evidence against this possibility is found in the results of the studies by Kraft (1972) and Kraft et al. (1977). Before reviewing these findings, it is appropriate to develop the relationship of meridional aniseikonia to overall magnification of the image to one eye.

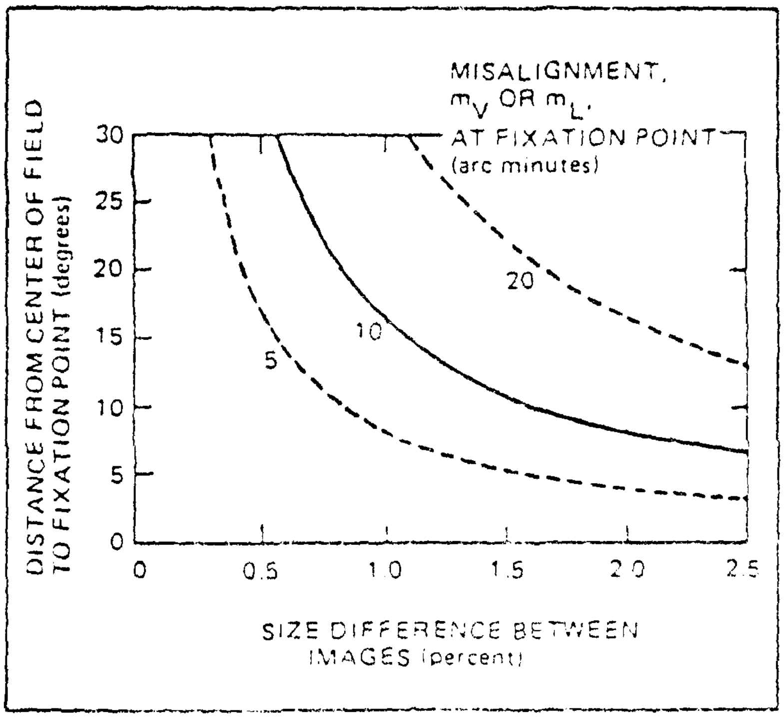


Figure 23. Conversion of image size differences to linear misalignment. (Farrell & Booth, 1975)

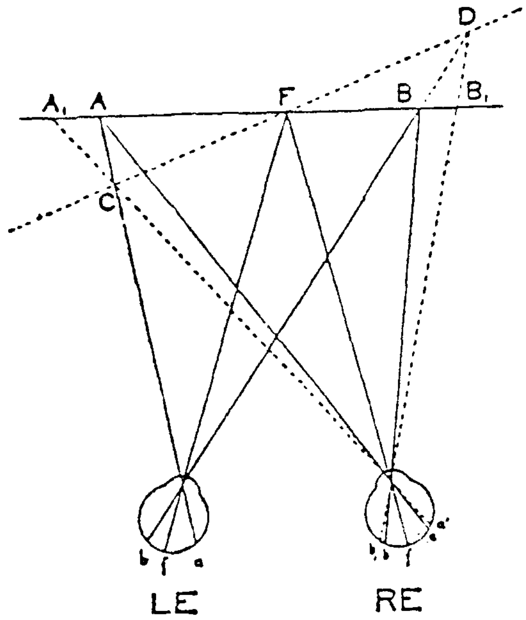


Figure 26. Geometric illustration of perceived spatial distortion of image plane with horizontal aniseikonia (from Ogle, In The Eye, H.Davson, Ed., 1962, as reprinted from Duke-Elder, 1970)

As noted earlier, the perceived rotation of the image plane under horizontal aniseikonia can be predicted by geometrical relationships, and Ogle and Boeder (1948) referred to this as the "geometric effect." Vertical meridional magnification, however, results in an effect on perception that is not as easily explained geometrically, and Ogle (1938) referred to this as the "induced effect." The perceptual effect in vertical aniseikonia is remarkable in that it also is an apparent rotation of the image plane about a vertical axis through the fixation point. However, the direction of image plane distortion is reversed, as if a horizontal magnification had been induced in the other eye.

Figure 27 presents data from four subjects on horizontal versus vertical magnification effects. As can be seen, the induced effect is similar, but opposite in direction, to the geometrical effect up to about 2 percent magnification, at which point the induced effect tends toward a limiting value and then is reduced as differential magnification continues to increase. In a detailed analysis of the induced effect, Ogle (1962) concluded that a psychological compensation mechanism was most likely responsible for this unique phenomenon.

One significant aspect of the induced and geometrical effects for vertical and horizontal aniseikonia can be seen in their relationship to overall or omni-meridional magnification of the image to one eye. These effects would predict that the combination of horizontal and vertical magnification in the same image should produce offsetting or nullifying effects, i.e., rotations in opposite directions which would cancel each other. This does indeed appear to be what happens, since overall aniseikonia results in very little distortion of the image plane.

It might be erroneously concluded that overall aniseikonia would result in little, if any, decrement in stereo acuity. In fact, such is not the case, as the following studies show.

Stereoscopic Discrimination and Aniseikonia

For a non-pilot population working on a stereoscopic discrimination task, an overall differential size of the retinal image attenuated performance significantly (Kraft, 1972). The effect of the right eye having a 2 percent larger retinal image than the left eye lowered the performance of eight observers viewing stereoscopic slides in a binocular microscope. The average score for this group of observers, with no size differences, was equivalent to the 82 percentile of a normal population. With differential sizes on the retina, their average score was lowered to the equivalent of the 65th percentile, a difference of 17 percentiles. However, the effect of having a differential magnification in which the image was expanded along one, instead of all meridians, did not significantly affect the overall stereoscopic skill of the observers. These results were common when the meridian expansions were horizontal vs. vertical, or 45 degrees vs. 225 degrees (see conditions 3 and 4 of Figure 22).

The discomfort ratings by these eight individuals indicated that all conditions of differential retinal size gave discomfort. The eight subjects were asked to rank the three trials in each session as to which

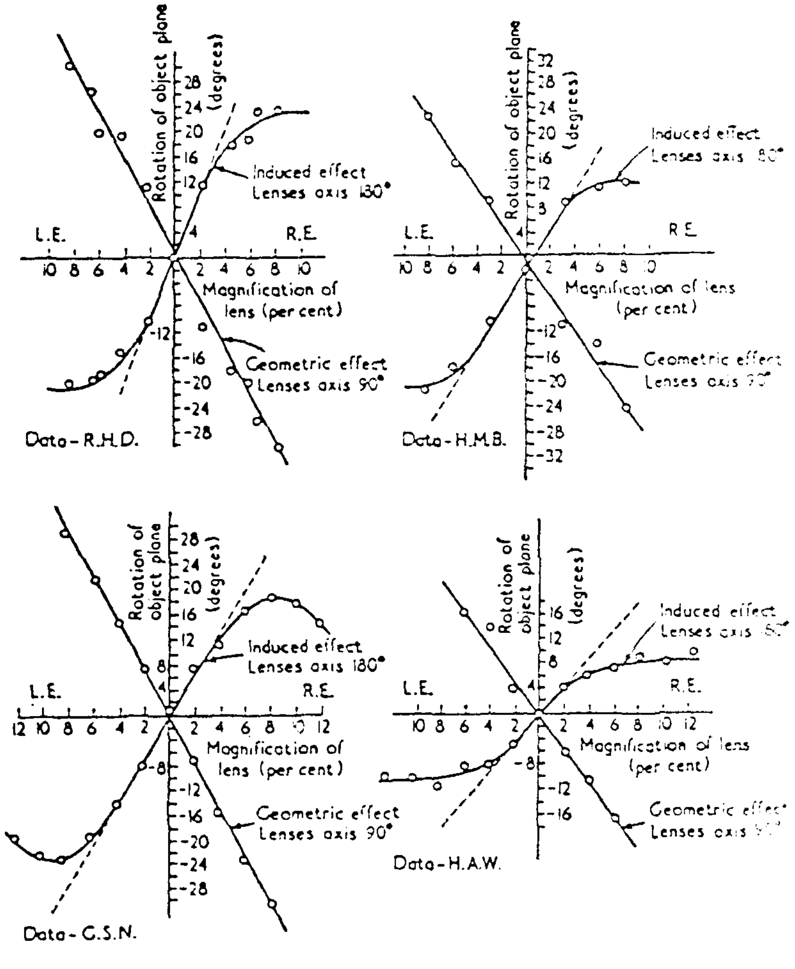


Figure 27. Typical data obtained with tilting plane for geometrical (magnification horizontal) and induced (magnification vertical) effects. Observation distance was 40 cm. (From Ogle: In The Eye, H. Davson, Ed., 1962).

conditions provided the greatest discomfort (1.0) to the least discomfort (3.0). The procedures provided eight ratings for the 'training' condition and sixteen ratings were given for each of the experimental conditions. The results are seen in Figure 28. Six of the eight subjects experienced marked discomfort. Two of the six experienced near nausea during their first session, and two suffered only mild discomfort. Symptoms were described as "eye pull," burning, watering of the eyes, and sustained headache. There was some decrease in the discomfort as a function of experience with the size lenses. The indication here is that the aniseikonic variable of overall size change versus meridional size change may influence the visual performance of a stereoscopic task differently than would be predicted from the reporting of apparent distortions or discomfort.

These results were used in developing the specifications for the visual displays used in the Boeing flight training simulators. Within the eye reference envelope ($\pm$ 2.25" lateral, $\pm$ 3.3" vertical and $\pm$ 3.3" longitudinal space), the right and left eye image do not differ by greater than 1.0 percent in size. The visual system has been in operation now for 3 years and no complaints have been received about headaches or other discomfort, and no perceived distortions have been reported by instructors or trainees. The operational experience therefore supports the use of the 1.0 percent aniseikonia limit based on the preliminary experimental study.

Effect of Magnification Distortions in Windscreens

In an experimental study designed to ascertain the influence of magnification errors in windscreens, a similar study was undertaken but without the use of size lenses (Kraft, Anderson, Elworth, & Larry, 1977). The objective was to determine whether differential magnification would alter visual stereoscopic performance. A Critical Limen Stereo Test was made with incremental size differences between the right and left members of the paired stimuli. Two stereoscopic pairs at each of four levels of size difference were made; pairs A and B were printed so that there was zero difference between the two images; pairs C and D had 1.7 percent increase of one image over the other, pairs G and H had 3.6 percent, and pairs E and F had 7.6 percent size differences.

For each of the four stereoscopic pairs, the threshold was calculated as a function of the mean size increase. The results indicated that, for a group of six pilots, the average threshold with equal-sized images was 8.2 arc seconds, while a 1.7 percent difference in size increased the threshold to 11.9 arc seconds. For the 3.6 percent size difference, the threshold was 10.6 arc seconds. The 7.6 percent size change raised the threshold to 29.3 arc seconds. This 3.6 times increase in threshold with a magnification difference between the two eyes of 7.6 percent raised the threshold almost to the USAF pilot acceptance threshold of 32 arc seconds. If windscreen standards allowed an 8 percent difference in magnification between any horizontally separated (2.0 to 2.5 inches) areas of the windscreen, a differential magnification between the pilot's right and left eyes would occur which should impose stereoscopic performance changes equivalent to that found in this study (Figure 29).

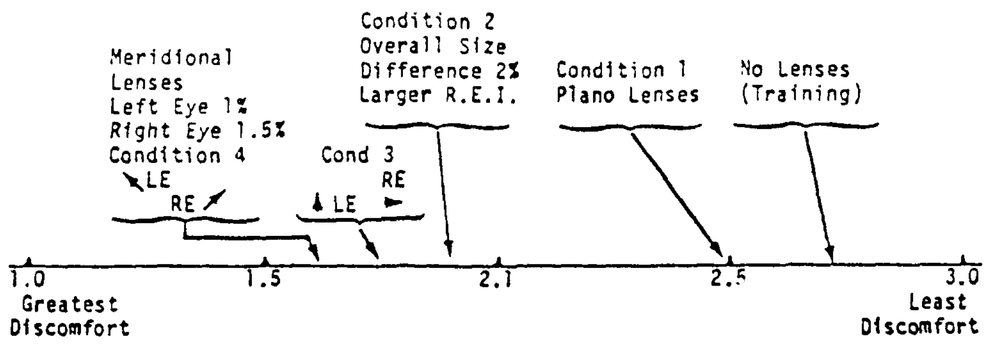
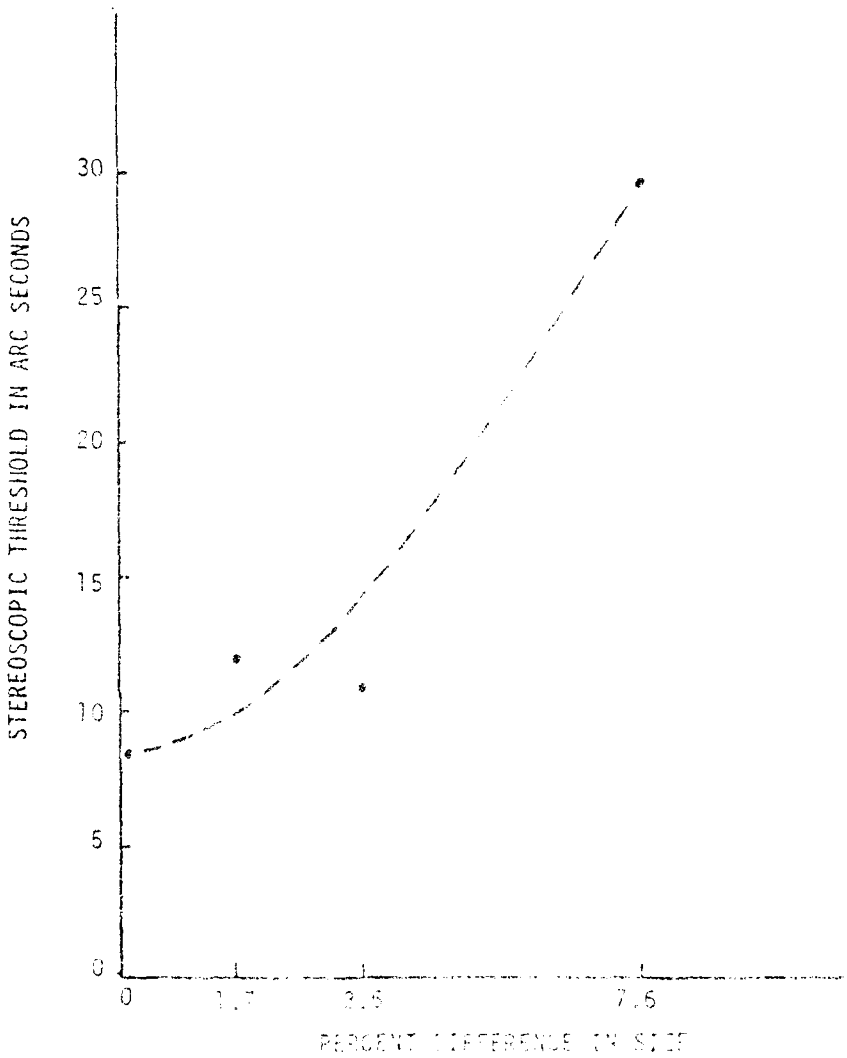


Figure 28. Scale of mean rankings as to visual discomfort. (Kraft, 1972)



[illegible] Effect [illegible] sizes [illegible]
[illegible]

Another way of assessing the effect of this magnification is to convert these results into percentiles. The pilots performed on the zero size difference at the equivalent of the 94th percentile (equal to or better than 94 percent of the young college population). With the 1.7 percent change in image size, the percentile drops to the 53rd. With the 3.6 percent change in size, the percentile increases slightly to the 57th. With the 7.6 percent size change, the same pilots could discriminate depth better than only the lower fifth of the college population (20th percentile).

The influence of the 1.7 percent change in image size for these pilots imposed a 41 percentile decrease in their performance. This larger change, compared with 17 for the non-pilots, may have its explanation in the differences between these studies. It is therefore not advisable to attribute these results solely to differences between the non-pilot and pilot populations. The non-pilots were highly practiced visual observers, such as photointerpreters, and photogrammetrists. The non-pilots used very small photographic reproductions of the imagery and size lenses to impose the different image sizes. The display device was a microscope set for 15x magnification. Comparatively, the pilots had some infrequent experience with stereoscopic tests, used a Troposcope with 1.25x magnification and larger photographic reproductions of the stimulus materials. The size differences were incorporated into the photographic images and the number of trials were one-fourth as many as the non-pilots made. The inclusion of data pertaining to the influence of windscreens on pilot performance is particularly germane in that, for the F-111, the compound curved windscreen with a 68-degree inclination is part of the display system in this aircraft's simulator.

There are two ways in which effects of horizontal aniseikonia may be especially relevant to flight simulation and for which no direct data have been uncovered. These are represented by the following questions:

1. How does this type of image plane distortion affect the detection threshold for an approaching object (aircraft)?

2. How does the rotational distortion of the image plane affect the recognition of the direction of travel of a detected moving object (aircraft)?

These two questions form the basis for the design of the experimental study of horizontal aniseikonia contained in the Experimental Designs section in Appendixes C to I.

BINOCULAR IMAGE DISTORTION AND ASTIGMATISM DIFFERENCES

Accommodation error, astigmatism and other lensatic aberrations have perceptual effects which are of concern in establishing visual system design criteria. In this section, however, the discussion will be centered upon the effects of differences in the amount or distribution of distortions, collimation error, astigmatism, etc. suffered by the images to the two eyes. In Kahlbaum's (1977) calculation of astigmatism and image distortion, he noted that, when considering the positions of the two eyes of the observer and allowing for head displacement, the rays of the tangential fan have a sagittal component and vice versa for the sagittal fan. The geometric relationships in Figure 30 were used by Kahlbaum in calculating image distance and astigmatism. This complex astigmatic interrelationship will produce general and variable degrading of image quality in perhaps unpredictable amounts. It would seem reasonable, however, that the resulting effect would consist of levels of refractive error less than those calculated for simple astigmatism in the same system. Errors in excess of Kahlbaum's chosen tolerance of 0.20 were found for eye positions beyond ± 6 cm; however, subjectively satisfactory binocular images were achieved. If this effect can be generalized to most or all systems, then it would be reasonable to base criteria for complex and differential astigmatism on those for simple astigmatism. In Figure 31, the equivalent refractive power for the tangential (T) and sagittal (S) and one half the distance between these two planes, i.e., the image surface (P), are plotted at different eye displacements for a typical refractive system. It can be seen that the two eyes may be subjected to considerably different levels of astigmatism.

Similar binocular differences may be found for other distortions or aberrations. The geometry for collimation error shown in Figure 32 and for spherical aberration shown in Figure 33 (Horton, Emerick, & Mount, 1969) is for a reflective (spherical mirror) infinity display system, and shows the increasing convergence of rays as a function of distance from the principal axis. The magnitude of such errors in the design of a large, wide-angle, multiviewer infinity display system were calculated by Rhinehart (1977) and are shown in Figure 34. Again wide variations are found, in this case as a function of viewing direction.

When collimation errors or aberration effects are of the same magnitude and direction for the two eyes, the perception is often one of distortion or displacement of the image. When "significant" differences exist, however, blurring of the image is not an unusual perceptual effect. Also, the supposition that the perceptual effects (and hence detection and tolerance levels) for such conditions may be assumed to follow the type, direction, and degree of effects for simpler more uniform distortions can be shown to be untenable.

In a proposal for the development of visual inspection techniques for the evaluation of distortions in aircraft windshields (Boeing Aerospace Company, 1977), Kraft and Anderson photographed a resolution target matrix through two portions (2.5 inches apart) of a simulated distorted windshield. These represented the images for the two eyes from the pilot's position and are shown in Figure 35. The distortions are evident (note that areas blurred in one image are often clear in the other) and one might assume that the fused image would be generally of poor quality. This however, is not at all the case, for when fused, the perceived image is of generally high quality - strikingly so in fact. This ability of the visual system to select out the high quality portions of the two images when forming the composite scene might if generalizable to other distortions, aberrations, etc. lead to a failure on the part of pilots or other observers to detect and/or report distortions in visual simulation displays that are obviously supra-threshold if viewed monocularly.

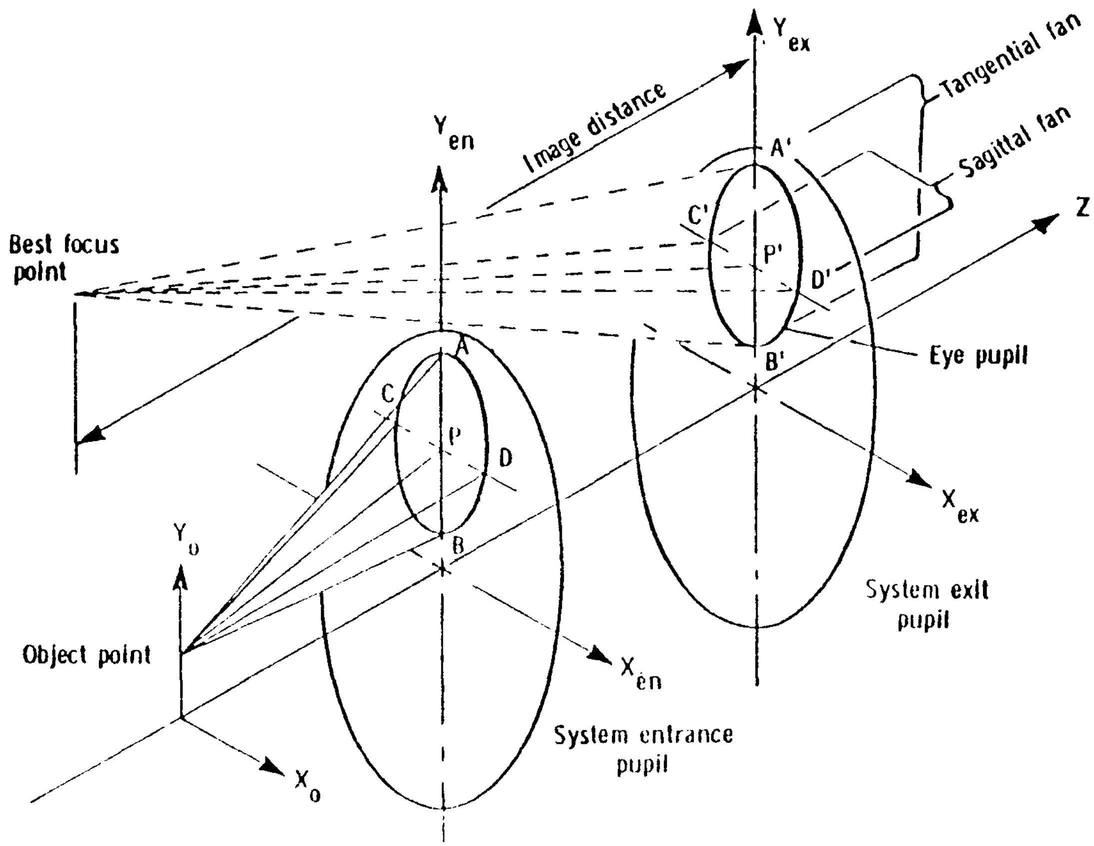


Image distance
Tangential fan
Sagittal fan
Best focus point
Eye pupil
System exit pupil
System entrance pupil
Object point
Z
A
B
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D
P
A'
B'
C'
D'
P'

Y_{en}
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X_{en}
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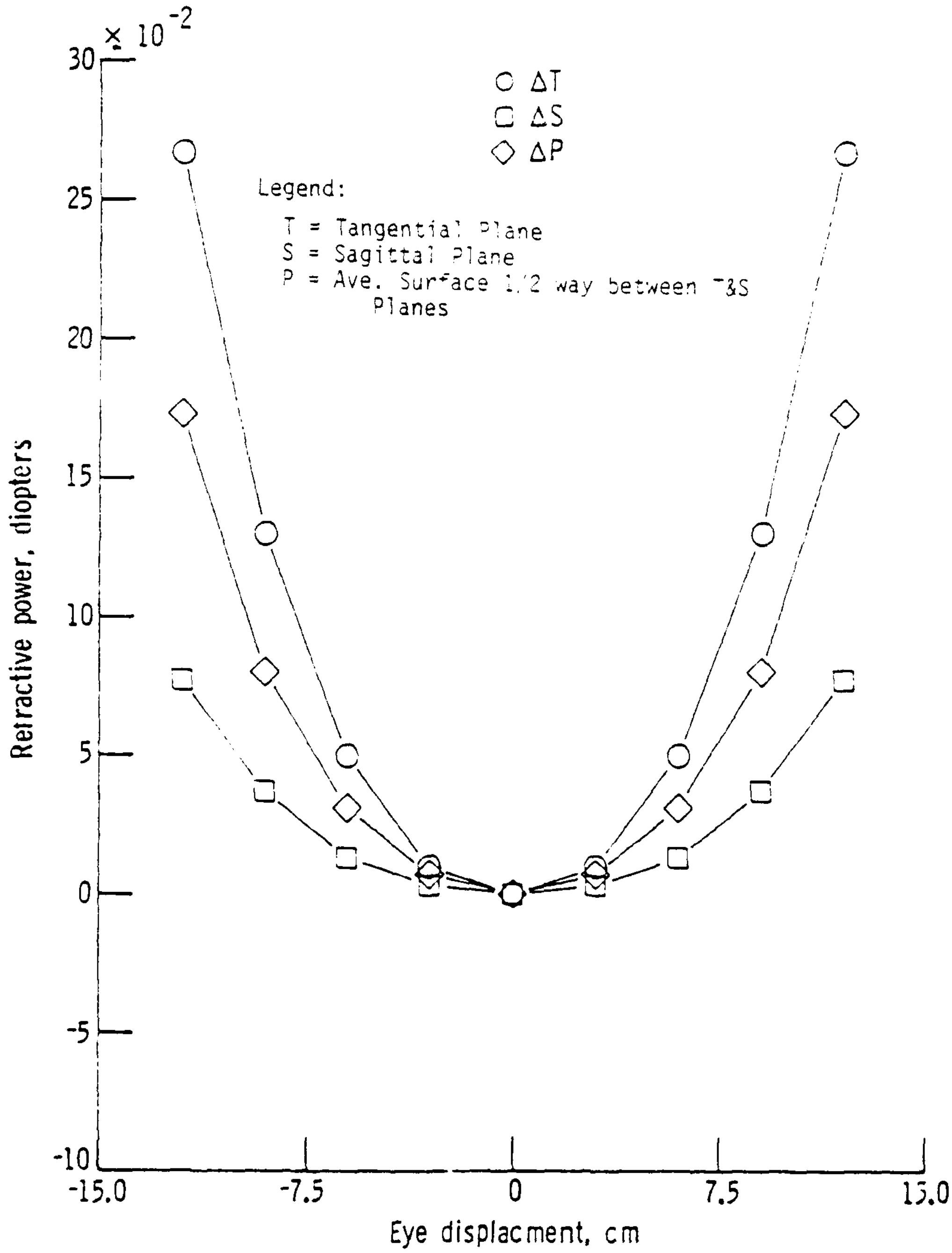

Figure 31. Typical plot of ΔT, ΔS, and ΔP. (Kahlbaum, 1977)

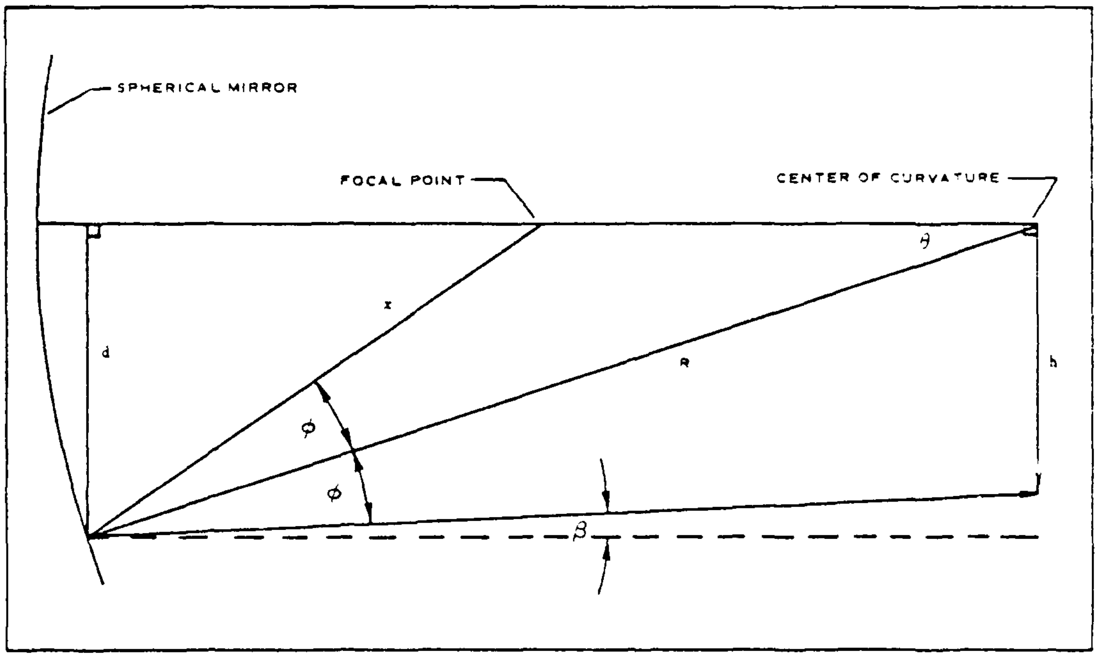

Figure 32. Departure of ray from collimation.
(Horton, Emerick & Mount, 1969)

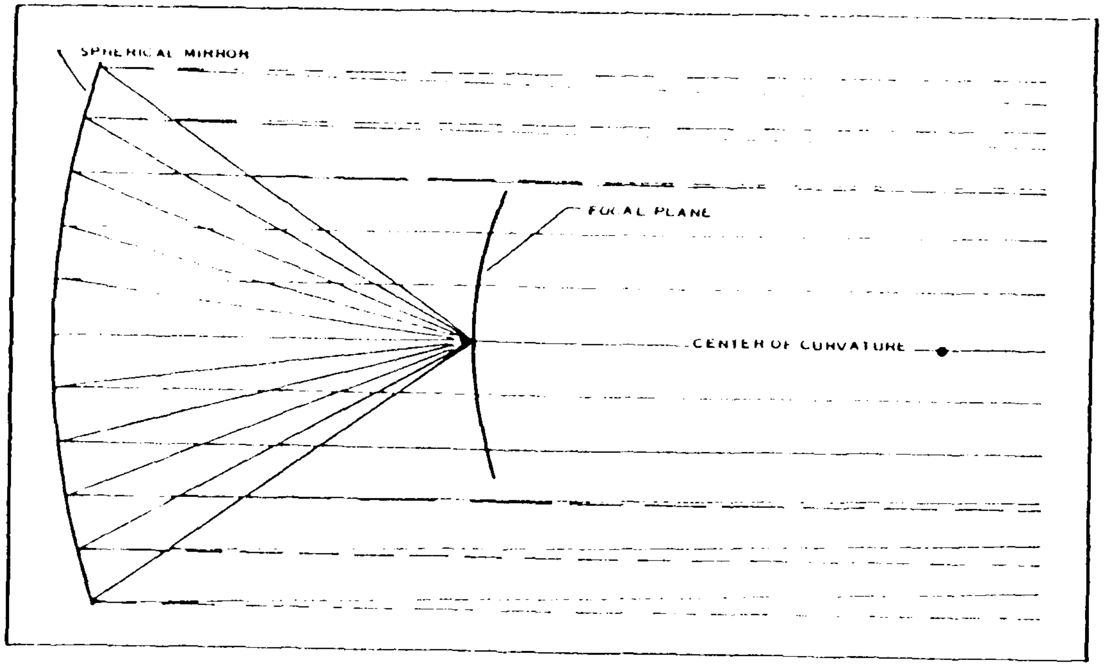

Figure 33. Spherical aberration.
(Horton, Emerick & Mount, 1969)

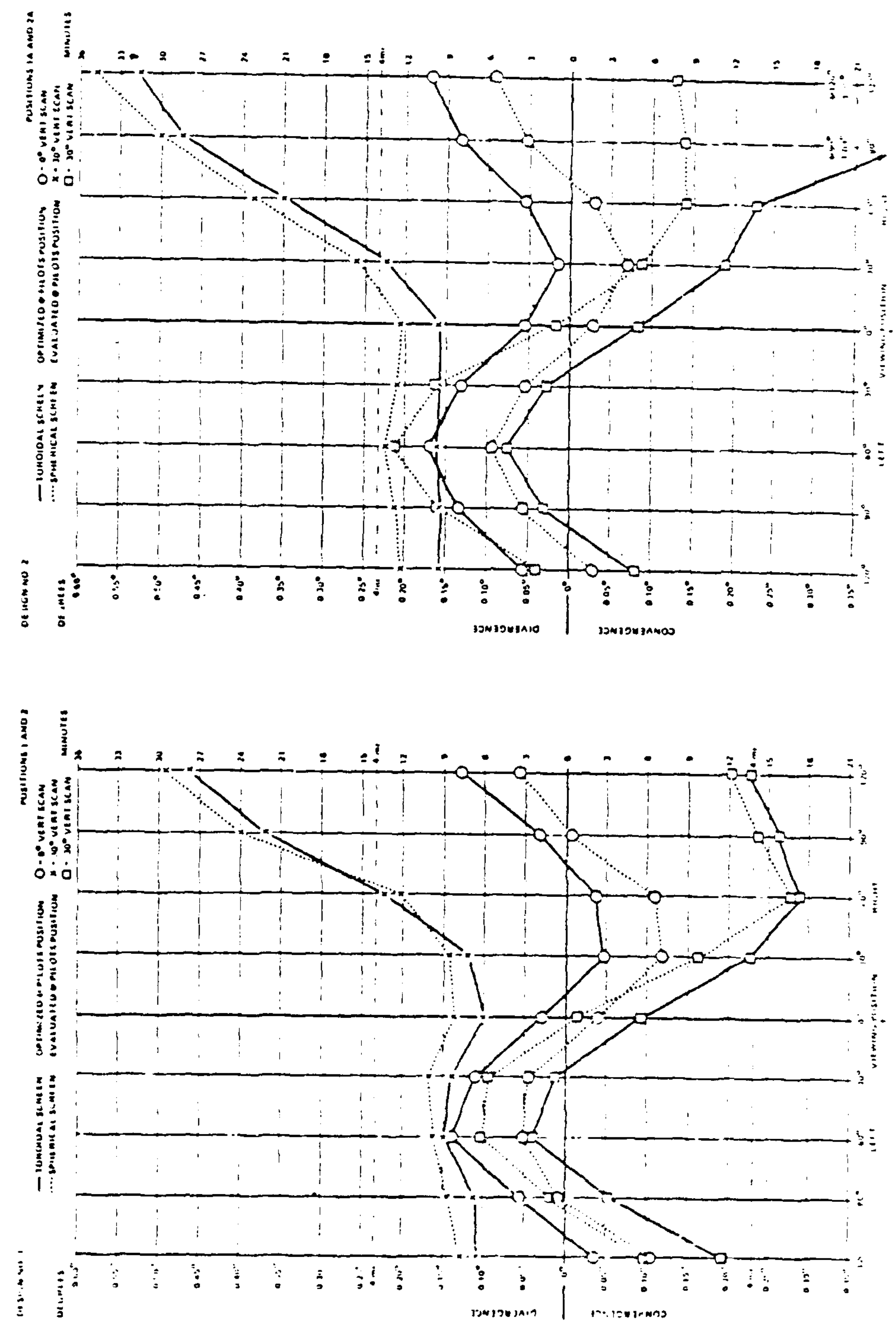

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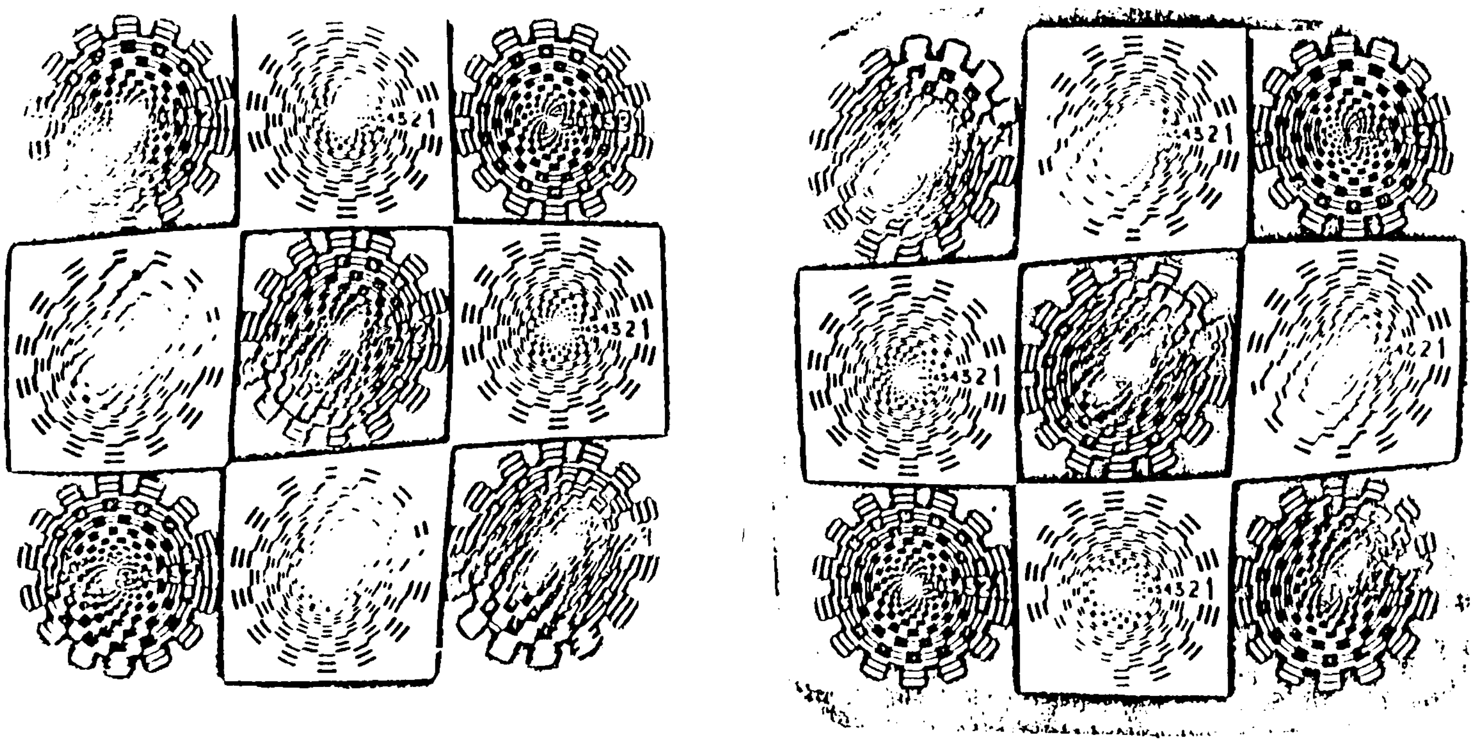
Figure 34. Collimation data from pilot's position (Rhinehart, 1977)



Left Eye View

Right Eye View

Figure 35. Left-eye and right-eye views of Hawley Test Target through X-3 distortion panel. (Kraft, Anderson, Elworth & Larry, 1977)

The failure to detect these types of binocular distortions would not necessarily mean, however, that they would not affect visual performance or cause eye strain and fatigue. In fact, there are some data which indicate that visual performance can be more seriously affected by one "good" and one "poor" quality image than by both images being of poor quality. In a study using stereo pairs of a sensitive test of stereo acuity, Pyle and Booth (1973) administered all combinations of eight levels of image quality (blur by de-focusing) to five skilled observers. A total of over 36,000 discriminations were made by each observer. The results are depicted in Figure 36 and show that, when both eyes had the poorest quality image (7.27 arc minute resolution), 48 percent of the discriminations were correct. When the "poor" image in one eye was replaced with the "best" quality image (19 arc seconds resolution), the proportion of correct responses fell to 26 percent. The best performance (81 percent correct) was with the highest quality image in both eyes, as would be expected.

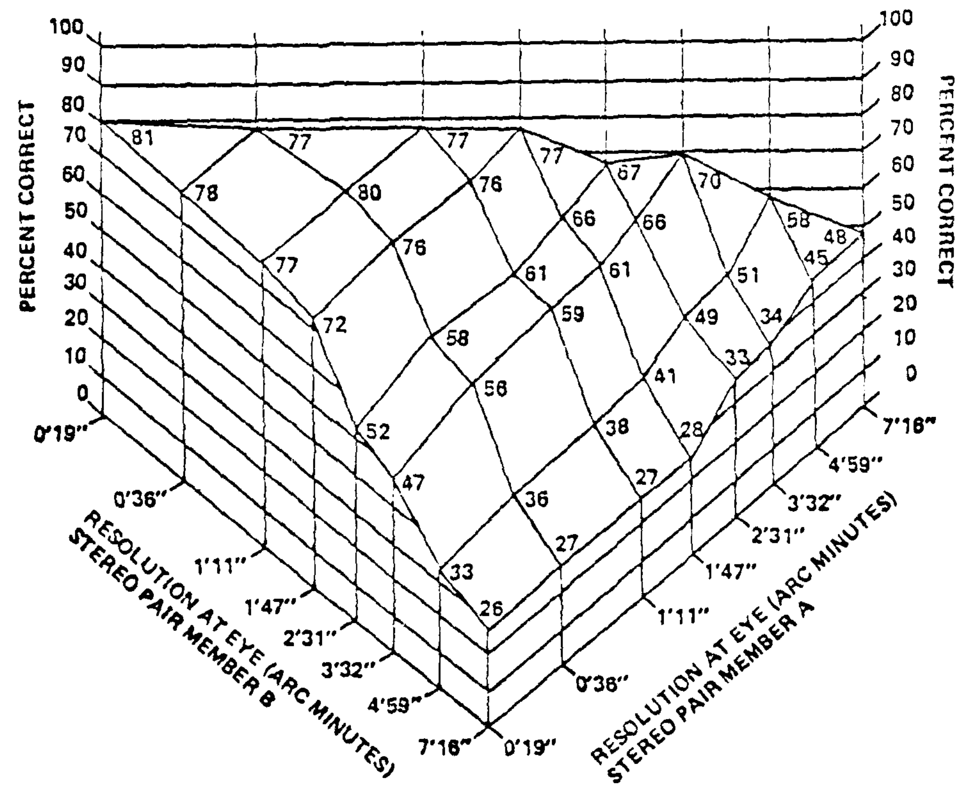


Figure 36. The effect of differential levels of image quality on stereo acuity. (Booth & Pyle, in press)

SCENE MISALIGNMENT

INTRODUCTION

Scene misalignment problems occur primarily at the joints of juxtaposed displays, although the perceptual characteristics of misalignment may also be of concern in scene overlays or inserts and in inadequate data base management of geometric perspective in CIG scenes. In addition, aliasing effects also present apparent misalignment characteristics to the observer in raster-formatted displays. However, since aliasing is discussed elsewhere in this report, this section will deal exclusively with misalignment problems at display joints.

There are two general types of joints that are of concern in this discussion. The first consists of those cases in which two displays or display fields are juxtaposed with the goal of achieving the smallest possible gap or separation between the two scenes. Examples of this situation include the pentagonal, pancake "windows" of the Advanced Simulator for Pilot Training (ASPT) at Williams AFB and the front windshield segments of the Boeing 747 Flight Crew Training simulator at Seattle. In both cases, the actual windshield or canopy area simulated is more extensive than can be covered by a single display, and the edge or gap between juxtaposed display fields is therefore an artificial one not found in the real world. In the case of the ASPT, a set of seven windows are juxtaposed to provide a 300°H x 150°V field of view. In the the 747 simulator, only two display fields are juxtaposed, side by side, for each of the pilot and co-pilot positions, providing a 74°H x 30°V forward field of view.

The second type of display joint of interest here occurs when the two display fields are separated by a definite gap or void which causes a portion of the scene to be occluded from any normal viewing position. Usually the occlusion is the result of a structure or frame member of the aircraft being simulated and therefore corresponds to the real world situation. When these frame members are a part of the simulation cab, the observer (pilot, co-pilot, etc.) may be able to "look around" the structure to pick up the occluded portion of the scene by simply moving his head sideways. In many situations, this frame member may be conveniently used to hide the physical joint between two displays. Thus, the amount of head motion permitted before this other type of joint is perceived may be quite limited. A similar head motion limitation applies to the first type of joint, that of direct juxtaposition. In the 747 simulator, for example, each of the two juxtaposed display channels overlaps the other by 3° as measured from the eye reference point. This overlap defines the angular extent of sideways head motion permissible without blanking a portion of the scene.

ASPECTS OF MISALIGNMENT

Types and Effects

The perceptual factors involved in misalignments can be applied to both types of joints, although to varying degrees of influence. One of these factors is the recognition of displacement of discontinuity in a line segment that bridges a joint, either in a part of the displayed scene or in the raster lines (for line scan systems). The perceptual task is primarily one of vernier acuity. Another type of misalignment involves rotational differences between the scenes or scene elements. For a continuous line segment, this would be represented either by a "bent line" forming an angle at the joint of something less than 180°, or in the case where the rotation originates in the central area of each display, both a displacement or discontinuity and a rotation or angular difference may be detected.

Displacement might also be in the form of either the doubling of scene elements or the deletion of some portion of the scene produced by mis-registration of the scenes in a direction normal to the joint. This case will not be treated here as it does not involve the detection of misalignment per se but is more accurately a task of form or pattern perception, dependent almost entirely upon elements of the displayed scene.

In addition to vernier acuity and the detection of rotation, "bent lines," or angles, other perceptual or display factors that affect detection of misalignments include individual physiological characteristics, stimulus separation, contrast sensitivity, display resolution, luminance level, and stimulus motion.

Vernier Acuity

Perhaps the most critical contributor to the detection of misalignment is the remarkable ability of most observers to resolve very small displacements in one part of an object with respect to other parts. Usually, a straight line broken into two segments, examples of which are shown in Figure 37, is used to measure this type of acuity.

The threshold measure of vernier acuity is generally taken as the visual angle (at the eye) of the lateral displacement (for vertical line segments) of corresponding points on the test stimuli with a 50% probability of detection. It should be mentioned here that the level of discrimination probability or the percentage of detection or discrimination responses used to define a threshold is not always fixed at 50%, but depends somewhat upon the method of discrimination used and a lot upon the proclivity of the researcher. Thus levels of 50, 75, 80, 95 and 98 percent, and perhaps others, have been used as criteria for visual thresholds. Often the thresholds reported in the literature are difficult or impossible to compare with confidence because of the different criterion levels used or sometimes because the criterion level used is not defined at all.

A comparison of vernier acuity with other similar visual thresholds is depicted in Figure 38, (from Farrell & Booth, 1975) for a wide range of luminance intensities. The threshold termed "minimum separable" refers to the detection of a separation or space between two segments, usually measured with line gratings, tri-bar resolution targets, or Landolt "C" test stimuli. Stereo acuity depends upon the integration of information from both eyes on relative displacement of test elements. The category of acuity termed "minimum perceptible" refers to the narrowest dark line that can be seen against a light background.

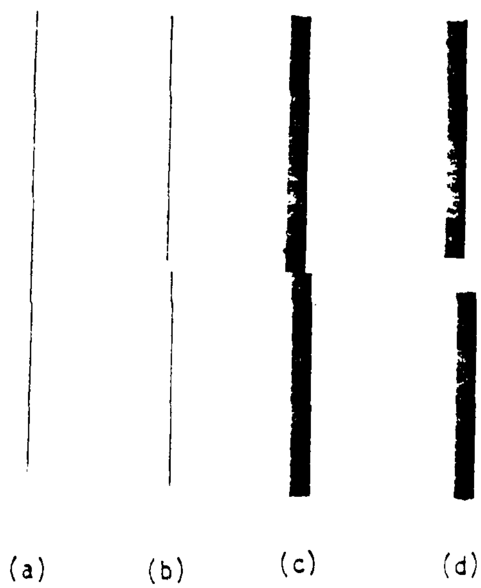


Figure 37. Vernier acuity

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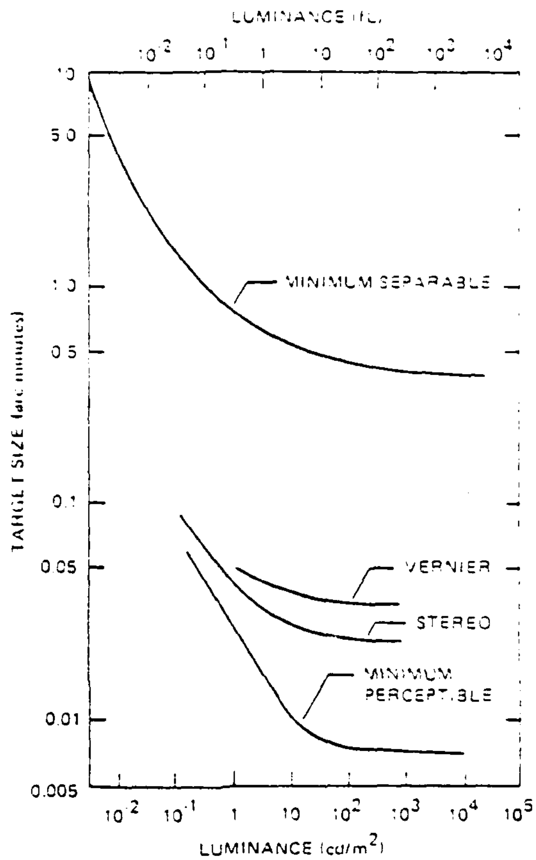


This figure illustrates, though with considerable oversimplification, the very large differences that exist among some of the measures that define the ability of the eye to resolve small targets.

Figure 38. Comparison of acuity measures.

LeGrand (1967) summarizes some of the early determinations of vernier acuity thresholds:

> "Wülfing (1892) was the first to note the remarkably small visual angle corresponding to the thresholds of alignment, which he found of the order of 10" for bright slits as well as for black bars on a white background. Stratton (1900) lowered this to 5" and Best (1900) to 2.5" for 80% correct responses."

Similar results were reported by Graham et al. (1965):

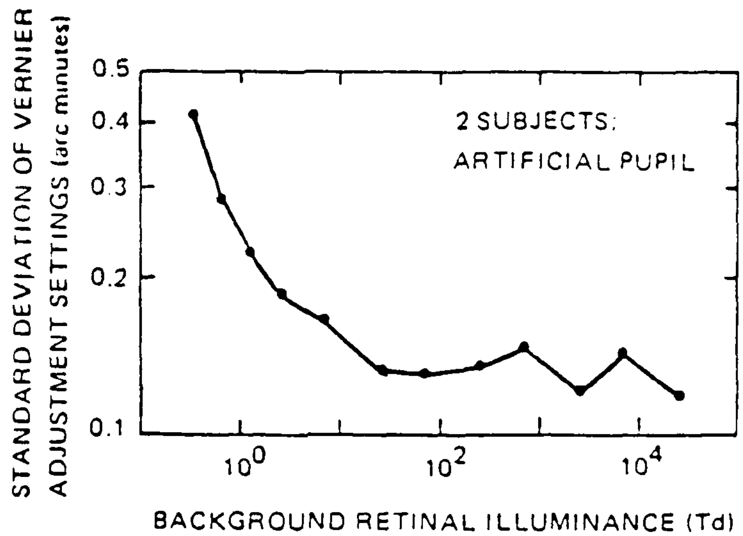
> "For example, Baker and Bryan (1912) report vernier displacement thresholds of about 4 seconds, Wright (1942) 2 seconds, and Berry (1948) 2 seconds."

Although luminance levels and response criteria were not provided in these notations, the results are fairly consistent with those depicted earlier (Figure 38).

In a test situation using the method of adjustments rather than that of constant stimuli, Baker (1949) determined the effect of background retinal illuminance upon the vernier alignment of two bars subtending 4.5 degrees (combined length) in a 12° field. Figure 39, (from Farrell & Booth, 1975) depicts the results which show little gain in performance above 20 Trolands. This level corresponds to a scene luminance of 1.3 candela per square meter (0.4 foot Lambert). The standard deviations of the settings indicate that this procedure may hield slightly different vernier acuity scores than those previously discussed, but certainly of the same general magnitude. They can be compared with the results found by Berry et al. (1950), as depicted in Figure 40, (also reported in VanCott & Kinkade, 1972).

When the scene misalignment is in the periphery, these detection thresholds will increase, following characteristic curves (shown in Figure 41(a) for relative visual acuity, and in Figure 41(b) for visual acuity (from Farrell & Booth, 1975). These results, from experiments by Blackwell and Moldauer (1958), Taylor (1961), and Mandelbaum and Sloan (1949) are representative of the rapid fall-off of visual acuity in the periphery. These data can be applied in a relative way to estimate the amount of misalignment that, under certain luminance and other conditions, will be detectable at various distances out from the fixation point. However, inasmuch as these data are not directly applicable, it is recommended that this function be more fully defined in an experimental study. Thus, this aspect is included in one of the experimental designs provided in Appendix H.

In visual simulation systems, most if not all scenes are displayed dynamically; therefore, the data thus far discussed (gathered under static conditions) likely require some attenuation to fit a dynamic situation. Data from Burg (1966) are shown in Figure 42, (from VanCott and Kinkade, 1975) for the variation of both static and dynamic visual acuity as a function of the age of the observer. From the figure, it



In this study two subjects aligned two narrow bars in a Vernier acuity task. The two bars combined were 4.5° long and were seen against a 12° field. The artificial pupil was projected into the subject's eye. Performance showed little improvement as retinal illuminance increased beyond about 20 Td. This corresponds to a scene luminance of 1.3 cd/m^2 (0.4 fL) viewed with a natural pupil. (From Baker, K. E., 1949.)

Figure 39. Effect of retinal illuminance on Vernier Acuity

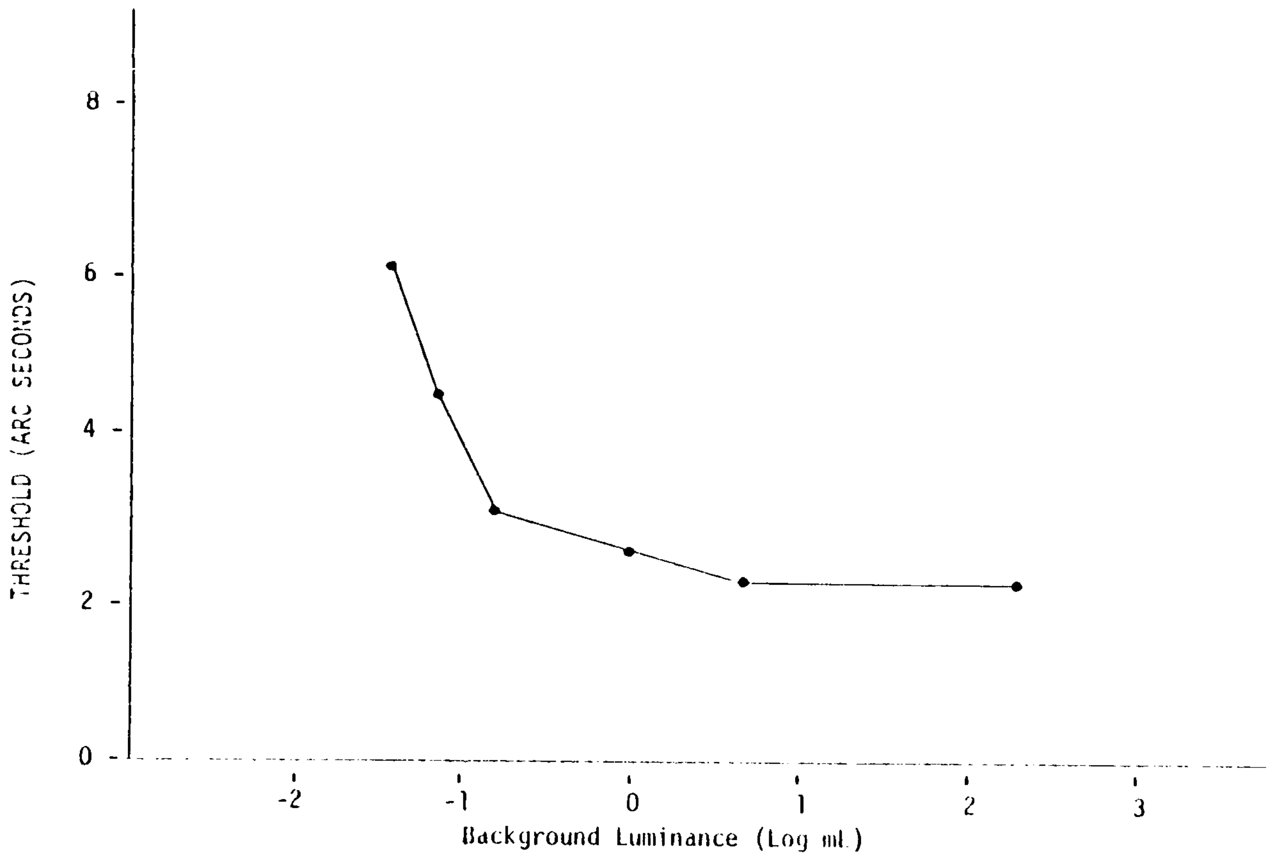
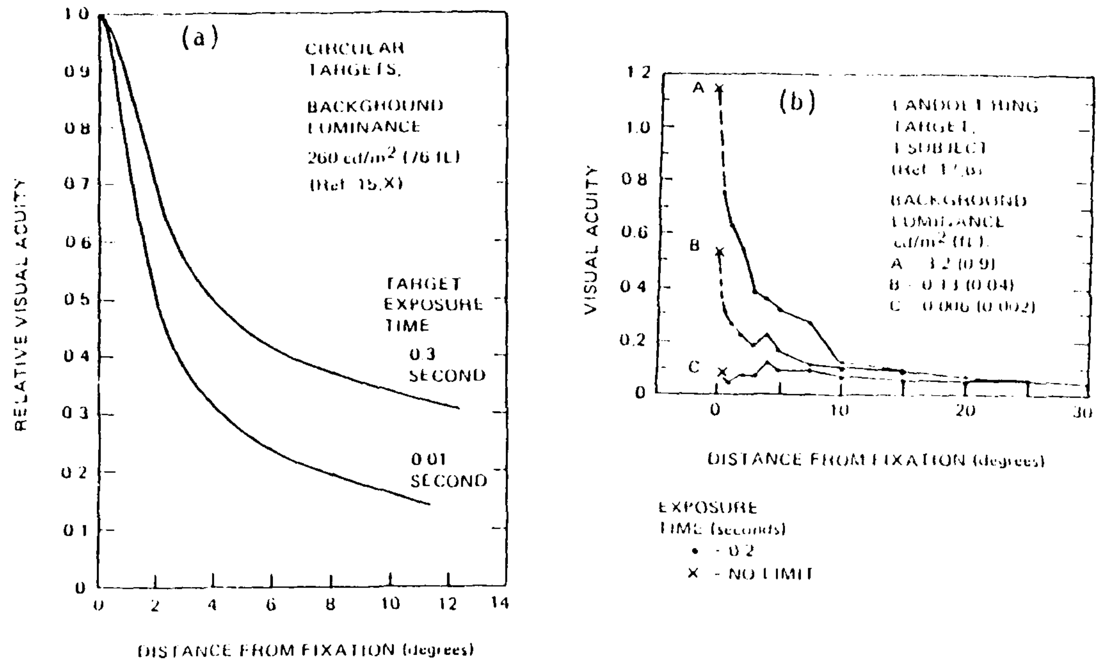


Figure 40. Effect of target background luminance on Vernier acuity (Van Cott and Kinkade, 1972)



(These figures show that ability to resolve image details is worse away from the point of fixation.)

Figure 41. Visual acuity in the periphery (Farrell & Booth, 1975)

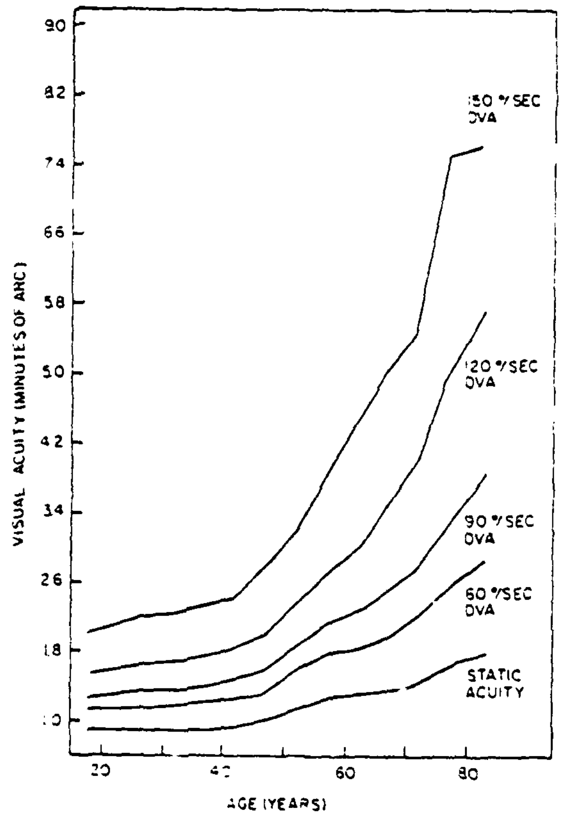


Figure 12. Variation of static and dynamic visual acuity with age (After Burg, 1966)

can be seen that age has a relatively greater effect on visual acuity with increasing rates of target motion. It should be noted, however, that there is only a very slight degradation with up to about 45 years in age. In addition, the fall off in acuity with increasing angular rates of target motion is approximately a geometric progression.

Reading (1972) has pointed out that the results of her study of static and dynamic visual acuities indicated no statistically significant relationship between these two visual discrimination abilities. She reports that this view was supported by Behrens (1958) and by Ludvigh and Miller (1958), but not by Hulbert, Burg, Knoll, and Mathewson (1958), Elkin (1962), and Burg (1966), all of whom found significant correlations between static acuity and performance on a dynamic task. Resolution of this question is still wanting, so caution should be exercised in applying data on static acuity to situations involving dynamic discriminations.

When the adjacent ends of the broken line test stimulus are separated longitudinally, vernier acuity is diminished. In a study done in 1920 and reported in LeGrand (1967), French found an average error of 0.5 arc second for segments with no separation. With a separation of 4 arc minutes between segments, the error was 1.1 arc second, and increased to 5 arc seconds for a separation of 19 arc minutes. A similar effect was found by Berry (1948), but with some significant differences. As the plots of the data show in Figure 43, vernier acuity was best at a separation of .36 arc minute, with performance poorer both at a lesser separation of .06 arc minute and at larger separations (.74, 2.23, 5.20, and 14.8 arc minute). Similar tests of acuity with real depth and stereoscopic depth tasks resulted in best performance with a vertical separation of 5.20 arc min. between the test stimuli. It is interesting to note that performance on the vernier acuity task appeared to be somewhat better than that for the stereo acuity tasks at the very small separations, but then grew worse with the larger separations while the stereo acuities remained relatively good.

The Problem of a Complex Scene

While the just discussed data are useful, they are not completely applicable to the problem of the detection in a complex scene. The data on vernier acuity are probably most generalizable to the case in which the scene is formatted by raster scan and the raster lines are visible. However, other types of misalignment between two juxtaposed displays are possible in addition to vernier displacement. For example, there may be some rotational alignment differences between the displays. In this case, the discrimination may involve detection of the rotational difference (or of an angle formed by the rasters on the two displays) with or without the vernier-type displacement at the joint. Since no data were found to be directly applicable to these specific situations, an experiment was designed to provide some of the missing data (see Experimental Design #6 in Appendix H).

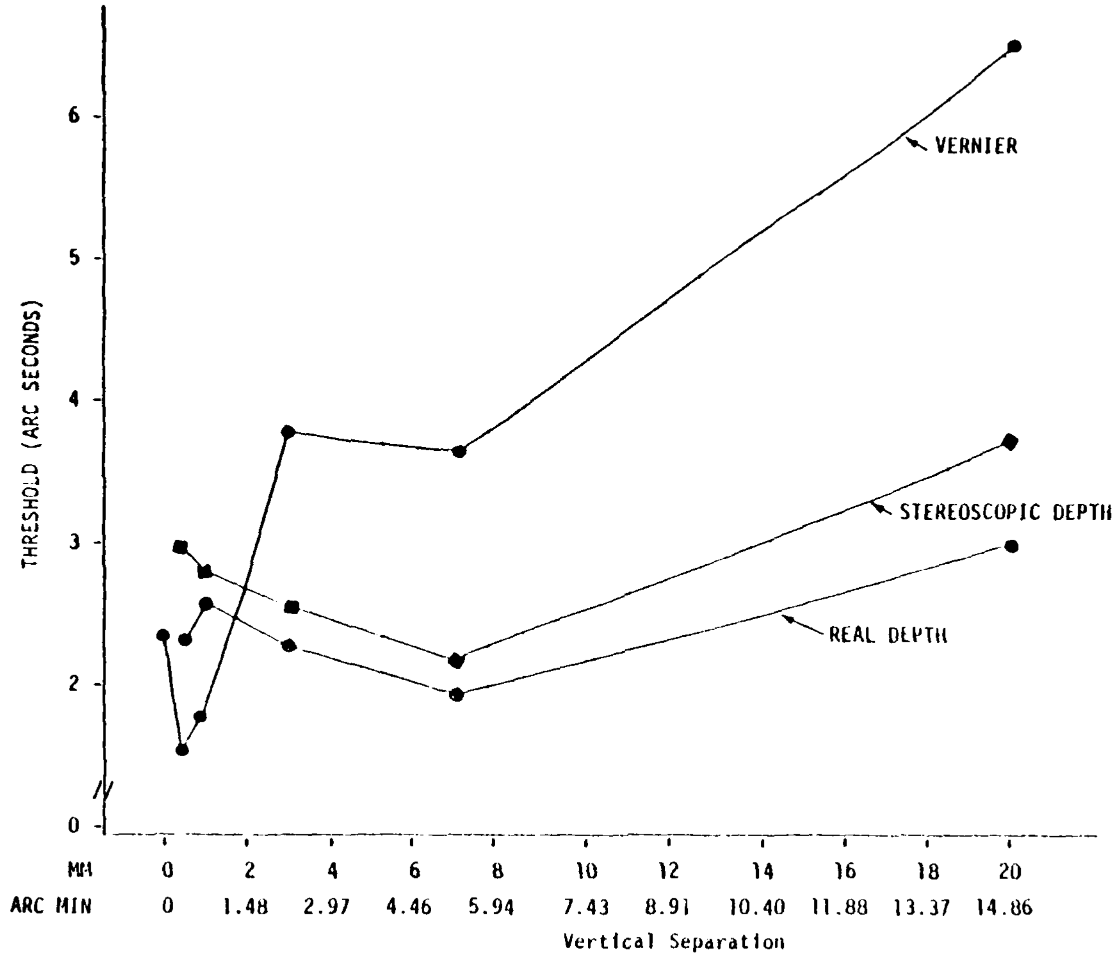


Figure 43. Effects of separation of adjacent ends of target line on vernier and stereoscopic acuity (Berry, 1948)

LATERAL VERGENCE/COLLIMATION/IMAGE DISTANCE ERROR

INTRODUCTION

Several characteristics have been combined in this section due to their close interrelationship. Lateral vergence, collimation and image distance error, and image distance variability were all treated as individual characteristics in the Visual Simulation Concepts Study and were given separate rank orders. It should be noted, however, that three of the four were ranked fairly high and close together in the original list. Combining these seemed to be the reasonable thing to do, therefore, as long as their individuality was not lost.

If the manner in which the unaided eye views the natural environment is considered, several points can be made that are relevant to this discussion:

1. For a fixated object, the accommodation necessary to bring the image into focus on the retina is compatible with the amount of convergence required to acquire fusion of the object through correspondence on the retinae.

2. With the eyes accommodated to an object at optical infinity (or beyond 6 meters), objects nearer the observer are represented on the retina by blur circles of various extent.

3. Objects at different distances can be discriminated via stereopsis up to at least 500 meters, depending on viewing conditions, the disparity of the objects, and the stereo skill of the observer.

4. The apparent distance of objects is determined by the combined effect of several factors including expectation based upon experience, stereopsis, the state of accommodation and convergence, relative motion, relative size, level of detail, interposition, relative brightness, and geometric and aerial perspective.

In visual simulation systems, any optical or scene generation projection characteristics which affect the factors or relationships just described above have the potential for causing perceptual effects or eye strain/ fatigue in the observer. Generally, such effects are likely to be small, partly because of fairly high design standards, but also because many effects are offset or overcome by a preponderance of other non-distorted cues to distance and scene continuity.

The term vergences is defined as a non-parallel or disjunctive binocular movements of the eye. If an object is presented to two eyes on the primary sagittal line but not intercepting the line of sight of either eye, the two eyes will make a movement to place the object on both lines of sight. If the lines of sight were at infinity and the object is nearby the rotation of the eyes will of necessity be in opposite directions and the right eye will turn toward the left and the left eye turn toward the right. Such a movement of the lines of sight away from parallelism is known as vergence. These may be either voluntary or involuntary although those of primary concern, fusional vergences are reflex in nature. This definition is from Borish (1970).

Vergence movements are also defined as those which change the angle formed by the intersecting lines of sight of the two eyes (Alpern 1962). When the lines of sight converge to a point in front of the eyes, they deviate inward and are said to be converging. The conjugation is between the internal recti of both eyes. When the lines of sight appear to diverge from a point behind the eyes, they deviate outward and are said to be diverging. The conjugation here is between the external recti (muscles) of both eyes.

The reader and the issue will be confused because those that work with display design talk about diverging rays as rays emitting from the display which impose converging or convergence on the human eye. In contrast a ray emitting from a display which is converging, forces a divergence on the human eye. It is unfortunate that two different professional groups have used identical terms which become opposites when the frame of references is the display or the observer.

From the frame of reference of the observer, vergences are classified into two major groups; lateral and vertical. In the lateral category they are subdivided into convergence and divergence. Convergence may be defined as when the lines of sight meet at a point in front of the eyes or the angle so formed is increased. Divergence is defined as when the lines of sight meet at a point behind the eye or the angle of convergence is decreased. Vertical vergences may be defined when the line of sight of one eye is directed upwards and that of the other is depressed; a situation which is normally only present as a compensation for some ocular imbalance or where some display presents a vertical disparity when viewed from one eye position compared with the other.

The tolerances for vertical and lateral vergence have been previously discussed under the category of "Horizontal and Vertical Disparities" within this report. Therefore, this discussion will summarize by saying only that the tolerance for vertical vergence is much less than for lateral vergence. In lateral vergence, there is a greater tolerance for convergence than for divergence. These are mediated by many display characteristics and the task at hand. One such special case, not discussed in the previous section, is that of the use or evaluation of a heads-up display in a simulator fitted with a CGI or closed circuit TV visual scene. For low level maneuvering of helicopters, such a display may be stereoscopic in form and the right and left eye images may be presented through separate channels against a common channel of the exterior scene. Gold and Perry (1972) studies determined that, under these conditions, the vertical vergence tolerance was about 3.5 arc minutes without pilot discomfort; 3.5 arc minutes also was the tolerance for lateral convergence display disparity. The tolerance is larger for lateral divergent (display disparities): i.e., 2.5 milliradians or 8.6 arc minutes. These data are consistent with previously reported findings in that the vertical vergence and the visual divergence are smaller tolerances than visual convergence. However the magnitude of these tolerances appear to be much smaller than those previously reported. Such smaller values should be expected since this is a comparative display of a moving scene on which a superimposed line drawing may have divergences vertically and horizontally and when they differ against a common scene.

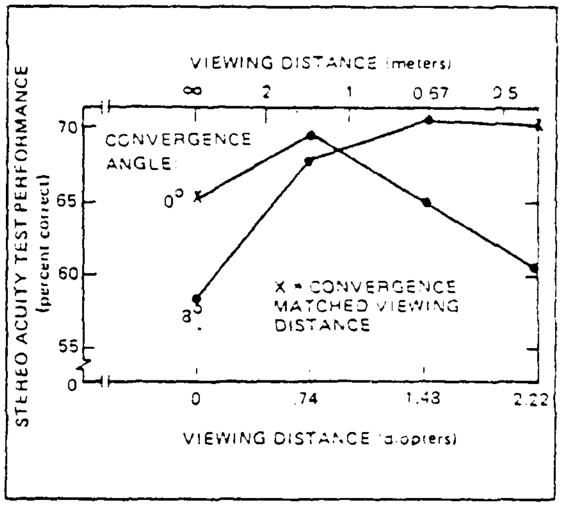
Collimation Errors

Collimation errors are errors in a display wherein the rays of luminous intensity, emitting from a point, diverge or converge from those expected from the theoretical optical design. In flight crew training simulators, the displays may be designed to have a variety of viewing distances. A cathode ray tube may be placed at the windshield aperture presenting a viewing distance of about 28 inches from the pilot's eyes. Or the scene may be projected onto screens or the interiors of domes at distances from 10 to 20 feet (3.05 to 6.09 meters) from the pilot's eyes. As such projection distances approach 6 meters, the visual accommodation becomes .16 of a diopter. This is a practical approximation of an infinity display. Real image displays at each of these distances have a compatible visual convergence and accommodation. The data from Farrell et al. (1970) indicate that optimum visual performance in stereoscopic tasks is obtained when the accommodation and convergence are compatible. In contrast with the real image displays, many virtual image display systems provide accommodation at infinity but convergence at something less than infinity.

Consider one such display that has a 25- inch cathode ray tube hung above the forward and side windows of the aircraft and facing downward. Beneath the cathode ray tube is a beam splitter that reflects the rays forward into a spherical mirror which has a 59.6-inch radius of curvature. The image is reflected back by the mirror through the beam splitter to the pilot's eyes which are, in effect, 1.2 meters from the cathode ray tube along this folded path. Therefore, the accommodation is by design at 10 meters and the convergence is at 1.2 meters. Such a disparity between accommodation and convergence may also occur for the "pancake" window system. An unanswered question then exists; does a mismatch of convergence and accommodation pose a problem by attenuating pilot performance or his comfort when using a virtual image display?

Figure 44, is from the "Design Handbook for Imagery Interpretation Equipment" (Farrell & Booth, 1975). The upper view in this figure indicates that the stereoscopic performance is lowered when the viewing distance differs by more than .75 of a diopter from a value that matches the convergence angle. Stereoscopic performance with static imagery, however, may not generalize too well to the problems in flight crew training with the dynamic imagery and a non-stereoscopic display. The tolerance for collimation errors should not be based entirely on the vertical and horizontal vergence limits as correct perception of the forward scene is the ultimate criterion in pilot training.

The apparent distance to the scene contributed to by accommodation convergence and relative motion of the elements in the scene may be significantly altered either by non-use of an infinity accommodation display or by a compatible convergence with such an infinity display. The correct perception of the slant of terrain in approach and landing,



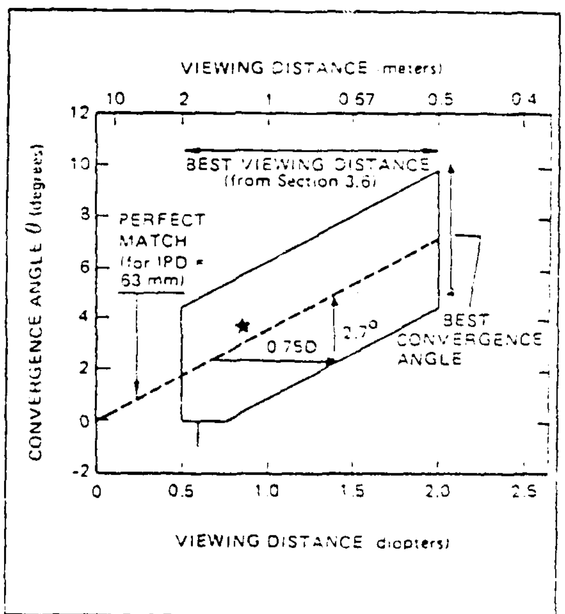


Figure 44. Reprinted page from "Design Handbook for Imagery Interpretation Equipment." (Farrell & Booth, 1975)

in takeoff, and in terrain-following indicates that the question of how that plane is perceived may become one of the most important criteria. Gibson and Gibson (1957), Flock (1964), and Braunstein (1968) all have investigated the individual's perception of a textured surface that is moving. It is found, whether the surface is moving in its own plane or any other direction, a subject's judgment of slant is very accurate. A possible explanation is that a subject would only have to follow the movement of two or three points on the textured surface to be able to know the exact slant of the surface. With a stationary surface however, noisy information must be correlated over many points on the surface to calculate its slant. Experiments with moving surfaces suggests that temporal integration of cues is superior to spatial integration. Quantitative data are needed to determine whether the relationship among spatial and temporal integration varies with the apparent distance to the scene. Until such data are available, the error of tolerances in a display that are based on the vergence requirements must be used. Some collimation errors have been measured in existing types of systems, and their relative relationship to the tolerance figures are shown.

Collimation Errors in Wide-Angle Multiviewer Infinity Display Designs

The works of Shaffer and Waidelich (1977) and of Rhinenart (1977), in their independent assessments of the possibility of a wide-angle, multiviewer, infinity display, indicate that tolerances in collimation could not be of the same magnitude as the relatively smaller field of the beamsplitter mirror systems.

Rhinenart (1977) undertook a research design study to define an extended field-of-view (60° x 180°), infinity image display, suitable for multiviewer use in a wide-bodied aircraft simulator cockpit. Mosaicking of single channel units, both reflective and refractive, was studied, including extended field-of-view reflective systems. Two specific designs were selected and optimized, and these were evaluated over an extended viewing volume (Table 4).

These maximum collimation errors occur at locations generally beyond the limits of the 30° x 40° field of view of the beam splitter and mirror system reviewed in Table 5. The maximum collimation error in the extended field of view system is more than six times the maximum measured in the conventional field-of-view system.

Collimation Errors in Beam Splitter and Mirror Display Systems

The infinity window displays have a finite distance as the divergence tolerance of the rays coming from the CRT toward the pilot. The human visual system has a relatively wide tolerance for such diverging rays and they are perceived as though the object were at a lesser distance than infinity. When talking about the display's "divergence," this corresponds to the convergence in the visual system, and the human converges to fixate near objects. Visual tolerance in this direction with a little practice on the part of the observer can exceed 60 prism diopters.

Display "convergence" is visual "divergence," and the human visual system has very small tolerance for errors in this direction. In every-

Table 4

Extended Field-of-View, Infinity Image Display
Suitable for Multiviewer Use

(Maximum Collimation Errors Predicted)

Location of Measurement Maximum		Collimation Errors: Lateral Design #1	Lateral Design #2	Vertical Design #1	Vertical Design #2
30°	Right			.23	.23
120°	Left			.22	.22
120°	Right	$.27_D$	$.32_D$		
60°	Right	$.28_C$			
70°	Right		$.35_C$		

NOTE: Values within table are diopters and the subscripts D and C represent display divergence and convergence direction of error.

Table 5

Collimation and chromatic errors measured in a beam splitter and mirror infinity display system with two types of mirrors

Location of Measurement From Center	Collimation Errors: Metal	Collimation Errors: Glass	Chromatic Errors: Metal	Chromatic Errors: Glass
18° L & 14° Up	0.0072	0.0163	0.0005	0.0035
18° L & 14° D	0.0414	0.0331	0.0005	0.0035
18° R & 14° Up	0.0438	0.0250	0.0094	0.0034
18° R & 14° D	0.0426	+0.0088	0.0087	0.0000

Note: Values within table are diopters and the single + value represents a display convergence error in collimation.

day visual activity, there is almost no occasion to diverge the eyes because very distant objects may be seen with zero convergence. Little if any practice of diverging the eyes occurs unless it is provided in a visual training device for clinical purposes.

"Infinity" or distant displays may have very strict design tolerances of 0.1 diopter of display divergence and 0.01 diopter of display convergence can be met by the modern beamsplitter and mirror infinity display systems. Table 2 provides the average values of collimation for the red, green, and blue sources at five positions within a 30° x 40° display on a full color CGI system.

The collimation errors are all less than 0.05 diopter. The rays then should appear to be emanating from a distance of 25 meters or more. The design specifications for this system were to have the visual convergence less than 0.1 diopter or that all rays appear to emanate from greater than 10 meters.

The single instance of a display convergence was measured as 0.0088 diopters and should not cause any distress due to collimation error. The chromatic errors are representative of the maximum range of displacements among red, blue, and green at each of the five locations measured. The maximum value measured was 0.0094 diopter. If this were a simple prismatic displacement, it would be equivalent to 0.94 millimeter at a 10 meter viewing distance. The radial distance that encloses a single triad is 0.53 millimeter, so the maximum measured chromatic error may be as small as 0.41 millimeter at 10 meters.

The empirical measurements discussed above are also well within the vertical displacement tolerances of 0.25 diopter given in MIL-HDBK-141 (1962). Vertical displacements between the right and left eyes are the source of many visual complaints as to "eye strain" etc. In the specific system measured above the relative distortion between the two eye positions within the nominal viewing sphere (± 3.3 inches) was measured as being from 0.13 percent to 0.93 percent within a visual field of 12.3 degrees. The largest measured relative distortion between the two eye positions was one twelfth of the MIL-HDBK-141 standard.

For the current designs of a beamsplitter-mirror infinity display of 40° x 30°, in field of view, these empirical tests support the earlier statement that collimation, lateral vergence, and image distance errors are likely to be small. Other cues such as motion should offset them to such an extent that they will not contribute to visual discomfort or attenuate performance.

Chromatic Aberration

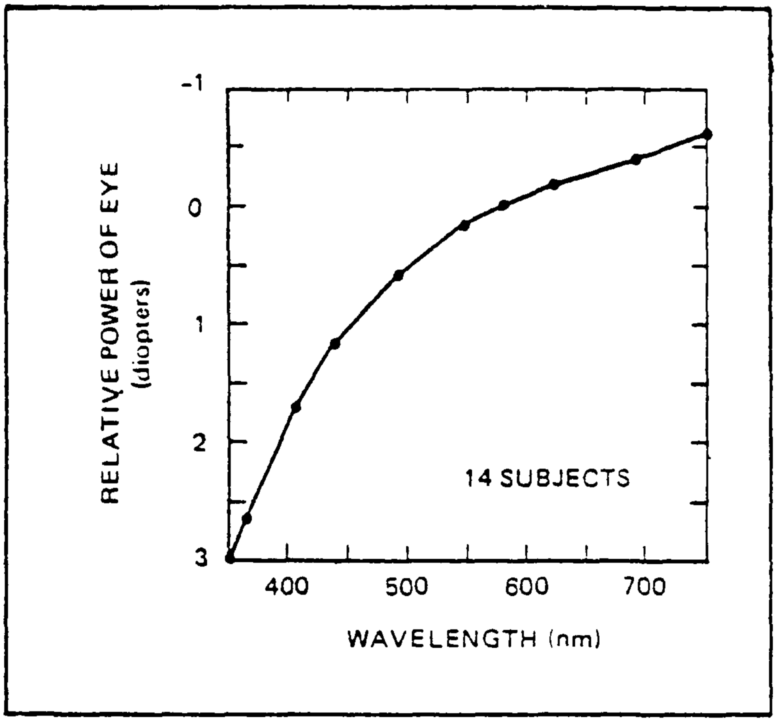
There are no user-based data to support a specific limit on chromatic aberration in a display, but if color fringes can be seen in the image, the chromatic aberration is definitely excessive. If the three color guns in the CRT are not converged properly, it appears as though there were chromatic aberrations in the optical system. Whatever the source, if the effect of dispersion of the three color primaries is to form a spot larger than 3 arc minutes, the influence on the legibility of the display is very appreciable.

The relatively large chromatic aberration of the eye is illustrated in Figure 45. For a significant portion of the population, the cues provided by chromatic aberration contribute to the process of accommodation apparently by providing the eye with information on the direction of the accommodative error (Fincham, 1951). Fincham has suggested that factors underlying monocular accommodation responses are complex and involve various aspects of the out-of-focus image, such as the discrimination of color fringes around a blurred image due to chromatic aberration as well as blurring due to spherical aberration. Fincham's data, when the light was made monochromatic (at 589 nanometers), show that most of his observers had difficulty accommodating properly, at least until they learned to use some other types of cues.

Campbell and Westheimer (1959), following the lines suggested by Fincham's experiments and interpretations performed some experiments in which the subject was required to adjust a test target viewed through a lens from an out-of-focus position to the region of sharpest focus. A subject who found this difficult to do when a monochromatic green filter had been placed in the beam of light, presumably depended on the chromatic aberration as a cue and made many errors before learning to use another cue. Compensation of the chromatic aberration of the eye by incorporating equal but opposite chromatic aberration into the display has been suggested as a way to increase what the user can see in the display. Lenses have been constructed that compensate for chromatic aberration of the eye. In very limiting testing, this kind of lens increases the ability of subjects to resolve large, low-contrast details but not small, high-contrast details. It is not possible to estimate whether this result would occur in other viewing situations. With a CGI system, the result would probably be less than the problem of converging the three guns to the precision of the chromatic aberration in the display optics.

The effect of alignment was very noticeable in a study of the display quality/legibility done by General Electric and Boeing. A Lincoln/Mitre dot matrix alphanumeric font based on a 5 x 7 matrix was utilized in completing an evaluation of the legibility of the Compuscene dislay. Prior research establishing the speed and accuracy for reading alphanumeric symbols on a similar Leroy font was done by Anderson (1977) and Vartebedian (1970). These data compare favorably with a continuous stroke alphanumerics of the Mackworth design studied by Howell and Kraft (1959). The legibility data base was created to consist of 20 characters headed in the intersections of a grid pattern which lay on the computed environmental ground surface. Several advantages were gained by this approach, namely the ability to easily vary contrast between the character and the display background, the ability to accurately control the time period over which a character was displayed, and the ability to move the character easily under program control.

The procedure was to ask four individuals to view one letter or number at a time for 1 second and then to respond verbally with his identification of the alphanumeric presented. With static imagery, centered on the cathode ray tube, the criteria were 90 percent correct, and the legibility provided a result of 92 percent correct. When the imagery was moving as though the airplane was turning at 3 degrees per



The refractive power of the eye is greater for short wavelengths than for longer ones. As a result, a normally sighted individual may be nearsighted for a blue object.

Figure 45. Chromatic aberration of the eye
(Farrell & Booth, 1975)

second, the criteria were 75 percent correct and the four observers were able to meet these criteria. However, most pertinent to this discussion was the fact that one of the observers under one condition, inadvertently was given the presentation only with the green gun on. This desaturated green looked like a white image that was not caught immediately. The data showed that this observer moved from the poorest performance to the maximum performance during the time that the green gun was on.

Later systematic changes in the convergence of the three guns of the display indicated that a very slight change in the convergence would destroy the legibility of these alphanumerics. The same effect could be expected from any display that has a significant amount of color fringes from chromatic aberration or color gun convergence as both increase minimal spot size, lower resolution, and decrease legibility of the letters and numbers made up of dots.

SUMMARY

Vertical and lateral vergences are defined and discussed in this section. The confusion between display divergence and convergence being opposite visual divergent and convergent vergences is raised. The rough equivalence of vertical and divergent lateral vergence tolerance limits are contrasted with the larger tolerance for convergent lateral vergence. This is related to display collimation error limits. The collimation error assessments of two infinity displays of widely different fields of view are presented. Figure 46 illustrates in a graphic manner how the collimation errors of these systems compare with some physiological and behavioral data applicable to establishing limits for collimation in display design.

Chromatic aberration as imposed by the optical aspects of display system imposing color fringes in images is discussed. The similar appearance and effect of lack of convergence of the red, green, and blue electron beams in color CRTs is shown to have generally much larger magnitude of error. The effect of either source of color fringes decreases system resolution and legibility.

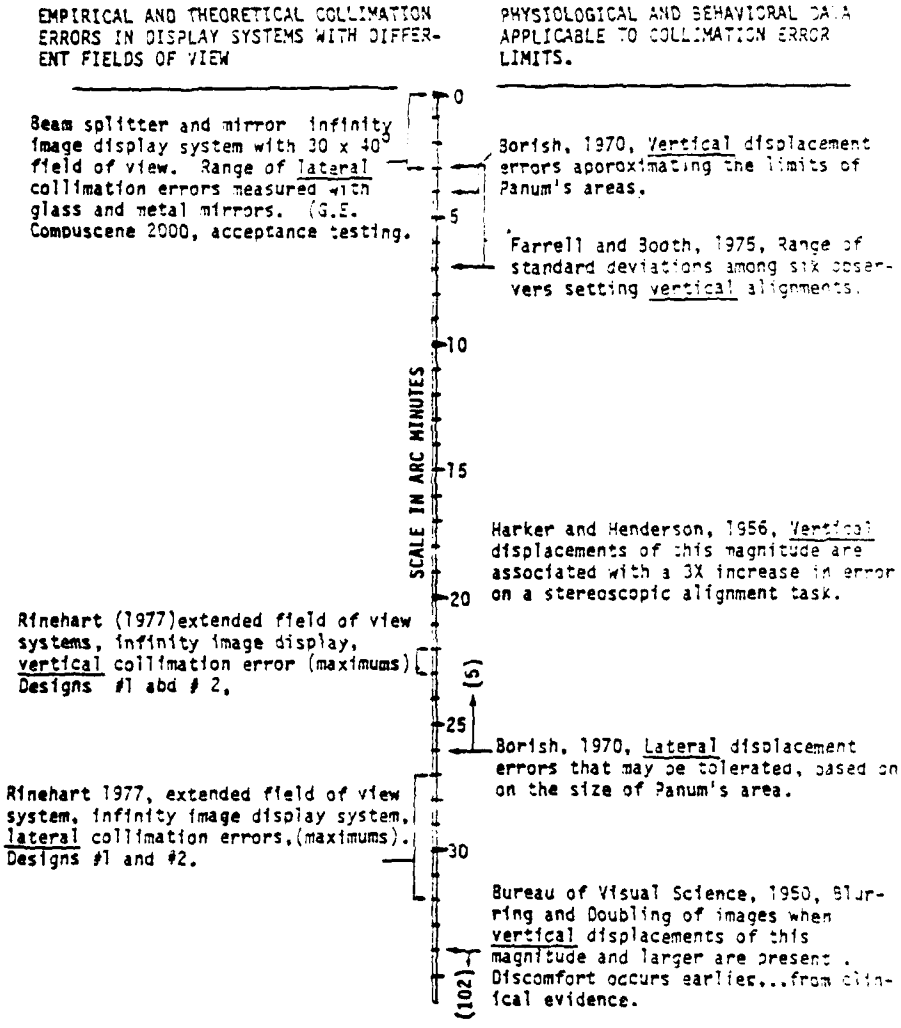


Figure 46. Comparison between collimation errors in two display systems and physiological and behavioral data applicable to collimation limits.

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APPENDIX A. System Characteristics and Associated Perceptual Effects

System Characteristic	Perceptual or Visuo-Physiological Effect
DISPLAY FORMATTING	
Type of scan or formatting	Flicker, shearing, strobing, raster dominance, apparent motion
Frame Rate	Flicker, shearing, strobing
Aliasing	Artificial spots, gradients, and patterns, jump and apparent motion
Field of View	Motion awareness, size-distance relationship, display shape
Visual System Lag	Temporal disorientation, video-vestibular conflict
Update Rate	Jitter, flicker
Vibration	Blur, jitter
DISPLAYED RESOLUTION	
Active lines per Unit Visual Angle	Sharpness, detail, raster dominance
Picture Elements	Detail, shearing
Uneven Line Resolution	False depth, sharpness, detail, edge smoothing
Depth of Field	Sharpness, near relative motion
Phosphor Decay Time	Smear, flicker, eye strain
Spot Size, Spread and Shape	Sharpness, detail, apparent contrast
COLLIMATION AND IMAGE DISTANCE	
Collimation and Image Distance Error	Eye strain, fatigue, size/distance relationship
Exit Pupil	Fatigue, eye strain
Lateral Vergence	Eye strain, fatigue size/distance relationship
Dipvergence	Eye strain, diplopia, fatigue
Image Distance and Variability	Eye strain, fatigue, size/distance relationship

System Characteristic	Perceptual or Visuo-physiological Effect
DISTORTION	
Geometric Perspective	Orientation, perception of distance
Eye Relief Envelope	Eye strain, fatigue
Reflections, glare, Ghosting, Scratches and seams	Eye strain, fatigue, distraction
Binocular Image Size Differences	Eye strain, fatigue, object distance/ size, blur, distance disparities
Magnification	Size/distance relationships, field flatness
Binocular Deviations	Blur, eye strain, fatigue, diplopia, distance disparities
LUMINANCE INTENSITY	
Luminance Range	Object resolution, adaptation, eye strain
Luminosity Function	Object distance/resolution/detection
Temporal Intensity Fluctuations	Eye strain, distraction, adaptation, flicker, jitter
Luminance Variation	Eye strain, adaptation
Contrast	Object resolution (detail) and distance adaptation
COLOR	
Temporal Changes in Color Balance	Distraction, Flicker
Hue Range (Wave-length Distribution)	Scene cartooning, adaptation
Color Fringes	Resolution, detail, blur
Variation Within Display	Distraction, realism
Saturation and Contrast	Scene cartooning, chromostereopsis, afterimages
Registration	Blur, edge smoothing, detail

System Characteristic	Perceptual or Visuo-physiological Effect
MULTIPLE DISPLAY CHARACTERISTICS	
Gaps in FOV (joints)	Disorientation, distraction
Scene Misalignment	Disorientation, distraction, eye strain
Luminance Differences	Adaptation, eye strain
Color Differences	Distraction, realism
Scene Overlays and Inserts	False cues, distraction, jitter, secondary

APPENDIX B

Scaling of Visual Simulation System Characteristics

EVALUATION FACTORS/(WEIGHTING)

System Characteristics	False Cues (Wt = 10)	Interaction of Characteristics (Wt = 9)	Current Prevalence (Wt = 8)	Realism Deficiency (Wt = 7)	Correction Cost (Wt = 6)	Sum/Weighted Sum
DISPLAY FORMATTING						
Type of Scan or Formatting	3/30	3/27	3/24	3/21	5/30	17/132
Frame Rate	3/30	3/27	1/8	3/21	4/24	14/110
Update Rate	3/30	4/36	2/16	4/28	4/24	17/134
Aliasing	4/40	4/36	3/24	4/28	3/18	18/146
Visual System Lag	5/50	3/27	1/8	4/28	4/24	17/137
Vibration	1/10	2/18	1/8	3/21	3/18	10/75
Field of View	3/30	3/27	2/16	5/35	5/30	18/138
Quantization	2/20	3/27	1/8	2/14	3/18	11/87
					AVE =	15.2/119.9
DISPLAYED RESOLUTION						
Active Lines per Unit Visual Angle	3/30	4/36	2/16	4/28	4/24	17/134
Picture Elements	3/30	3/27	4/32	3/21	4/24	17/134
Uneven Line Resolution	2/20	2/18	2/16	2/14	3/18	11/86
Phosphor Decay Time	1/10	4/36	1/8	2/14	2/12	10/80
Spot Size/Shape/Spread	1/10	4/36	1/8	2/14	3/18	11/86
Displayed Depth of Field	3/30	3/27	2/16	4/28	3/18	15/119
					AVE =	13.5/106.5

System Characteristics	False Cues (Wt = 10)	Interaction of Characteristics (Wt = 9)	Current prevalence (Wt = 8)	Realism Deficiency (Wt = 7)	Correction Cost (Wt = 6)	Sum/Weighted Sum
COLLIMATION AND IMAGE DISTANCE						
Collimation/Image Distance Error	2/20	4/36	2/16	2/14	4/24	14/110
Exit Pupil	2/20	3/27	4/32	5/35	4/24	19/138
Lateral Vergence	4/40	4/36	2/16	2/14	3/18	15/124
Dipvergence	3/30	5/45	2/16	1/7	3/18	14/116
Image Distance and Variability	4/40	3/27	2/16	3/21	4/24	16/128
					AVE =	15.6/123.2
DISTORTION						
Geometric Perspective	3/30	2/18	4/32	3/21	4/24	16/125
Eye Relief Envelope	2/20	3/27	3/24	4/28	4/24	17/123
Reflections, Glare, Ghosting, Scratches, Seams	4/40	2/18	3/24	4/28	3/18	16/128
Binocular Image Size Differences	3/30	4/36	1/8	2/14	2/12	12/100
Magnification	5/50	4/36	3/24	2/14	2/12	16/136
Binocular Deviations	3/30	5/45	2/16	4/28	3/18	17/137
					AVE =	15.7/124.8
LUMINANCE INTENSITY						
Luminance Range	2/20	4/36	4/32	2/14	4/24	16/126
Luminosity Function	3/30	4/36	3/24	3/21	3/18	16/129
Temporal Intensity Fluctuations	4/40	3/27	4/32	3/21	3/18	17/138
Luminance Variation	1/10	2/18	3/24	2/14	3/18	11/84
Contrast	3/30	4/36	2/16	2/14	2/12	13/108
					AVE =	14.6/117.0

System Characteristics	False Cues (Wt = 10)	Interaction of Characteristics (Wt = 9)	Current prevalence (Wt = 8)	Realism Deficiency (Wt = 7)	Correction Cost (Wt = 6)	Sum/Weighted Sum
COLOR						
Temporal Changes in Color Balance	2/20	3/27	4/32	3/21	3/18	15/118
Hue Range (Wavelength Distribution)	3/30	3/27	4/32	3/21	4/24	17/134
Color Fringes	2/20	2/18	2/16	2/14	2/12	10/80
Variation Within Display	1/10	2/18	2/16	2/14	3/18	10/76
Saturation and Contrast	3/30	2/18	4/32	4/28	4/24	17/132
Registration	3/30	3/27	1/8	3/21	1/6	11/92
					AVE =	13.3/105.3
MULTIPLE DISPLAY CHARACTERISTICS						
Gaps in FOV (Joints)	2/20	2/18	3/24	5/35	5/30	17/127
Scene Misalignment	4/40	2/18	4/32	4/28	3/18	17/136
Luminance Differences	2/20	3/27	5/40	2/14	3/18	15/119
Color Differences	3/30	3/27	5/40	3/21	2/12	16/130
Scene Overlays and Inserts	5/50	3/27	2/16	3/21	4/24	17/138
					AVE =	16.4/130.0

APPENDIX C

EXPERIMENTAL DESIGN #1

THE EFFECT OF HORIZONTAL ANISEIKONIA ON TARGET DETECTION AND MOTION RECOGNITION

Two questions posed in reference to the potential effects of horizontal aniseikonia on target detection and on motion recognition can be represented by the following two hypotheses:

Hypothesis #1: Horizontal meridional magnification of the image to one eye will increase the detection threshold for an approaching target.

Hypothesis #2: Horizontal meridional aniseikonia will attenuate the recognition of direction of travel (toward or away) of a detected target moving rapidly across the field of view.

The effects postulated in these hypotheses are of practical importance. In recent conversations with pilots of high performance fighter aircraft, it was indicated that in a one-on-one confrontation, a considerable combat advantage accrues to the pilot that first achieves visual contact. Once visual contact is made, it is important to determine, also as quickly as possible, the heading of the "aggressor" aircraft. Often this is accomplished almost simultaneously with detection when the target is acquired foveally. However, when initial detection is through motion perception in the near periphery, foveal attention is generally needed in order to integrate the cues required to establish the three-dimensional motion vector. The horizontal and vertical (two-dimensional) components of this vector are usually the easiest to determine, with the third component (toward or away) being dependent upon detecting, for a distant target, changes in the subtended angle, or size, of the target image.

Detection of this change in image size may be significantly affected by horizontal aniseikonia. A target moving across the image field in a true fronto-parallel plane (no motion component toward or away from observer and no change in image size) will undergo a change in perceived distance proportional to the degree of aniseikonia or image plane rotation. When there are no other stable referents in the field, the target may be erroneously perceived as moving toward or away from the observer. It must be noted here that since the size of the target image on the retina is not changing, the perceived change in target distance may produce, through size constancy effects, a counterbalancing change in perceived size of the target (Emmert's Law) (Ogle, 1962). Thus, for the aniseikonia condition diagrammed in Figure 26, an object in the right-hand extent of the image field is seen as farther <u>and</u> larger, while an object in the left side of the field is seen as closer <u>and</u> smaller. The question of whether these two perceived effects nullify each other or whether there is a residual effect under the motion recognition conditions outlined above is the subject of hypothesis #2.

METHOD

Apparatus

Hypotheses 1 and 2 will be tested as a two-step procedure in the same experimental setup. A large projection dome or screen will be used with a viewing distance of at least 20 feet (6 meters). The observers will be positioned at approximately the radius of curvature, if a curved dome or screen is used, or along the midline if a flat screen is used. A headrest or other appropriate technique will be used to prevent extraneous head motions by the observers. The headrest will be provided with a lens holder to hold aniseikonic or plano lenses during the training and test trials. If a dome is used, an alternative is preferable, i.e., the plano and size lenses would be ground to the same shape and size as flight glasses. These would then be mounted in a frame with adjustable nose pads and interchangeable bows. A darkened room with a non-reflective, dark viewing frame or window will be utilized to act as a viewing aperture stop.

One projection system will be used to provide a background scene of dark blue sky with several light, contrasty clouds. A second system will provide a target overlay of positive contrast which, for the target detection task, will originate in one of four quadrants but close enough to the fixation point that scanning search is not attempted by the observer. The target size will be controllable from well below the detection threshold to well above (< .5' to > 25'). Rate of change in target size will be controllable with a range to simulate closing velocities of from 500 to 2000 feet per second, although only one rate will be used in the detection trials.

For the motion vector recognition task, the target overlay will move rapidly across the field of view on one of several frontal plane meridians. The size of the target for this task will be well above the peripheral threshold. Subtended angle (size) of the target for this task will also be controllable but over a smaller range than for the detection study. At least four different rates of change will be used to simulate four (or more) heading vectors of the target.

The "trigger" microswitch of a joystick control will be used by the observers to signal time of detection or recognition and to freeze the target "motion."

Experimental Design

Figure C-1, depicts the basic design for the main investigation of the effect of horizontal aniseikonia on target detection and motion recognition. The design is basically a 4 x 4 x 2 factorial with the following three independent variables:

1. Amount of aniseikonia - four levels of magnification will be used: 0, 1, 2 and 4 percent;

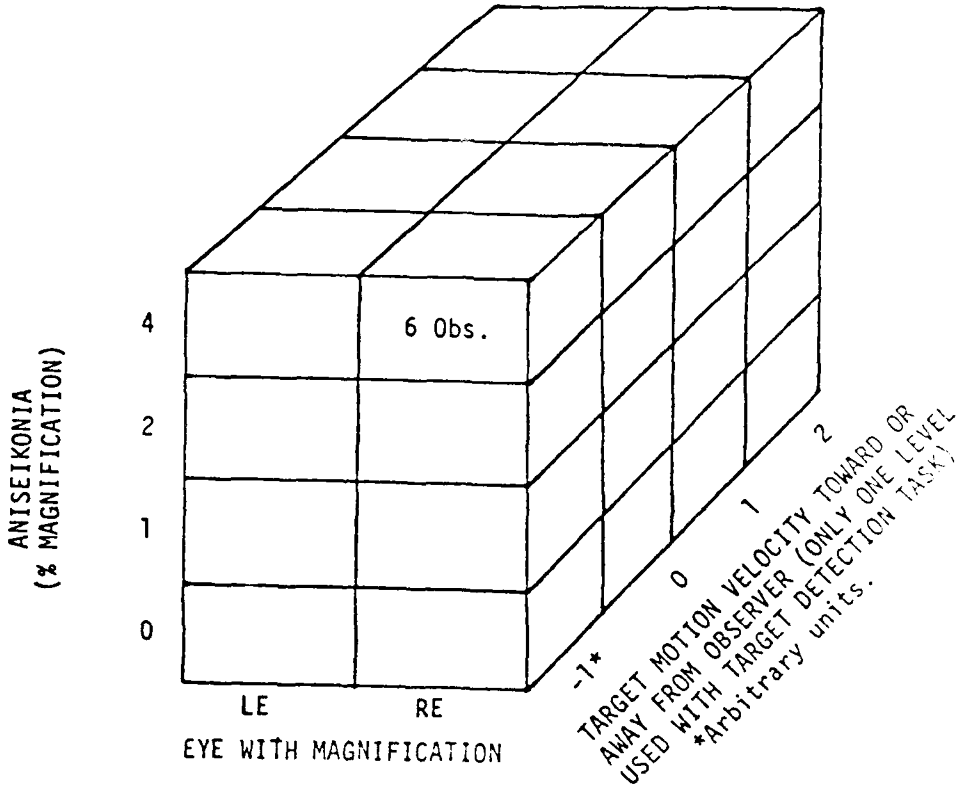


Figure C-1. Experimental design for effect of horizontal aniseikonia on target detection and motion recognition.

2. Velocity of target motion - four levels of motion toward or away from the observer will be used in conjunction with horizontal motion across the field of view for the motion recognition task. For the target detection task, only one "toward" velocity will be used, and without any horizontal component.

3. Eye with magnification - in half of the experimental trials, the magnifying cylinder lens will be placed before the component.

4. Eye with magnification - the magnifying cylinder lens will be placed before the observer's left eye in half of the experimental trials and before the right eye in the other half. This procedure will tend to balance out dominant eye effects.

The dependent variable in the Critical Limen Stereo Test (CLST) is the number of correct responses at each disparity level, transformed into a 50-percent stereo acuity threshold. In the target detection task, the dependent measure will be the size of the target (in subtended angle) when first detected, the response being to depress a trigger microswitch which freezes the target's motion, and then to report which of the four quadrants the target is located in. The percent correct of location responses will be a secondary measure.

The dependent measure in the motion recognition task will be a forced choice response of "toward" or "away" as representative of perceiving the target as moving closer to, or farther from, the observer in its translation across the field of view. A secondary measure will be the elapsed time from appearance of the target in the visual field.

Observers

Six observers will be selected, after an examination of visual skills, to serve as test subjects. These observers will have a visual acuity skill of at least 20/25 (0.8 decimal equivalent) uncorrected with differential acuity between the two eyes less than 0.1 decimal equivalency, and a stereo acuity skill of at least 15 arc seconds (50 percent threshold), as determined by the CLST. The observers shall have measurable natural aniseikonia of less than .2 percent in any meridian and phorias at far point no greater than .25 diopter vertical and 1.5 diopters disassociated lateral. The accommodative range and resting point will be measured, along with the depth of field with a sky/clouds stimulus field at 6 meters. The preference will be to use pilots as observers so that any special skills they have developed in recognizing the first and third quarter views of the aircraft or rates of change of aspect angle may be included in these data.

Procedure

After the visual screening process, each observer elected as a test subject will be given the CLST to provide baseline data on the effects of horizontal aniseikonia on stereo acuity. The CLST is a sensitive test of stereoscopic acuity, with discrimination levels ranging from 6 to 60 seconds. Four of the tests' eight formats (32 responses) will be given each observer under each level of aniseikonia: Half the trials with the magnification in the left eye, half in the right eye. The observers will each be given the CLST under the four levels of magnification (0, 1, 2, and 4 percent). Plano lenses will be used before both eyes for the "zero" condition and for the "non-magnified" eye on the other conditions. The format of the CLST will be administered in the Wottring Troposcope at "infinity" focus and zero convergence.

Following the training trials, the observers will perform first the target detection task and then the motion recognition task. Six representations of each combination of independent variables will be given, with random ordering of conditions. Delay times between initiation of each trial and "appearance" of the target will also be varied randomly between a minimum of 5 seconds and a maximum of 20 seconds.

Activation of a microswitch will provide the discrete target detection and motion recognition responses and terminate the observer's view of the display. Following the switch activation, the observer will be asked to indicate quadrant location of the target (for target detection) and direction of motion - toward or away (for motion recognition). After each trial in the CLST, target detection, and motion recognition tasks the observer will be asked to rate the condition for visual discomfort or strain on a scale of 1 to 5.

Analysis of Results

The data from the CLST administration and from the target detection and motion recognition trials will be subjected to analysis of variance techniques to determine the main effects of the independent variables. Range statistics and Chi Square tests of significance will be used to provide more specific analysis, as will correlational analyses between CLST and target detection and motion recognition data.

The statistical packages available on the contractor's IBM 360/65 and 370 computers will be utilized for the majority of the statistical analyses.

The discomfort data will be analyzed with rank order statistics and correlated with the detection/recognition data.

Conclusions, Recommendations and Documentation

The conclusions drawn from the data analyses will be integrated with any existing reliable data as the bases for recommendations of design criteria or tolerance levels for differential magnification in visual simulator systems.

APPENDIX D

EXPERIMENTAL DESIGN #2

THE EFFECT OF UPDATE RATE ON ALIASING, TURNING RATE, AND TRANSFER OF TRAINING

The question posed in reference to the effect of update rate on aliasing turning rate, and transfer of training can be represented by the following hypothesis:

Hypothesis: Perceived speed and training results are affected by the doubling of images at angular velocities that are common to taxiing, takeoff, and landing.

During acceptance testing on the Compuscene 2000 visual simulator system, it was found that the turning rates from runway to taxiway on a 747 were 18 degrees/second. A turn rate of 5 degrees/second on this visual system gives a double imaging of runway edge lights.

A survey of six current visual systems, including the Compuscene 2000, showed that update rates vary from 30 to 60 cycles/second. These systems and their respective update rates are as follows:

Compuscene 1000	60 cycles/second
*E&S DLH	50 cycles/second
*E&S SP-2 DLH	40 cycles/second
ASPT	30 cycles/second
Night Only Scenes	30 cycles/second
Compuscene 2000	30 cycles/second

*Evans & Sutherland, subsidiary of Redifon

METHOD

Apparatus

The apparatus used in matching the sub-group of pilots as to their skill in juding 5, 10, and 15 degree per second rates of turn will be a high speed photographic representation of the visual scene taken from the 747-1 on a turn onto the runway from the taxiway on the north end of the field. The playback mechanism will be a variable speed, non-flickering, Eastman analyzer projector. The apparatus in the main experiments will be two 747 simulators; the Conductron number one with its current visual system with 60-cycle persecond update rate and the new Redifon 747 simulator with the Compuscene 2000 with 30-cycle per second update rate.

Experimental Design

In Figure D-1 the experimental design is represented as a 2 x 3 factorial. The independent measures will be the update rate at 30 cycles per second and 60 cycles per second; the dimension of speed of turn at three levels, 5, 10, and 15 degrees; two groups of six pilots each

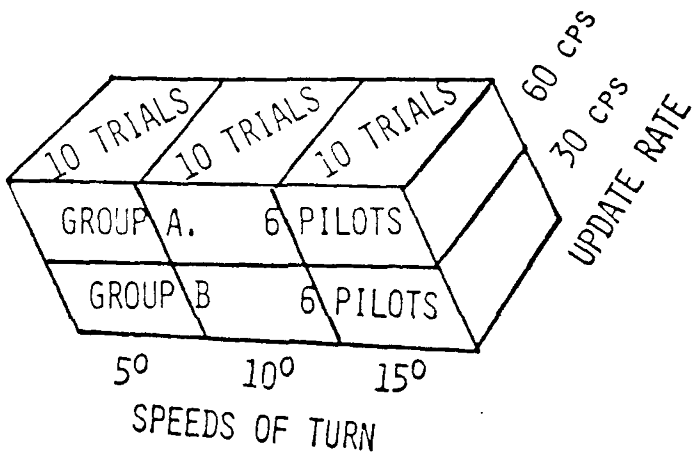


Figure D-1. Experimental design for effect of update rate on aliasing, turning rate and transfer of training.

divided into groups A and B; and within each cell, there will be 10 trials. The dependent measure will be reproduction of speeds of turn in the simulator.

Observers

Two groups of six pilots each will be drawn from the population of qualified 747 instructors from the Flight Services Center of the Boeing Commercial Airplane Company.

Procedure

Two groups with six pilots in each group will be used. Pilot groups A and B will be matched in skills. The two groups should be about even in their judgments of turning rates on the photographs. Group A then will be given work limits criteria training in the 747 simulator with the 60 Hz update rate. Each man will make 10 turns at 5 degrees per second, another 10 at 10 degrees and then 10 at 15 degrees. During this time they will have immediate feedback as to the rates of turn on each of the previous trials. Group B will receive the same type of training on the simulator with the 30 Hz update rate.

Following the training session both groups will be tested on the same motion picture films and asked to precisely reproduce 5, 10 and 15 degree per second rates of turn from the image of the real world scene. In this instance, they will not be provided with feedback as to how well they did on each previous trial. Since the two simulators may differ as to their handling quality, a second posttraining test will be instituted. Group A, initially trained on the 60 Hz will be re-tested on the 30 Hz update rate visual system and the different simulator. The reverse will be true for group B. In this case there will be no feedback as to their performance on each trial.

Analysis of Results

The data on the rates of turn for both motion picture films and for the re-testing on the simulators will be submitted for an analysis of variance treatment to ascertain the contribution that could be expected from chance.

Conclusions Recommendations and Documentation

The expected results are (a) that if 30 and 60 Hz updates provide similar training and transfer of this training, the proposed training performance should show no differences for groups A and B; (b) if, through incidental learning, pilots acquire a skill that is different on the 30 Hz and 60 Hz update rates, then non-transfer of training will lower the performance on motion pictures for one of the two groups; if some things are learned on the 30 Hz and not transferred to the 60 Hz it is also expected that the performance will differ between the two simulators, but only in one direction; (c) if the differential rates of turn show different performances within the two groups, then a specific aspect at one of the rates of turn may be attributed to the update rate. The possible recommendations will depend of course on the results, but if the second and third expected results just mentioned are found to be true, re-evaluation of the update rates on simulators currently being built may have to be reconsidered.

APPENDIX E

EXPERIMENTAL DESIGN #3

THE EFFECT OF OPTICAL MAGNIFICATION ON THE RUNWAY PLANE

The question posed in reference to the effect of optical magnification on the runway plane can be represented by the following two hypotheses:

Hypothesis #1: Optical magnification of the runway scene as viewed at a point on final approach will produce errors in the perceived slant angle of the runway plane and will result in biased estimates of approach angle/altitude.

Hypothesis #2: The magnitude of this effect will vary under night versus day scene conditions.

With the introduction of closed circuit TV systems and also computer generated image systems for flight simulators, the question of whether the display should reproduce the outside world on a one-to-one relationship or if there should be some magnification represented has been a problem for the designer. The work of Stan Roscoe (1951), University of Illinois, indicated that pilots flying light airplanes and viewing an optical image of the runway out ahead at the distance of the windshield required a magnification of this image of 1.25:1 to provide equal skill to their flight performance looking through a non-magnifying window. This ratio of 1.25:1 is also found for the size constancy judgments of Sam Renshaw and Associates (1949) when they were measuring the matching of a 30 cm square disc photographed from 1 to 6 meters and the matching object was also at near point. In the current optical systems which use infinity display, the question as to whether a 1.25:1 magnification is required or 1:1 has not been definitively established.

Since the introduction of Life magazine in 1934, we have been treated to photographs taken with exceptionally long focal length lenses, and in recent years, these have been commonplace within the news media. Sporting events are televised where zoom lenses of unusually long focal length are available and have become an every day affair. Most everyone has recently seen the modification of the depth of objects and the inter spaces between objects as collapsed by long focal length lenses. No designer would choose to use such long focal length lenses in presenting visual scenes for flight crew training; however, even smaller magnifications might have rather subtle influences on the perception of the runway plane and the relative distances between objects. It is therefore proposed that we look at the relative estimations of glideslope angle and distance from runway as a function of changes in magnification.

METHOD

Apparatus

It is proposed that a series of photographs be made of one of the more precise models of runway scene by five different focal lengths of lenses. Within each one of the magnification categories, use five different distances and five different altitudes to make up 25 photographs. In all there would be 125 photographs representing five magnifications within the range from 1:1 to 2:1 and these would be reproduced for both night and day scenes. The projection equipment would be a carousel projector. The images would be displayed on a screen which would be viewed by the observer through a windshield-like cutout. Each of the scenes would be displayed such that the field of view was constant; that is, the field of view would be 30 degrees vertical and 40 degrees horizontal and the image size of objects within the scene would be allowed to vary to maintain the field of view. Displayed on the same screen, at given intervals of time, would be a comparison standard which would represent a day scene or a night scene at a magnification at an intermediate distance to all photographs. This will be the magnitude estimation scaling standard.

Experimental Design

The experimental design for this optical magnification study is represented in Figure E-1. It is a 2 x 5 factorial design where, in each cell, 12 pilots participate. They will have a chance to look at each of the photographs twice; i.e. two replications.

Observers

Twelve pilots from McChord Air Force Base will be assigned temporary duty. They will not be specially tested for general vision requirements, but they will be given a special test to estimate their size constancy judgments.

Procedure

The magnitude estimation scaling technique will be used with the standard representing a 3-degree glideslope, 1:1 magnification, and an intermediate distance for all photographs. The standard will be assigned a unit value of five and all the other photographs will be assigned values above and below five. Using values 1 through 10, the subjects will be asked to estimate the representative distance to the runway threshold from the viewpoint as they are seeing it and, also on a scale of 1 through 10, whether they are above or below the conventional 3 degree glideslope. Each of the observers will have four presentation sessions; two for day scenes and two for night. They will see 125 presentations and make the estimates of the two values of distance and glideslope for each. Each photograph will be presented for about 3 seconds and the intertrial interval will be approximately 3 seconds. The experimenter will indicate the numerical response and will be backed up by a tape recorder in case a response is missed.

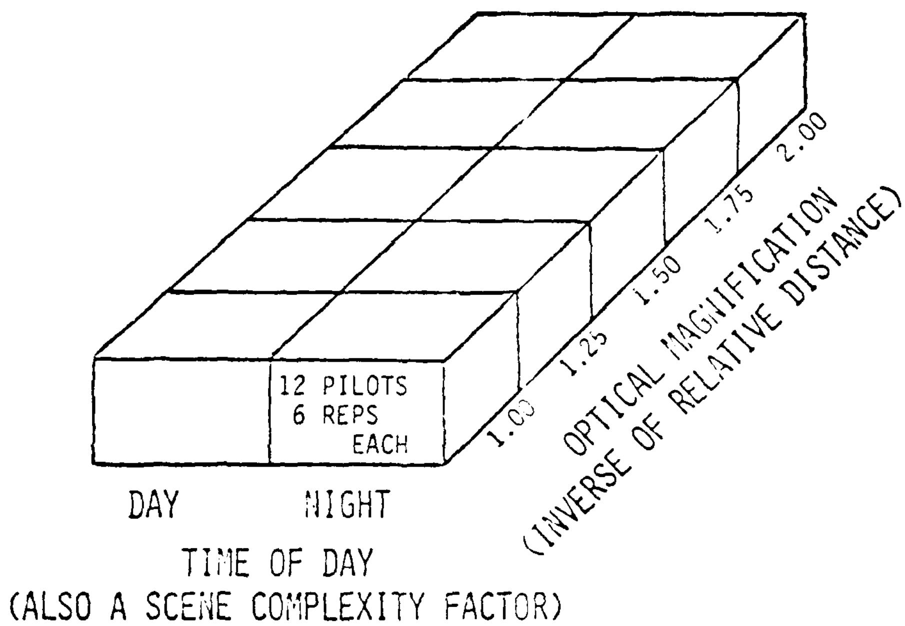


Figure E-1. Experimental design for optical magnification study.

Analysis of Results

The conventional techniques of recording magnitude estimation scaling will be used and statistical treatments will be applied to ascertain whether the magnitudes of the differences in estimates could be attributed to chance.

Conclusions, Recommendations and Documentation

If the results indicate that the perceived slant of the runway plane is altered by magnification resulting in underestimation of the distance to the runway, the data should provide (a) magnification limits beyond which pilot performance should be expected to change; (b) optical corrections that might be used to alter optical display designs. A complete report of the study, the analysis of the results and the recommendations will be documented.

APPENDIX F

EXPERIMENTAL DESIGN #4

THE EFFECTS OF ACCOMMODATION/CONVERGENCE ERRORS INTERACTING WITH QUALITY OF DISPLAYED IMAGE

Two questions posed in reference to collimation mismatch between the two eyes as it affects pilot performance and how such errors interact with image quality in visual displays are represented by the following two hypotheses:

Hypothesis #1: Collimation mismatch between the two eyes has an effect upon pilot performance and comfort.

Hypothesis #2: Collimation errors have an interaction with image qualities found among today's visual displays.

Collimation errors comprising divergent rays produce visual discomfort for many individuals (Farrell & Booth, 1975). The reasons for such discomfort are well established in the ophthalmological, optometric, and behavioral-optics literature. Collimation errors with non-corresponding convergent rays do not produce the same level of discomfort and most individuals can tolerate this type of error. Performance on a difficult visual task is attenuated when convergence and accommodation are not matched (Farrell, et al., 1970). Most physiological distress will probably occur when accommodation is not matched with convergence, for example if the virtual or real image is at less than 10 meters but the convergence is maintained at zero degrees or parallel. Additional probability of discomfort or disorientation may occur when a blurred image is added to the mismatch of convergence and accommodation. Pyle and Booth (1978) have very recently shown that with resolution (image quality) attenuated for one eye while the other eye has a high quality image, visual stereoacuity is reduced more than if both images are of the same poor quality (personal communication).

In many virtual image display systems that use a beam splitter and spherical mirror the design goal is to present an infinity image. One such display has 25 inch CRTs hung above the forward and side windows of the "aircraft"and facing downward. Beneath the CRT is a beam splitter that reflects the rays forward into a spherical mirror which has a 59.6 inch radius of curvature. The image is reflected through the beam splitter to the pilot's eyes, which are 47 inches from the CRT along this folded path.

This infinity window has been tested optically and no rays are focused short of 10 meters. Thus if the eye is focused exactly where the image is the amount of accommodation would be 0.1 diopter. If collimation is at the design value of zero degrees, there will be a slight mismatch between accommodation and convergence.

The question then is whether a mismatch of convergence and accommodation poses a problem by attenuating performance or comfort. Figure 44 is from the "Design Handbook for Imagery Interpretation Equipment"

(Farrell & Booth, 1975). The upper figure on this page indicates that stereoscopic performance is degraded when the viewing distance differs by more than 0.75 diopter from a value that matches the convergence angle.

In the example described, the dioptric value is significantly less than the experimentally determined 0.75 limit. Conversion of the 0.75 diopter tolerance in viewing distance into a 2.7 degree tolerance in convergence, and combining these into a tolerance zone, gives the lower illustration in the figure. Note that the example display (starred in Figure 44) falls well within this comfort and performance zone. In answer to the question, it can now be ascertained that the accommodation-convergence mismatch probably does not attenuate performance nor cause discomfort for this particular simulator display.

In most designs of infinity displays, the manufacturer would not permit errors of mirror curvature that would impose differential accommodative distances between the two eyes. However, when developing simulators for high speed combat aircraft, the interactions of an operational windshield and the external scene display may become significant. For discussion purposes only, consider the F-111 windscreen, with its more than 60 degree angle of incidence and compound curve. In some of these windows a magnification difference of 27 percent has been measured in the inspection process. Such a magnification could alter the accommodated distances to one eye while the other eye is accommodated to the design reference distance. Prismatic distortions could also alter convergence distances.

METHOD

Five sets of "Defocused Series" of the CLST would be used to represent five levels of image quality in scene generators. The range of resolutions. or first independent variable, would extend from 0.4 to 9 arc minutes of visual resolution. This is a range from "just slightly better than the eye can resolve" to almost the equivalent of "clinically blind." This range includes three steps that are possible with current simulators and two steps approximating the ideal.

The second independent variable will be accommodative differences between the eyes. One or the other eye will always have accommodation at a 10 meter distance and the other eye will have an image at 10, 4, 2, 1 or .5 meter. Convergence will be kept at zero degrees.

Apparatus

These five sets of eight pairs each of stereoscopic slides would be shown to eight observers in the long focal length Badal Optometer. This instrument can be very precisely set as to accommodation and convergence. The instrument's unique feature is that the same retinal image size can be maintained while changing the accommodative distance from 0 to 2.3 diopters or ∞ to 44 centimeters.

Experimental Design

Figure F-1 depicts the basic design for the main investigation of the effect of collimation error on visual performance. The design is a 5 x 5 factorial with the following two independent variables:

1. Five resolutions with values of .4, 1.3, 2.9, 5.0 and 9.0 arc minutes.

2. Accommodation difference between the two eyes, measured in both diopters and in distance, or meters. The diopter levels are 0.0, .15, .4, .9, and 1.9 for one eye while the other remains at 0.0 diopters accommodation.

Observers

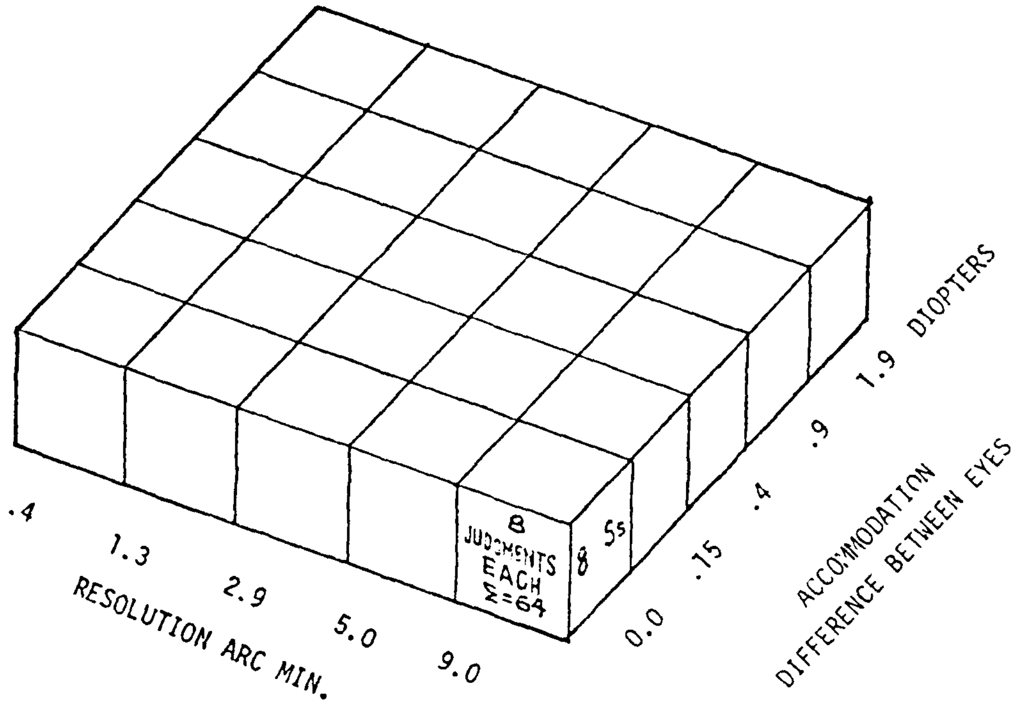
Eight observers will be selected, on the basis of an examination of visual skills, to serve as test subjects. These observers will have a visual acuity skill of at least 20/25 (0.8 decimal equivalent) uncorrected with differential acuity between the two eyes less than 0.1 decimal equivalency, and a stereo acuity skill of at least 13 arc seconds (50 percent threshold), as determined by the CLST. The observers shall have measurable natural aniseikonia of less than .2 percent in any meridian and phorias at far point no greater than .25 diopter vertical and 1.5 diopters disassociated lateral.

Procedure

The procedure would be to select eight observers for their visual skills including a stereoacuity of at least 13 arc seconds. (This matches the mean of our sample of USAF C-141 pilots as to this skill on the CLST test.) They will be given one pair of stereo slides under each cell of the diagram given in Figure F-1. Each pair requires eight judgments per slide pair. Therefore, each cell will receive 64 judgments from the eight observers. The task will be to select the stereoscopic disc from a line of 10 that appears nearest the observer's eyes. The observer will be instructed that the end disc in each line is an anchor, so the choice is one out of eight. The whole matrix is a 10 x 10 arrangement of discs in rows or columns. Four sizes and four brightnesses are confusion dimensions that must be disregarded in selecting the one disc with relative disparity.

Analysis of Results

When data collection is complete, the data will be transferred to punched cards and analyzed. The data can be reported in number of correct responses, errors, types of errors, etc. and also by a cubic equation into threshold units directly comparable to the USAF vision tester or the Verhoeff test used by School of Aviation Medicine. The statistics utilized will be analysis of variance, Student's t's or non-parametric tests.



<u>DEPENDENT MEASURES</u>

TOTAL CORRECT RESPONSES

STEREOSCOPIC THRESHOLDS

<u>TASK</u>

STEREOSCOPIC DISCRIMINATION

Figure F-1. Experimental design for hypothetical study no. 1: *Interaction between collimation errors and image* quality (resolution).

Conclusions, Recommendations and Documentation

It is anticipated that with the increased difference in the collimation distance, the stereoscopic performance of the observers will be measurably decreased. The rate of attenuation of performance will be more rapid with each level of poorer image quality. Discomfort in terms of selected comments, complaints of "eye strain," and for some dizziness and near nausea, will parallel visual performance.

It is believed that a description of performance and comfort envelopes for each image quality can be made wherein collimation errors should not be allowed to occur in simulation. Such data may also be translated into windscreen design parameters.

APPENDIX G

EXPERIMENTAL DESIGN #5

DETECTION OF ROTATION IN A SCENE INSERT AS A FUNCTION OF INSERT SIZE, RASTER-LINE DENSITY, AND SCENE COMPLEXITY

The questions raised in regard to the detection of misalignment in a scene insert are represented by the following hypotheses:

Hypothesis #1: The size of the scene insert will have a proportional effect upon the ability of the observer to detect rotational misalignment of the insert.

Hypothesis #2: Increasing the raster-line density ratio between the insert and the surrounding scene will lower the detection threshold for rotational misalignment of the insert.

Hypothesis #3: More complex scenes, particularly where there are more "straight lines" in the scene, will make rotational misalignment of the insert easier to detect.

One of the goals of visual flight simulation design is to produce a display system which can take full advantage of CGI signals, provide adequate luminous intensity, realistic scene movement and velocities, large field of view, and an area of interest or target-associated insert with high resolution. One of the major problems is in placing, stabilizing, and matching this area of interest or target insert to the surrounding scene such that the high resolution image is provided with minimal scene distortion, misalignment, or intrusiveness. Since line scan imagery is one of the current display techniques, raster line density will be one of the recognizable differences between the insert and peripheral portions of the display. Discrimination, by the raster line density, of any misalignment may decrease as scene complexity increases.

The problem of this study will be to determine the just noticeable rotation of an insert as a function of (a) the size of the central insert, (b) the comparative number of raster lines between insert and peripheral field, and (c) the complexity of the scene.

METHOD

Apparatus

For this study, three types of CGI scenes will be used, representing different levels of scene complexity: on the runway, ground-to-air, and approach to runway. These scenes will be photographed from the pilot's eye point in the Boeing 747 Flight Training Simulator with a Crown Graphic camera, having a 4 x 5 inch film size. The 4 x 5 inch transpositives will then be used to produce 35-mm slides with the rotated insert and raster densities built into them.

A total of 180 35-mm slides will be made to represent four levels of raster density ratios, three levels of insert size, and three levels of scene complexity. Five levels of insert will also be built into the slides.

Basically, each slide will be developed using a double exposure technique, one exposure for the surround and a second exposure for the insert scene. In between the exposures, the rotation will be put in using precise positions with .002 mm accuracy on a large Mann Comparator, upon which the 4 x 5 transpositives and the 35-mm camera will be mounted. Registration pins on a glass plate will be used for location accuracy and pairs of masks precisely cut on a Coordinatograph and reduced down onto Kodalith film will be used for scene masking and the raster grid. These slides will be presented to the pilot/observers using a random access projector and a rear projection screen.

Experimental Design

For this study, it is proposed to use 3, 6, and 12 degrees (at the eye) as sizes for square-shaped inserts which will be located in the center of a 48 horizontal x 28 degree vertical field of view.

Likewise, it is proposed that the rotational misalignment levels for the insert portion of the scene (the insert frame itself will not be rotated) be selected at 0, .25, .50, 1.0, and 2.0 degrees, measured as rotation around the center of the scene.

For the different raster line densities, a slightly defocused square wave line grid with a 2 to 1 line width to space width ratio will be superimposed on the insert and surrounding scene at four levels of spatial frequency ratios: 0, 9:9, 9:3, and 9:1. In the first, no line grid will be used for either the insert or the surround. For the other three ratio levels, the insert will have a grid spatial frequency of 60 cycles per degree (one line pair subtends 1 arc minute). The surrounding scene will have grid spatial frequencies of 60, 20, and 6.67 cycles per degree vertical field. The experimental design is shown in Figure G-1.

Observers

Sixteen pilots from McChord Air Force Base will be selected, after an examination of visual skills, to serve as test subjects. These pilot/observers will have a visual acuity skill of at least 20/20 corrected.

Procedure

The 180 slides comprising the stimulus material will be randomly arranged in slide trays for presentation on a rear screen projector. The pilot/observers will be seated at a distance of 28 inches from the screen and the projector will be situated such that the scene field of view provided the observer will cover 42 degrees horizontal and 28 degrees vertical.

Each of the 16 observers will see all 180 slides. Their task will be to determine if the insert appears to be rotated relative to the peri-

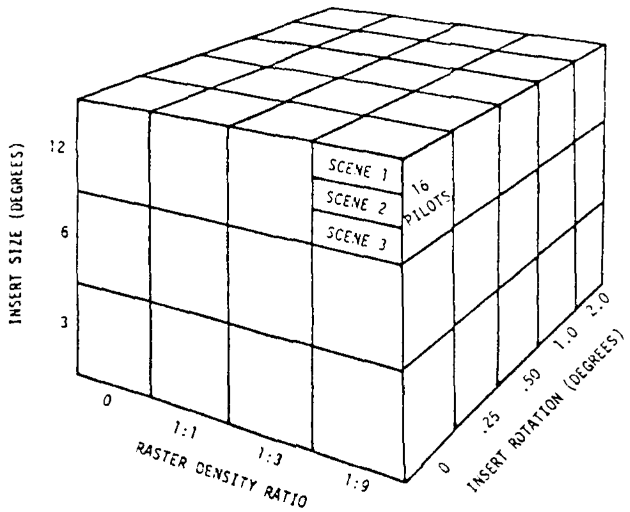


Figure G-1. Experimental design for study of effects of insert size, scene complexity and raster density ratio on the detection of insert scene rotation.

pheral portions of the scene, and if so, in which direction. The responses required will be of three category forced choice specification (aligned, rotated clockwise, rotated counterclockwise). A short set of training slides will be given each observer prior to testing.

Analysis of Results

When data collection is complete, they will be transferred to punched cards for computer analysis. The data can be reported in number or percent responses, errors, types of errors, etc. and also converted into threshold units. The statistics utilized will be analysis of variance and appropriate range of correlation tests.

A quantitative value for a just not noticeable rotation of the insert scene will be established. Whether the imposed raster density of the peripheral field (realtive to field of view) alters the just not noticeable threshold will be ascertained. The 50 percent and 95 percent detection thresholds will also be calculated. In addition, whether the 3, 6, or 12 degree central insert size results in greater or less discrimination and whether a more complex scene influences this discrimination will also be determined.

Conclusions, Recommendations and Documentation

If the 6 or 12 degree field of view for an insert does not alter discrimination of rotation mismatch the smaller field of view may be used when higher resolution is desired for a central insert. How wide a field of view may be used for the surround before the line scan sizes become too large and force an easy discrimination of the insert may also be established. The detection thresholds will help establish how much misalignment or rotation of the insert can be tolerated before affecting detection of the insert border.

APPENDIX [illegible]

EXPERIMENTAL DESIGN #6

THE EFFECTS OF SCENE COMPLEXITY AND SEPARATION ON THE DETECTION OF SCENE MISALIGNMENT

Two questions posed in reference to the effects of scene complexity and separation on the detection of scene misalignment are represented by the following two hypotheses:

Hypothesis #1: The tolerance for scene misalignment increased with the width of the joint or separation between two displays.

Hypothesis #2: This tolerance will vary with the dimension of scene complexity.

Scenes may be divided into any number of separate windows in aircraft simulators. As an example, the 747 simulator at the Boeing Flight Crew Training Center has six displays. The directly forward scene is provided to the Captain and First Officer from a single channel of the image generator. Two forward oblique displays increase the field of view for each pilot, and in addition, there is a right and a left side window. Each of the last four requires a separate video channel. Separations between these displays vary from 3 arc minutes to about 20 degrees. Differences in scene misalignment across the 3 arc minute "joint" are the subject of pilot's complaints but are often smaller than objectionable misalignments which exist across the 20 degree separation. Acceptable matches in color take three times longer to achieve across the 3 arc minute gap because smaller differences are more easily recognized by the maintenance personnel.

This experiment is designed to provide some threshold measures for detection of scene misalignments with (a) rotation centered around the middle of the picture with the fulcrum at the right side of the left picture (at a display joint), (b) vertical displacement of whole scene, (c) display joints of various widths, and (d) scenes with different levels of complexity.

METHOD

Apparatus

An approach scene to Boeing International Field (heading 13) will be made on 4 x 5 inch color transpositives from the pilot's eye position in the 747 flight simulators with the G.E. Compuscene CGI visual system. Similarly, photographs will be taken of the CGI scene with the aircraft sitting on the runway and as though it were viewed from the ground at the same altitude and distance as in the approach scene.

The three 4 x 5 inch photographs will be rephotographed onto 35-mm slides with a vertical strip of blackness separating left and right portions of the scene to make up a series of slides.

In each slide, the left hand scene (16 degrees of the total 42 degree horizontal field) will be either rotated or displaced to produce misalignment at the joint. Four levels of rotation will be used, and likewide, when displacements are present, four levels will be built into the 35-mm slides.

These slides will be projected by a digitally accessed projector on a rear projection screen set at an appropriate distance to provide the observer with a 42 x 28 degree field of view.

Experimental Design

Figure H-1 depicts the basic design for the main investigation of the effect of scene complexity and separation on the detection of scene misalignment. The design is basically a "double" 3 x 4 x 5 factorial with the following three independent variables:

1. Amount of scene complexity - three levels which include a "runway" scene, an "approach to runway" scene, and a "ground to air" scene. The dependent variables is a number of mis-alignment detections recorded as the number of correct recognitions of the type of misalignment (displacement or rotation).

2. Amount of scene misalignment (either displacement or rotation) - with rotations to be 0, .5, 1.0, and 2.0 degrees from center of joint. Likewise, four levels of displacement will be used: 0.0, 14.1, 42.3, and 84.6 arc seconds of visual angle.

3. Width of display joint - five levels will be used: .125, .25, .50, 1.0 and 2.0 degrees of visual angle as viewed by the observer.

Observers

Sixteen pilots from McChord Air Force Base will be selected to serve as observers in the experiment. They will be screened for vertical and lateral phoria, and have a visual acuity of at least 20/20 corrected.

Procedure

The slides will be presented for 3 seconds followed by a 5 second dark interval for a response. Each observer will judge (a) whether a misalignment exists, and (b) the kind of misalignment seen. The observer will be shown each slide once in a prearranged random order which will be counterbalanced across subjects. Each observer will see 120 slides, with a short set of training slides to precede the test session.

Analysis of Results

The data will be treated statistically with analysis of variance, and Duncan's Multiple range test, along with calculations of various detection thresholds. The results and interpretation will be included in a report of all phases of the study.

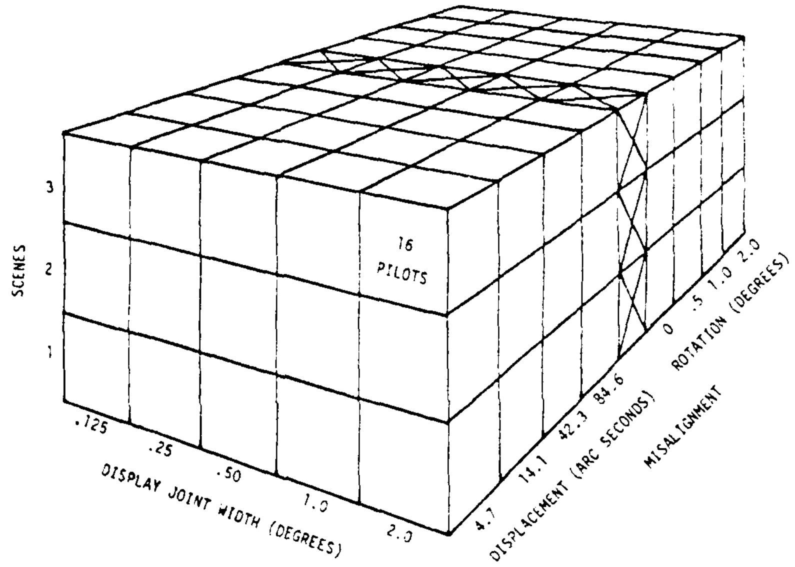


Figure H-1. Experimental design for study of the effects of display joint width and scene complexity on the detection of scene misalignment (rotation or displacement).

Conclusions, Recommendations and Documentation

The threshold for discrimination of misalignment across a display joint should be provided by these data. It is expected that this threshold should rise as the width of the separation (joint) increases. This would indicate greater tolerance for misalignment the larger the separation of displays. It is likely that straight lines in imagery will maximize discrimination of misalignment.

Preliminary quantitative standards should be established for specifictions on scene alignments across disparity joints.

APPENDIX I

EXPERIMENTAL DESIGN #7

ABSOLUTE BRIGHTNESS LEVELS IN SIMULATORS

The single question posed in reference to the effects of absolute brightness levels in simulators on pilot performance can be represented by the following hypothesis.

Hypothesis: The absolute brightness level in a simulator will affect pilot performance in the areas of training, rate of learning, reaction time, comfort, orientation, etc.

Luminance levels in the medium and high photopic range are difficult to achieve in simulator external visual scenes. Two current full color, day-dawn-night, raster, computer generated image systems have 6.05 and 2.5 fL as central screen luminances when viewed from the pilot's eye reference point. In Figure 7-1, the abscissa is in foot Lamberts running from .06, such as with snow in full moonlight (rod and cone vision or mesopic range) to 10^4, such as with fresh snow on a clear day (cone vision only). The eleven references used are the best of 150 studies on luminance and performance. These are excellent investigations with good experimental designs, controls, statistics and publications. The data contained in these reports are deemed very useful in this proposed investigation.

The two vertical lines are nearly representative of the range of the day-dawn-night scene generators mentioned above. Another class of scene generators are night scenes with some low level luminances of surfaces. This second group generally range in the 0.2 to 0.4 foot Lambert luminance levels. The small dashed vertical lines on the left bracket this range. The luminances in the projection dome systems may define yet a third level.

A very recent development is a night only, stroke writer system fitted with a three color cathode ray tube. This development, in addition to providing blue within the night scenes, may provide luminous intensity levels equal to or above the raster type day, dusk, and night full color systems. Single flashing lights do have much greater intensities without increasing the size by software control of the area. A fourth level of intensities may soon be available in this development.

In comparing the day-dusk-night systems with the night only plus surface systems as to luminances, only the former reach the cone vision only levels like the real-world, day vision luminances. For the purchaser of such systems, this higher luminance comes at a price nearly five times greater than the night only plus surface systems.

The literature on visual phenomena shows that changes in pupil size, changes in contrast threshold, shifts in accommodation, age and luminance interactions, changes in color perception, and many other physiological and behavioral changes occur within this range. In Figure I-1, the horizontal lines show, by their extent, the luminous intensity range included by these investigators in their study. Within the brackets behind the investigator's name are designators of the principal dependent measure that was investigated; i.e., MTF refers to modulation transfer function. However, there are no data to show that pilot performance in the simulator, the learning rate, or the transfer of training are modulated by luminance levels.

This experiment is designed to obtain some preliminary data on the influence of absolute luminance level on pilot performance and any indication of fatigue, eye strain, discomfort, or kinetosis.

METHOD

Apparatus

The 707 simulator at Boeing Commercial Airplane Company will be rented as the vehicle. This will be rented with the visual system and an instructor pilot but no other crewmembers. The availability of this simulator is greater than for the remaining simulators. This is the reason for its choice; however, this brings with it the disadvantage that the line printer cannot be used with its host computer due to limitations of its drum memory. This eliminates quantitative readouts of flight parameters such as have been used in previous studies.

The visual system will be used in the "day" mode and three different data bases will be used as a means for combating boredom and basic color effects. The flying task will be approach and landings from offset origins with variable crosswinds. To require dependence on the visual scenes, the pilots will be asked to fly without altimetry, vertical speed indication, or glideslope indication.

The Compuscene will be set to give a control luminance of 6 foot-Lamberts. Three pairs of soft-sided, wide field, and ventilated goggles will be fitted with neutral density filters: each pair with a different density, 0.0, 1.0, and 2.0. These should provide absolute luminance levels of 6.0, 0.6 and .06 foot-Lamberts. These levels are designated by the triangles in Figure I-1 just below the abcissa.

Experimental Design

Figure I-2 depicts the basic design for the investigating of the effect of absolute brightness on pilot performance and comfort. The design is a treatment by subjects design with the single independent variable of absolute luminance at the levels of 6.0, 0.6 and 0.06 foot Lamberts.

The dependent variable will be the measures of: instructor pilot ratings, frequency and content of pilot commands on conditions such as stress and visual discomfort, reaction time to failures, and loss of orientation or kinetosis.

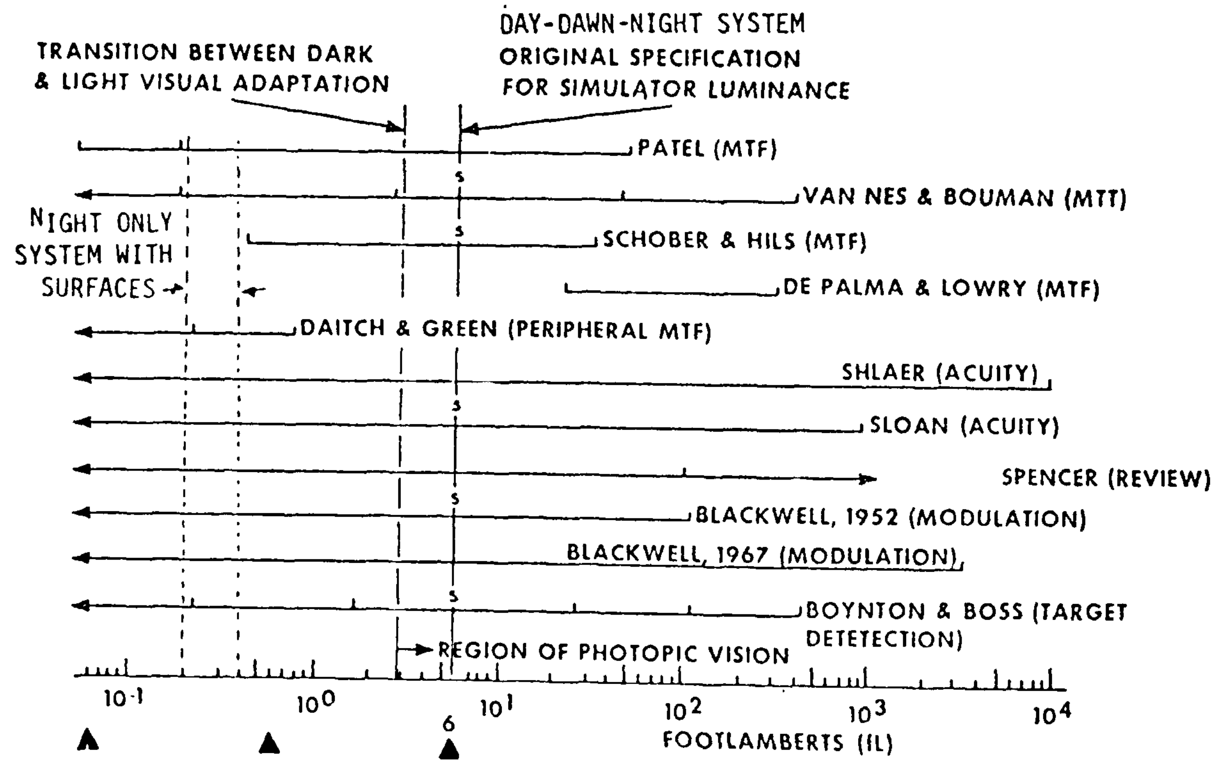


Figure I-1. Illumination levels at which visual performance was measured.

Observers

For this preliminary study two pilots will serve as observers. Preferably USAF pilots from McChord will be used. The requirement would be a full day and 2 half-days of temporary duty each. The full day would include some special visual tests in the half-day when they were not flying the simulator.

Procedure

The experimental runs will follow the diagram of Figure I-2. Each pilot will participate in each cell. Each cell will be a flight session of 4-hour duration without a rest. Standardized airborne failures will be instituted to measure reaction time and/or vigilance.

The effects of three levels of display brightness 4-hour flight times encountered in simulators will be assessed by reports of eye strain, fatigue, stress, and pilot preference. In addition, measurement of reaction time to displayed information such as an oil pressure drop in engine will be taken.

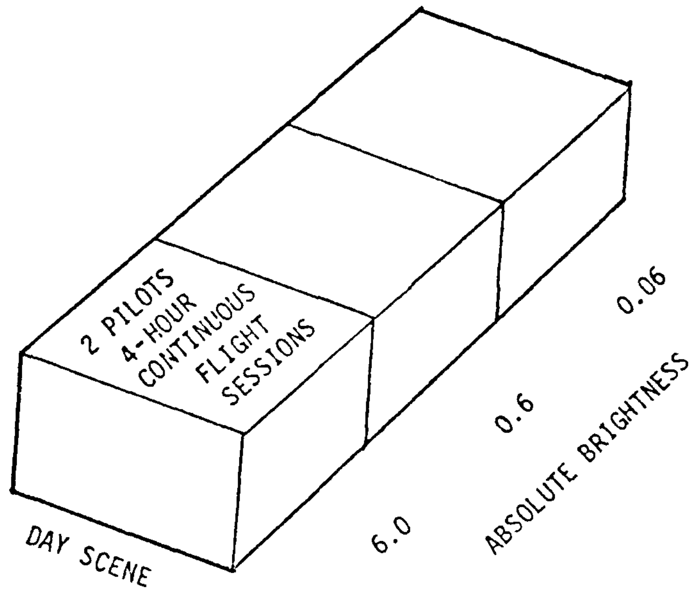
Analysis of Results

Since eye strain, fatigue, and stress do not have objective measures, subjective measures will be frequency of complaints, recording of all comments, and responses to verbal questions from a standard set used under each condition. An instructor pilot will be scaling the performance of flight maneuvers. Reaction times will be by stop watch from insertion of failure until pilot response.

Conclusions, Recommendations and Documentation

The performance of the pilots should show a higher frequency of omissions and small deviations in the flightpaths for at least the lowest luminance level. Instructor ratings should show a falloff in performance as a function of time for the lower luminances. The frequency of complaints, comments about the wind, and failure deviations should follow the loss of performance. Some comments about loss of image quality may reflect accommodation spasms. Some discrimination of differences in colors among the fields should occur and possibly be reflected in performance variations. Eye strain, fatigue comments, and irritability may show up. It is doubtful that rated and current pilots will experience any motion sickness or disorientation.

If two pilots, which is an insufficient sample, show a trend that indicates that the experiment is sensitive enough to pick up differences, reallocation of funds or additional funding may be warranted to increase the pilot population from two to eight.



Dependent Measures

IP ratings
Frequency and content of comments on conditions
Reaction time to failures
Comments of stress, visual discomfort, loss of orientation or kinetosis.

Task

Repeated approach and landings on 3 different data bases, cross winds and scheduled failures, no altimetry, vertical speed indication or glide slope. Continuous activity for four hours.

Figure I-2. Experimental design for hypothetical study no. 7. Absolute luminance level and performance in a simulator.