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HORIZONTAL DIPLOPIA THRESHOLDS FOR HEAD-UP DISPLAYS

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NOTICES

TECHNICAL REVIEW AND APPROVAL

AFAMRL-TR-84-018

This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

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

FOR THE COMMANDER

CHARLES BATES, JR.
Director, Human Engineering Division
Air Force Aerospace Medical Research Laboratory

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ERRATA

The following corrections should be noted for AFAMRL TR-84-018

The photographs appearing as Figures 5 and 6 on pages 20 and 21 should be interchanged.

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Horizontal diplopia thresholds were determined using a Head-Up Display (HUD) emulator which superimposed a small vertical line at various degrees of binocular disparity on a rich outdoor scene. The main findings are that observers are more intolerant of negative disparity than positive disparity. In negative disparity, a non-fixated object is optically further than a fixated object. For 32 observers, the overall median negative disparity threshold was 1.2 mrad and the overall median positive disparity threshold was 2.6 mrad. Assuming that pilots fixate on external targets, these results suggest that HUD imagery should be placed at a slightly nearer optical distance than background targets. The results also indicate that (1) longer viewing is more likely to lead to a diplopia effect than short glances, (2) resistance to diplopia appears to be an individual trait, and (3) a large proportion of responses involve suppression of the image in one eye. The report also includes a table of the percentage of observers reporting diplopia as a function of disparity magnitude. This table may be used to predict the incidence rate of diplopia among pilots for any allowed degree of disparity.

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PREFACE

This study and report were done at the Crew Systems Effectiveness Branch, Human Engineering Division, Air Force Aerospace Medical Research Laboratory under Project 7184, Man-Machine Integration Technology, Work Unit 7184-11-44, Image Display Mensuration/Enhancement.

The research was co-sponsored by the F-16 SPO, ASD/YP.

We would like to thank Dr. H. Lee Task of AFAMRL/HEF for help with the optical analysis and, for their support in the conduct of the experiment, Mary Ann Barbato and Rebecca A. Unger of Systems Research Laboratories.

SUMMARY

The purpose of this study was to determine the value of the horizontal diplopia threshold for use in providing pilots with better canopy-HUD combinations. Better combinations are needed to alleviate pilot discomfort and complaints of double vision (diplopia) of target or head-up display (HUD) imagery when using wide field of view HUDs on the F-16 aircraft. This doubling of vision occurs when there is a sufficient binocular disparity in the vergence of light coming from the target compared to the vergence of light coming from the HUD. Ideally, light rays from both the HUD and a distant target should be collimated which implies zero vergence angles and no binocular disparity. However, disparity may arise due to the HUD not being perfectly collimated or due to light from a distant target changing its vergence when transmitted through a canopy that is optically a weak lens.

The human visual system is tolerant of a small amount of disparity, but when a critical or threshold value is reached, a noticeable doubling of vision occurs. Thresholds were determined using a HUD emulator which superimposed a small vertical line at various degrees of binocular disparity on a rich outdoor scene. The main findings are that observers are more intolerant of negative disparity than positive disparity. In negative disparity, a non-fixated object is optically further than a fixated object. For 32 observers, the overall median negative disparity threshold was 1.2 mrad and the overall median positive disparity threshold was 2.6 mrad. Assuming that pilots fixate on external targets, these results suggest that HUD imagery should be placed at a slightly nearer optical distance than background targets.

The results also indicate that (1) longer viewing is more likely to lead to a diplopia effect than short glances, (2) resistance to diplopia appears to be an individual trait, and (3) a large proportion of responses involve suppression of the image in one eye. The report also includes a table of the percentage of observers reporting diplopia as a function of disparity magnitude. This table may be used to predict the incidence rate of diplopia among pilots for any allowed degree of disparity.

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INTRODUCTION

This study was initiated in response to reports of pilot discomfort and complaints of double vision of target or HUD symbology when using the LANTIRN wide field of view (WFOV) HUD on the F-16 aircraft.

This doubling of vision occurs when there is a sufficient binocular disparity in the vergence of light coming from the target compared to the vergence of light coming from the HUD. Ideally, light rays from both the HUD and a distant target should be collimated (which implies a zero vergence angle), and thus there should be no binocular disparity. However, light from a distant target changes its vergence when transmitted through a canopy and is thus no longer collimated or parallel. AFAMRL studies indicate that the canopy acts as if it were a weak negative lens, which causes a light divergence of approximately 3.5 mrad in the forward area (Genco, 1983, 1984; Task, 1983). The light from the HUD may also be uncollimated either deliberately or due to error. When the deviations from collimation are unequal, we say that there is binocular disparity.

The human visual system is tolerant of a small amount of disparity, but when a critical or threshold value is reached, a noticeable doubling of vision may occur. This doubling of vision, also known as "diplopia", is readily self-demonstrated: Place both your forefingers about 25 cm in front of you. Keep one finger immobile and always fixate it. Slowly move the other finger further away and notice that at some distance it appears double. This doubling also occurs by moving your non-fixated finger closer.

The general problem addressed in this report is that of determining the value of the horizontal diplopia threshold for use in providng F-16 pilots with better canopy-HUD combinations. Although there already exists a literature on diplopia thresholds, published threshold values are either questionable or gathered under circumstances inappropriate for generalization to F-16 HUD application. Thus, The F-16 SPO asked AFAMRL to conduct its own study.

Before reviewing the literature and describing the experiment, the specific objectives will be enumerated and the concepts of vergence and disparity as they apply to HUD displays and targets will be discussed.

Objectives

1. To determine the limits of the region of single vision as indicated by the horizontal diplopia thresholds of positive and negative disparity.

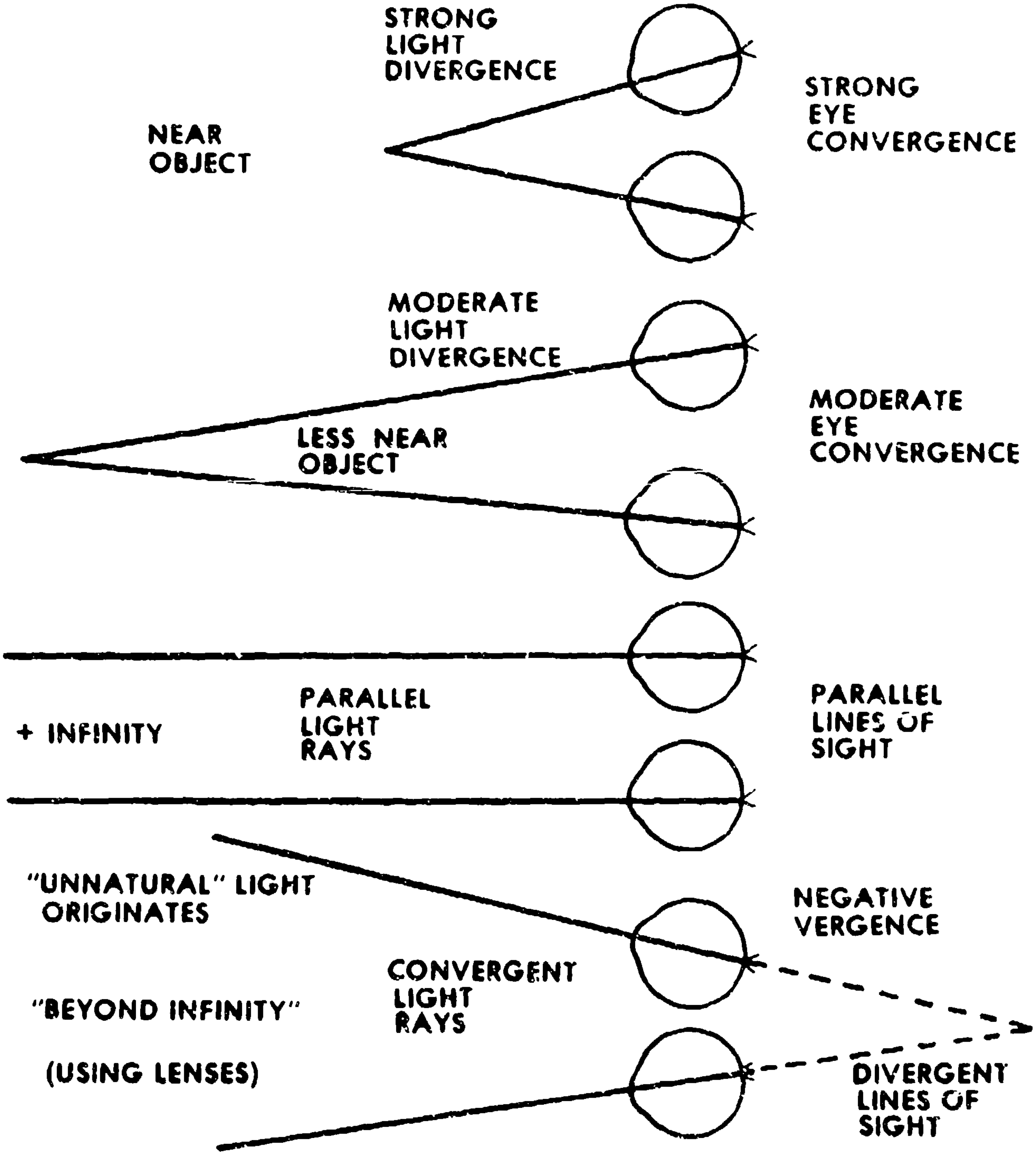
2. To determine the extent and nature of the distribution of individual differences in a Flying Class II Vision population.

Disparity/Vergence Sign Conventions

Vergence refers to a deviation from a parallel state and may refer either to rays of light or to the alignment of the eyes. Because of its usefulness in understanding the results, vergence here refers to the alignment of the eyes.

Eye vergence. The following sign conventions are used: Light from a source infinitely far from an observer is collimated and thus both the light and the eyes have a zero vergence angle. Light from a source nearer the observer requires positive eye vergence in order for the lines of sight to converge and intersect at the source. This in turn implies that the light rays coming from the source are divergent. Divergent light is "normal" in nature and converging the eyes is "natural" especially for close objects, hence the "positive" designation. Similarly, negative eye vergence means that the eyes' lines of sight are required to diverge outwards in response to converging light from some source. This situation is "unnatural" in two ways: (a) the eyes do not normally diverge outwards, and (b) light from an object in the world does not approach the eyes in a convergent fashion unless an artificial mechanism intervenes. If permitted, such convergent light would form an image behind the observer's head and the image is said to originate "beyond infinity". Figure 1 illustrates these relationships and also the fact that vergence (eye or source) covaries with source optical distance.

FIGURE 1. Eye Vergence and Distance



Disparity. Disparity arises when two objects are at different optical distances from an observer. The different distances entail different vergences (both eye and source) and hence the discrepancy or disparity. Disparity is here defined as:

Disparity = (eye vergence to nonfixated object)
- (eye vergence to fixated object)

and, assuming that pilots fixate the target,

Disparity = (HUD eye vergence) - (target eye vergence)

Disparity may be positive or negative and the sign conventions used here imply that positive disparity arises when the HUD symbology is optically closer than the target, and that negative disparity arises when the symbology is optically further than the target. Figure 2 and Table 1 illustrate these relationships.

The terms crossed and uncrossed disparity are also used. When a secondary (that is, nonfixated) object is physically closer than a fixated object and appears double about it, the left eye sees the rightmost image of the secondary object and vice versa, hence the term crossed disparity. When a secondary object is physically farther than a fixated object and appears double around it, the left eye sees the leftmost image of the secondary object, hence the term uncrossed disparity. Thus, here both positive and crossed disparity imply that a nonfixated object is nearer than a fixated object. Similarly, negative and uncrossed disparity are equivalent terms and imply that a nonfixated object is farther than a fixated object.

Table 1

Sign Conventions

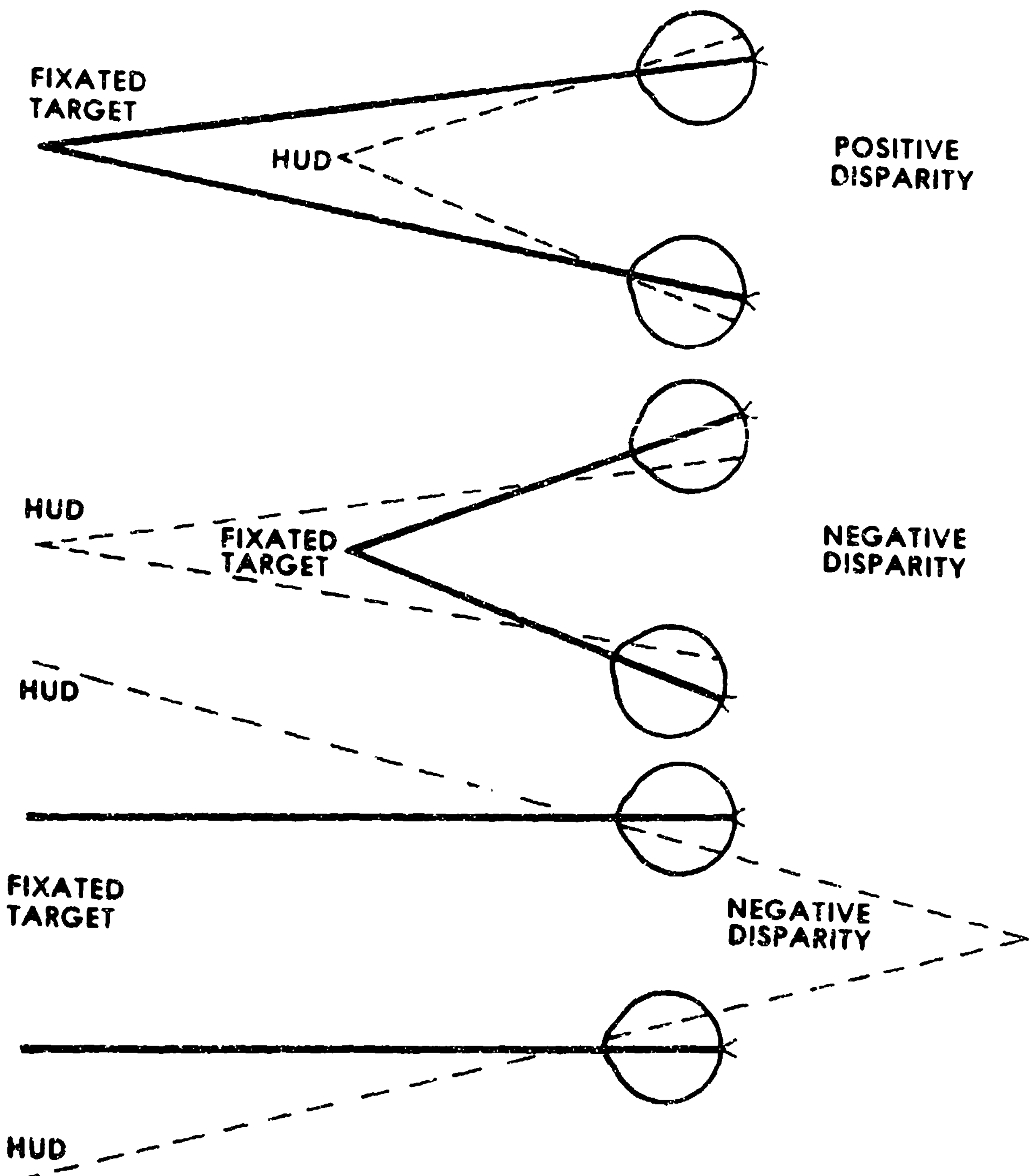
Vergence: Central Angle Between Lines of Sight

Positive: Eyes Converge
Zero : Parallel
Negative: Diverge

Disparity: Assume Target is Fixated, then

Disparity = HUD Vergence - Target Vergence
Positive Disparity: HUD Closer Than Target
Negative Disparity: HUD Farther Than Target

FIGURE 2. Disparity Examples



Literature Review

Units. The vast majority of articles report their measurements in minutes of arc. For comparability with the original articles, original values in minutes are reported with conversion to milliradians given in brackets. For reference, 1 minute of arc equals 0.2909 mrad.

Panum's area. Much of the research on diplopia thresholds has been conducted for the purpose of measuring the size of Panum's area. Panum's area is the region of tolerance for disparity and as such corresponds to a zone of single vision. Its extent is given by the sum of the limits (i.e., thresholds) obtained under positive and negative disparity (or equivalently, crossed and uncrossed disparity). Thus it is necessary to divide the values for Panum's area by two to obtain an estimate of the diplopia threshold. This estimate is equivalent to averaging the separate positive and negative disparity thresholds. This averaging unfortunately entails a subsequent loss of information and utility since, in all probability, the separate thresholds are not equal (i.e., Panum's area is asymmetric). For consistency within this report, values given here are the estimated diplopia thresholds rather than the size of Panum's area cited in the original articles.

The diplopia threshold may be tested either with a tachistoscopic presentation of a fixed disparity value or with a continuously changing display. Continuously increasing displays yield higher threshold values than tachistoscopic displays (Fender & Julesz, 1967; Schor & Tyler, 1981), but these dynamically obtained values are excluded from this report since the requisite conditions are not typical of HUD and target viewing. The viewing of HUDs and targets generally involves relatively short glances during which the viewed elements maintain a reasonably constant disparity. Hence all further discussion is with respect to statically obtained thresholds.

The classical threshold value. The "classic static value" of Panum's area (so designated by Shor & Tyler, 1981) is 14′ [4.1 mrad] which implies a direction averaged diplopia threshold of 2.0 mrad. This value is distilled from the reviews of Mitchell (1966) and Woo (1974).

Problems with the classic value. How seriously should this value be taken? Two factors stand out immediately in the reviews of Mitchel and Woo: The first is the large range of values reported in each reviewed study, and the second is that the reported values are based on very few observers. These factors suggest, at the very least using caution in basing decisions on these values.

Indeed, in a key article significantly entitled "What is the diplopia threshold?," Duwaer and Brink (1981), specifically argue that (p. 295): "Measured values of the diplopia threshold quoted in the literature have little or no utility, due to the enormous variation between the results reported by different authors. Reported diplopia values have ranged from 2′ to 20′ [0.6 to 5.8 mrad] for horizontal diplopia in the fovea." This range, they argue, is due to a number of factors which can affect the diplopia threshold including (1) the actual psychophysical method used for determining the threshold, i. e., tachistoscopic presentation of particular disparity levels versus a continuous change in the displays; (2) the criteria used to define diplopia, for example, any noticeable change in image appearance versus a distinct doubling of an image, and (3) individual differences among observers.

For foveal horizontal disparity, Duwaer and Brink report that their observers′ disparity thresholds vary by a factor of nearly 100 from 0.25′ to 22.2′ [0.07 to 6.46 mrad]. For a 160 msec presentation and a criterion of distinct doubling of vision, they report the mean thresholds for their two observers as 7.5′ and 22.2′ [2.18 and 6.46 mrad]. One observer′s thresholds for distinct doubling were 2.2′ +/- 0.8′ [0.6 +/- 0.2 mrad] for a 200 msec exposure of a display consisting of two aligned vertical lines each 30′ [8.7 mrad] long separated by 3′ [0.9 mrad].

How useful are these threshold values for Air Force application? Although Duwaer and Brink explicitly control for threshold criterion and continuous versus tachistoscopic presentation, there are a number of points to consider before accepting their values for making decisions with respect to canopy/HUD design: First, Duwaer and Brink′s thresholds were obtained using an empty white screen as a background. There is no guarantee that thresholds remain the same when the background is a rich environmental scene as may often be encountered in low altitude flight maneuvers. Second, their study used a 105 cm fixation point. It is not obvious what effect fixation distance has on the diplopia threshold, but fixation distances to targets or HUD symbology greatly exceed 105 cm.

Third, Duwaer and Brink's reported values are the average of separate positive and negative disparity conditions. This is unfortunate for HUD/canopy applications since neither the relative incidences nor the relative costs of rectifying positive and negative disparities are equal. It is thus important to know what the separate thresholds are since they are not necessarily equal. Fourth, Duwaer and Brink's results for horizontal diplopia are based on just two observers. Any application involving pilot safety and equipment expense merits a much larger data base.

In conclusion, Duwaer and Brink's study, although incorporating several improvements over previous studies, still does not provide diplopia threshold values which may be confidently used for HUD/canopy applications.

<u>Diplopia and Head-Up Displays.</u> Given the problems in applying general diplopia research findings to HUD design, it seems reasonable to obtain the thresholds directly with HUDs.

Gold and Hyman (1970) and Gold and Perry (1972) conducted HUD disparity tolerance studies using a comfort rating technique and found no differences for disparity tolerance between static and moving backgrounds. On the basis of both studies, they consider as reasonable a horizontal disparity tolerance of 1 mrad for negative disparity (their terms are exophoria and divergence) and 2.5 mrad for positive disparity (their terms are esophoria and convergence). Their studies differ from non-HUD studies in that (1) they distinguished between positive and negative disparity and found a large asymmetry, and (2) they used rich backgrounds instead of blank fields. The backgrounds were static aerial views or 16 mm motion pictures made during low altitude flight. They found <u>lower</u> disparity tolerance for rich as opposed to homogeneous backgrounds. These results are very interesting and, by design, more relevant to HUD applications especially with respect to the asymmetric tolerance for positive and negative disparity. The visual system is relatively intolerant of negative disparity, that is, a disparity which requires a divergent eye movement for correction.

C. P. Gibson (1980) also investigated discomfort due to disparity in HUDs using structured displays against a well-structured background. Although he used continuously varying disparity procedures, his results are similar to those of Gold: the mean discomfort threshold was 0.83 mrad of negative disparity for four observers. He notes that the disparity level leading to discomfort is significantly less than that needed for diplopia. This point should be kept in mind in any decisions with respect to HUD/canopy recommendations or specifications. Gibson went further and investigated the possibility that zero disparity itself is not the preferred amount of disparity. He found the optimal disparity level with respect to viewing comfort to be at 0.38 mrad of positive disparity. That is, people prefer the HUD symbology to appear slightly in front of the fixated target. This finding is intriguing and awaits verification.

The Present Study

Both Gold and Gibson found a relative intolerance for negative disparity using rich HUD displays and a criterion of discomfort. The present study was specifically designed to determine the diplopia threshold, as opposed to a discomfort threshold, in a large sample.

EXPERIMENT

Method

Observers

A total of 32 persons (25 men and 7 women) completed the experiment. All were volunteers from AFAMRL or provided through ASD/YP or ASD/EN. Nineteen wore glasses and 13 had uncorrected vision. Their interpupillary distances ranged from 58 to 71 mm with a mean of 64.6 mm and an SD of 3.0 mm. Their ages ranged from 20 to 45 with a mean of 27.4 years and an SD of 6.9 years.

All observers had been pre-selected to meet at least Flying Class II Vision Standards and, further, none wore contact lenses since Air Force pilots may not wear them. Flying Class II Vision Standards essentially require corrected vision to be 20/20 or better and the eyes to be healthy (for details see Air Force Regulation AFR 160-43). Vision screenings were performed by the staff of the Occupational Medicine Service at Wright-Patterson AFB or by a resident optometrist at AFAMRL.

Apparatus

Figure 3 is a photograph of the experimental setup. The HUD emulator and the viewing window are on the right side. The large rectangle on the left side is a bulletin board and not a window.

Binocular vision screening tests. Two standard binocular vision screening tests were used. They were the "No. 553 FD/ Fixation Disparity at Far" test and the "Stereo Reindeer Test" which tests stereopsis, fixation disparity, and suppression. Both tests were manufactured by the Bernell Corporation of South Bend, Indiana.

HUD emulator. The HUD emulator consisted of three main units: a housing unit, an optical system and a symbology projection unit. The housing unit consisted of a movable support platform with lockable castor wheels; a chair fixed to the platform and centered with the optical unit; and a 74 cm long by 61.0 cm wide by 102 cm high metal cabinet which supported the optical system and housed the drives and power units.

The optical system was based on a convex 13.97 cm (5.5") diameter lens with a 30.48 cm (12") focal length. This lens was mounted with its axis

Figure 3. Apparatus Layout

vertical in a hole in the top of the cabinet. Figure 4 is a diagram of the system. A beamsplitter (partially silvered mirror or combining glass) was placed at a 45 deg angle on the observer's side of the lens 9 cm above the cabinet to make the axial path of light from the symbology projector horizontal and, in turn, to permit the observer to look over the cabinet and through the mirror out towards the horizon. A chin rest was mounted on the cabinet to help position the eyes 56 cm from the lens center (41 cm from the combining glass) and also 112 cm from the platform (126 cm from the room floor). The symbology projector side of the lens similarly had a fully silvered mirror at 45 deg to make the optical axis horizontal with a shelf of the cabinet.

The symbology projection unit was placed on an optical track and consisted of a Welch-Allyn miniature line-filament halogen lamp behind a Uniblitz Model 3108 Shutter (Vincent Associates, Rochester, NY). The Model 3108 Shutter Controller was also on the shelf, but the shutter release cable was passed outside the cabinet to the observer. The light from the lamp was white but the symbology was made luminous green by placing a sheet of translucent green plastic over the lens' upper surface.

HUD emulator controller. The desired HUD symbology disparity was achieved by varying the distance of the line-filament lamp from the emulator lens. The lamp was positioned (with a step increment precision of .00025 inch) along an optical track with a Systems Research Laboratories Instrument Interface. This interface consisted of (1) a Velmex Linear Slide and stepping motor drive, (2) a Baldwin shaft encoder, (3) an Instrument Interface package SRL 6633-01-23-1182 Model A, and (4) a Hewlett Packard HP 9825 computer.

Psychophysical procedures computer. An IBM personal computer was used to record data and calculate the optimal disparity test values on each trial as described in the procedure section.

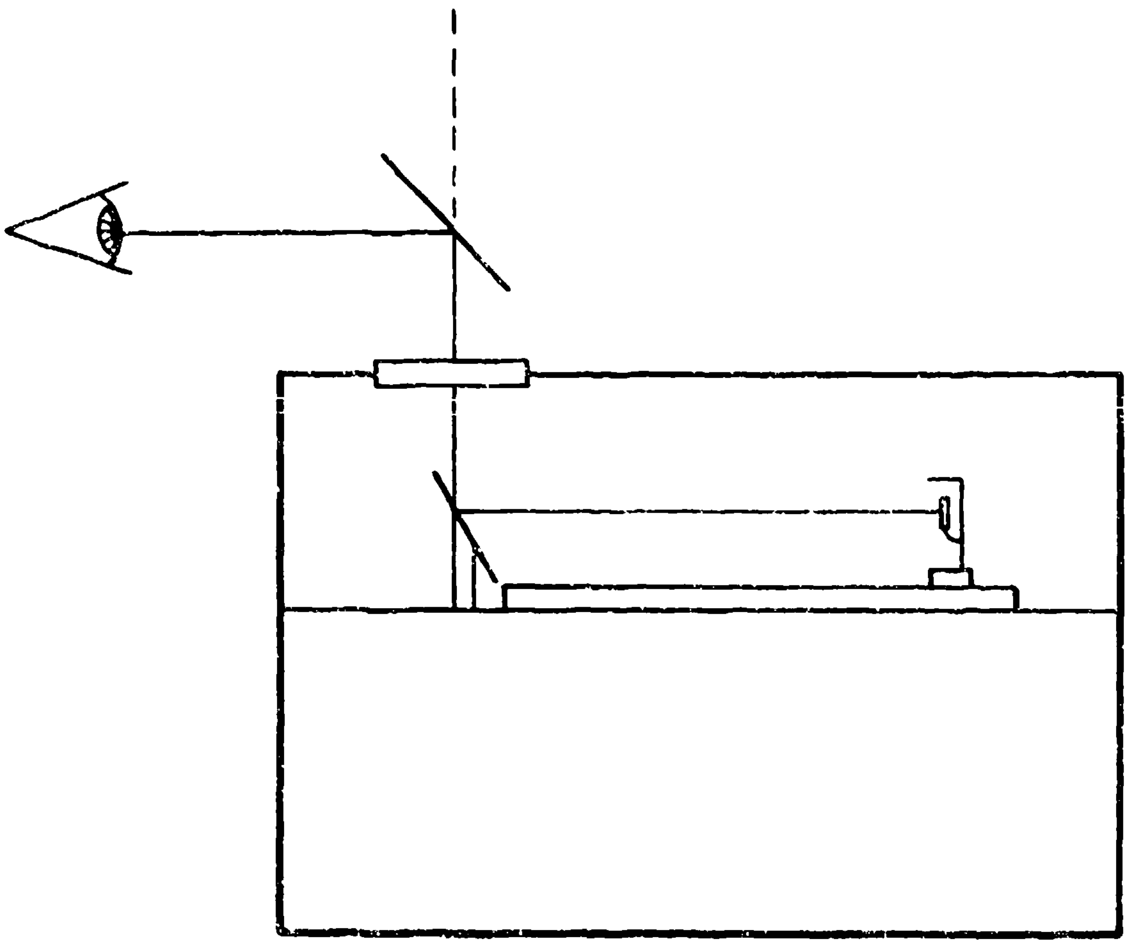


FIGURE 4. Optical Pathway in HUD Emulator

Visual Displays

The visible scene. The observer's eyes were positioned 160 cm from a 74 cm high by 140 cm long window, hence the optical size of the window was 47.3 deg horizontal by 26 deg vertical. Figure 5 is a photograph of the view through the window. The small central vertical line is the superposed HUD symbology. The window was on the third floor of a building and overlooked a complex scene consisting of fields, woods, and hills. Two roads with traffic flow were also visible. About 1.4 km ahead and in the middle of the scene was a white pole 5 mrad high and relatively isolated against an uncluttered patch of field. This scene was always visible to an observer. Observers were only tested during good daylight and weather conditions.

HUD symbology. For a brief interval during each trial, a short vertical luminous green line (6 mrad high by 1 mrad thick) was optically superposed on the visual scene by the HUD emulator. When the light from the HUD was collimated, the vertical green line was apparently aligned with, the same distance as, and just on top of, the white pole visible in the center of the scene. When the light from the HUD was deliberatly uncollimated, the green line could appear doubled with one line each to the left and right of the white pole. In addition, depending on the disparity introduced, the green line could appear either closer or further than the white pole. Figure 6 is the same view as in Figure 5 except that the double symbology image has been simulated by filming through a lens cover with two holes in it.

In this study, light coming from the far background including the white pole is undistorted and essentially collimated. (Since the target was at 1.4 km, each eye ideally converged inward by only 0.023 mrad from the straight ahead.) Thus, almost all optical disparity here is due to the vergence of light from the HUD symbology. (This is opposite to the case in an aircraft for which the light from the background is distorted and noncollimated due to the canopy and the light from the HUD is "intended" to be collimated.) Positve disparity thus means that the HUD symbology appeared closer than the target and that the eyes would have had to converge to fixate the HUD symbology. Negative disparity means that the HUD symbology appeared further than the target white pole and that the eyes would have had to diverge from their fixation to the target. Since the target was almost at optical infinity and required near-zero convergence to fixate, the HUD symbology had to be placed "beyond" optical infinity in order to produce the requisite negative disparities and appear further than the target.

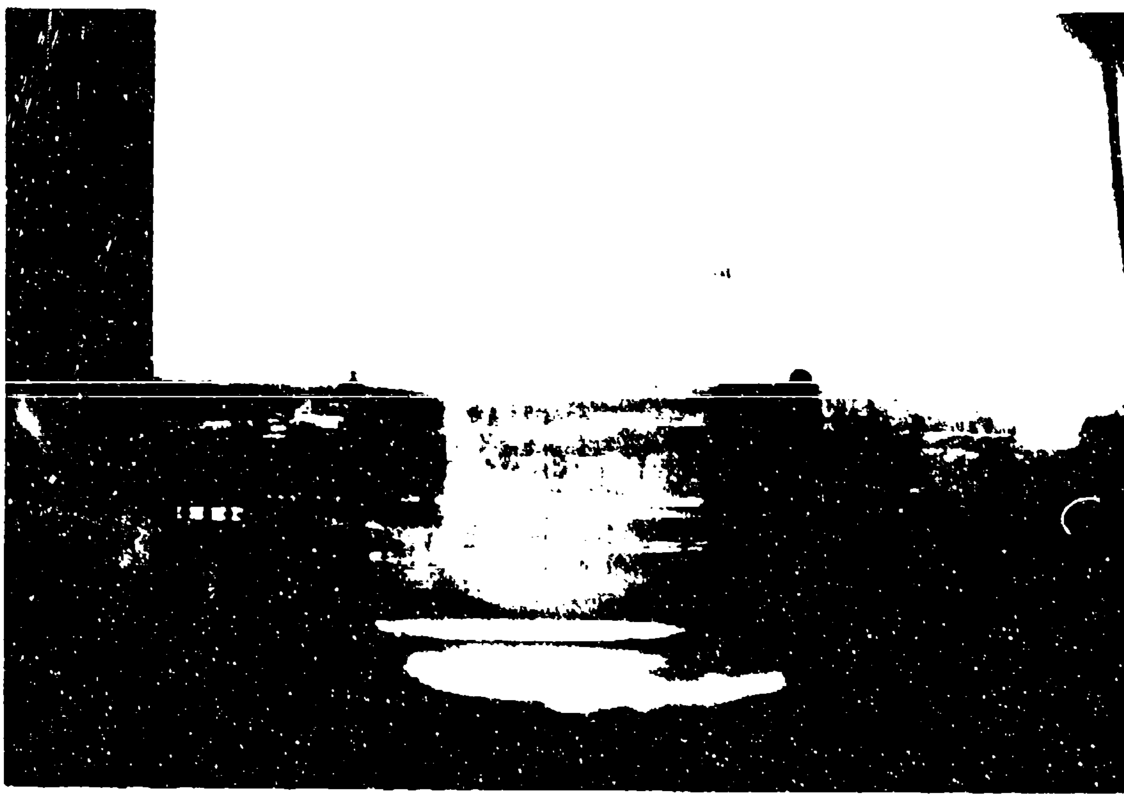


Figure 5. View Through HUD

Figure 6. Simulation of Disparity in Field of View

Procedure

Preliminary activities. Upon entering the experimental room, an observer was briefed on the experimental procedure and apparatus. After being given an opportunity to ask any questions, the observer was asked to read and sign a voluntary consent form. All observers gave consent. Following the consent giving, an observer's interpupillary distance (IPD) was measured and sex, age, and spectacle-wearing status were recorded. The observer was then tested for stereopsis, fixation disparity, and suppression with the Stereo Reindeer and "Fixation Disparity at Far" tests using standard procedures.

If no problems were revealed, an observer was seated in the HUD emulator, checked for proper head placement, and instructed in detail as to the task to be performed on each trial. Double vision was explained and the observer was asked to self-demonstrate the phenomenon by placing one index finger at arms length directly in front of the nose, then placing the other index finger midway between the first and the nose, and finally, shifting his or her fixation between the two finger tips and noticing the doubling effect. An observer was then made familiar with the scene visible through the HUD and the criterion to be used in judging double vision. After answering any questions, the experimenter measured the observer's IPD a second time and administered six preliminary trials using a range of preselected HUD emulator settings in order to familiarize the observer with the procedure. When the experimenter was satisfied that the subject understood the procedures, she entered the observer's IPD into the psychophysical procedures computer and began data collection.

Single trial procedure. The disparity value and the corresponding HUD emulator setting specific to the observer's IPD were determined by a computer as described in the psychophysical technique section. After the experimenter set the HUD emulator controller to the desired value, she gave the observer a ready signal. The observer then positioned his head in the chin rest, looked at the target white pole, and pressed a shutter release button. A shutter in the HUD emulator then briefly displayed a luminous green line. Immediately following the presentation, the observer said whether or not the luminous green line appeared double or single and, if single, if it was aligned with or displaced left or right from the target white pole.

Diplopia criterion. A judgment of single-vision, and hence the diplopia threshold, depends on the criterion used to define a diplopia effect (Duwaer & van den Brink, 1981). For example, three possible bases for declaring a diplopia effect include (1) when any discrepancy from "normal' single appearance is noticed such as a slight fuzziness, (2) when the line has "significantly" increased in apparent width over its "normal" appearance albeit the line is still single, or (3) when the line has apparently split into two lines and there is a perceptible space between the two images. This last and most stringent criterion was adopted for this study because it entails the largest threshold value. Thresholds under the looser criteria may easily be estimated from the maximum value, for example, by halfing it.

Criterion for diplopia: suppression case. If an observer suppresses, neither a double image of the background nor the symbology will be seen. Instead, there is an apparent displacement of the symbology relative to the background. Here in particular, the symbology line would no longer appear aligned with, and at the same distance as, the white pole; but rather shifted right or left and (sometimes) also nearer or farther than the pole. In case of suppression, observers were instructed to adopt a diplopia criterion equivalent to that for double images: the misalignment should be clear and complete.

Diplopia effect threshold definition. The diplopia effect threshold is defined as the amount of disparity (positive or negative) between the HUD symbology and the farground which elicits a report of a diplopia effect on 50% of the occasions when it is presented. A smaller disparity may also induce a diplopia effect but only on less than 50% of its presentations; likewise, a larger disparity may fail to elicit a diplopia report but only on less than 50% of its presentations.

Thresholds generally entail a binary choice, a simple "yes" or "no" to a detection question. But here an observer has four choices: double, single and centered, single and to the left, or single and to the right. A simple single-vision versus double-vision response is not really appropriate in this study because a diplopia effect need not manifest itself only in double vision. A diplopia effect, in this study, may include either a report of double vision proper or a report which indicates the observer was suppressing. Supression here indicates the apparent image of the symbology was displaced laterally and hence indicates an effect due to disparity. This is why the term "diplopia effect threshold" is technically more correct than just "diplopia threshold".

Single threshold procedure. Individual thresholds were determined using the "best" Parameter Estimation by Sequential Testing Procedure (PEST). The Best PEST is a maximum likelihood estimation technique which results in the most efficient psychophysical parameter estimation possible, given a known class of psychometric function (Pentland, 1980). Because this technique is fairly new, the logic is elaborated here. In essence, the Best PEST is a bracketing procedure which "zeros in" on the value of a threshold by using the information in an observer's response history to probe at the most likely value of the threshold.

For the first trial of a threshold determination series, the Best PEST probes the middle value of the total range available since, in the absence of any response history, the middle value is statistically the most likely value of the threshold. If the response to the midrange value was positive ("yes, the image is double" or "displaced"), then the second value probed would reduce the disparity to halfway between the midrange and zero disparity. Else if the response to the midrange probe was negative ("the image is single and centered"), the second value probed would increase the disparity to be halfway between the midrange and the maximum disparity possible, since that value would now be statistically the most likely threshold value. Later probe values are determined by a maximum likelihood estimation algorithm which allows for apparent inconsistencies in the response history (Lieberman & Pentland, 1982).

The range of disparity values probed was from zero (no disparity) to 9.8 mrad of disparity. For a particular threshold determination, all disparity values were of the same type, i. e., either all positive or all negative disparity. The smallest step size possible, and hence the resolution of the probe technique, was .1 mrad. Thus, 99 disparity values were availabe for a threshold determination.

A total of 50 trials were run for one threshold determination. The threshold value reported is the value the Best PEST algorithm would use as a probe if there were a 51st trial since the Best PEST always probes at the currently most likely value of the threshold. Inspection of the response histories indicates that 50 trials is definitely sufficient for a stable threshold value to emerge and yet not be too long for the value to drift, for example, due to fatigue.

Threshold conditions and experimental design. Four thresholds were obtained for each observer by crossing two levels of disparity direction (positive or negative) with two viewing exposures (100 msec and 3 sec). Thus, the statistical design is a 2x2 entirely repeated measures design with disparity direction and exposure duration as within subjects factors.

The 100 msec HUD symbology exposure was chosen in order to determine the diplopia threshold when there is no possible confounding due to vergence eye movements. The 3 sec exposure was chosen to determine the diplopia threshold that might apply when an observer stops to deliberately look at, and possibly study, an item in the HUD symbology or external scene.

The order of the four crossings was counterbalanced across observers by presenting each possible permutation at least once and no more than twice. The entire experiment took about 45 minutes per observer.

Results and Technical Discussion

The data for all 32 observers is presented without deletion of atypical observers since one objective of this study was to determine the distribution of results in a general population. Thresholds are treated first and then suppression data.

Disparity Thresholds

The mean thresholds are always greater than the median thresholds due to a skewing in the distribution caused by a few observers with large thresholds. For this reason median thresholds are more representative and the main discussion and conclusions are generally with respect to medians. Formal statistical analyses of the means are still presented.

Main effects of disparity direction. In general, positive disparity led to higher thresholds than negative disparity. The overall median positive disparity threshold, irrespective of exposure, was 2.6 mrad and the overall median negative disparity threshold was 1.2 mrad. The overall mean positive disparity threshold was 3.01 mrad and the overall mean negative threshold was 1.82 mrad. Disparity direction accounts for 8.7% of the total variance and the difference in the means is statistically significant, $F(1, 31) = 19.28$, $p<.01$. The higher threshold for positive disparity indicates a greater tolerance of the visual system for positive disparity than for negative disparity.

One explanation of this finding is that: Positive disparity arises when the HUD symbology is optically closer than the fixated target. Thus, resolution or fusion of the disparity with respect to the two retinal images of the symbology requires that the eyes turn inward to fixate the symbology. This turning inward is a natural request to make of the eyes. In contrast, negative disparity arises when the symbology is optically farther than the fixated target. Fusion here requires the eyes to rotate outwards to fixate the symbology since the light from the HUD is converging toward the eyes (and thus "beyond" the almost infinitly distant target). Rotating one's eyes outwards is unnatural and hence less tolerable. This explanation is one way of accounting for the asymmetry of Panum's area.

Saying that people tolerate positive disparity better is equivalent to saying that negative disparity is more easily detected. Although psychophysical studies generally refer to detection ability rather than to its inverse of "perceptual tolerance," we use both concepts here especially since "tolerance" can sometimes be more useful for understanding and for applying our findings to aviation needs.

Main effects of viewing duration. The overall median disparity threshold, irrespective of disparity direction, at a 100 msec exposure was 2 mrad, and at 3 sec was 1.6 mrad. The overall mean at 100 msec was 2.85 mrad and at 3 sec was 1.98 mrad. The difference in the means accounts for 4.6% of the variance and is statistically significant, $F(1, 31)$, $p < .05$. The higher threshold at 100 msec exposure indicates that the observers are more tolerant of disparity during short glances than during longer viewing. Equivalently, disparity is easier to detect the longer the viewing.

The 100 msec exposure corresponds to a quick glance at the symbology and also is too short a time for a vergence eye movement to occur. The 3 sec exposure permits a more careful study of the symbology but does allow time for a vergence movement to the symbology to occur. Thus, during a 3 sec exposure, the initial disparity in the two retinal images of the symbology may be reduced or eliminated. However, reduction in the disparity of the symbology entails a concommitant increase in the disparity of the images of the target. In either case, whether a vergence movement takes place or not, the longer exposure allows more time for the disparity to become apparent. One speculation from this finding is that diplopia is more likely to occur when a pilot views relatively more complex items of the symbology since those items take more time to inspect.

Interaction of exposure and disparity direction. The median and mean thresholds for each of the four disparity direction by exposure conditions are presented in Tables 2 and 3. The exposure by disparity direction interaction accounts for only 0.2% of the total variance in the data and is not significant, $F(1, 31) = 1.03$. This lack of an interaction suggests that the differences in the cell means in Table 3 are due to the simple summing of the significant main effects of exposure and disparity direction.

Table 2

Median Disparity Thresholds (in mrad)

	Exposure (sec)	
Disparity	.1	3.
Negative	1.6	1.2
Positive	2.8	2.5

Table 3

Mean Disparity Thresholds (in mrad)

	Exposure (sec)	
Disparity	.1	3.
Negative	2.3	1.3
Positive	3.4	2.7

Although there is no interaction in terms of the cell means, inspection of Table 4 suggests that there is an interaction in terms of the variability within the cells. In general, positive disparity results in greater standard deviations than negative disparity. Detection of positive disparity is both more difficult and more variable than detection of negative disparity. Table 4 also shows that short exposures result in greater variability than long exposures. This is not surprising and is consistent with the finding that short exposures make disparity detection more difficult than long exposures.

Parenthetically, the apparent differences in the variability within the cells do not necessarily invalidate the analysis of variance results for the mean thresholds. This is so because the analysis of variance is fairly robust to violations of the assumption of homogeneous variances.

Table 4

Standard Deviation of

Disparity Thresholds (in mrad)

	Exposure (sec)	
Disparity	.1	3.
Negative	2.4	0.8
Positive	2.6	1.2

Threshold distributions. Knowing average thresholds is important, but any application must also take into account the entire distribution of the thresholds. Table 5 presents the cumulative distributions of the percentage of observers experiencing diplopia effects as a function of both disparity direction and viewing duration. Cumulative percentages are also presented for the two disparity directions with results averaged across durations. One striking result in Table 5 is the relative intolerance of observers for negative disparity with long viewing: 100% of observers showed a diplopia effect when as little as 3.75 mrad of negative disparity was present. The general intolerance to negative disparity is also seen by comparing the entire threshold distributions when the effects of duration are pooled: at every level of disparity, the percentage of observers experiencing a diplopia effect under negative disparity is greater or equal than under positive disparity.

Table 5

Percentage of Observers Experiencing Diplopia

Disparity	Looking Duration in sec					
	.1	3	Average	.1	3	Average
	Negative			Positive		
0.00	9	3	6	0	0	0
0.25	13	6	9	0	0	0
0.50	25	16	20	6	0	3
0.75	25	19	22	13	0	6
1.00	34	31	33	25	0	13
1.25	47	66	56	28	6	17
1.50	47	81	64	34	19	27
1.75	59	84	72	34	28	31
2.00	59	84	72	38	38	38
2.25	66	84	75	44	41	42
2.50	66	91	78	44	56	50
2.75	66	91	78	50	63	56
3.00	69	94	81	56	66	61
3.25	72	94	83	59	75	67
3.50	78	94	88	59	81	70
3.75	78	100	89	59	88	73
4.00	81	100	91	51	91	75
4.25	81	100	91	63	91	77
4.50	88	100	94	63	94	78
4.75	88	100	94	66	94	80
5.00	88	100	94	78	94	86
5.25	88	100	94	81	94	88
5.50	91	100	95	84	94	89
5.75	91	100	95	84	94	89
6.00	94	100	97	84	97	91
6.25	94	100	97	91	100	95
6.50	94	100	97	91	100	95
6.75	94	100	97	94	100	97
....						
9.00	97	100	98	94	100	97
9.80	100	100	100	100	100	100

Threshold correlations. So far, all thresholds have been treated as if they were independent from condition to condition and observer to observer. In fact, tolerance for disparity seems to be an individual trait: people with high thresholds in one condition tend to have high thresholds in the other conditions and similarly for people with low thresholds. This may be seen by inspecting the scatterplots in Figures 7 to 10. These scatterplots and the correlations they illustrate are based on the data from all 32 observers. Hence, statistical significance at the $p=.05$ level requires a linear correlation coefficient of $r=.349$ and at the $p=.01$ level, an $r=.449$. The linear relationships at these critical r values would account for 12% and 20% of the respective variances.

Figure 7 shows a high ($r=.59$) positive correlation between positive and negative disparity thresholds at the 100 msec exposure. Notice the wide range and distribution of both positive and negative thresholds. Figure 8, by contrast, shows a nonsignificant positive correlation ($r=.29$) when the exposure is increased to 3 sec. The weaker correlation may be due to the tighter clustering of the thresholds. In addition, Figure 8 shows the general lowering of the diplopia thresholds with longer viewing. This threshold lowering effect with duration is shown even more clearly in Figures 9 and 10 since the only independent variable within each figure is duration. Figure 9 shows a high correlation ($r=.45$) between the short and long exposure thresholds under negative disparity. Figure 10 shows a similar high correlation ($r=.49$) for the two exposures under positive disparity.

The marginal distributions in Figures 7 to 10 provide a visualization of the distributions presented in Table 5. The table is useful for summary information and for applications; the figures are useful for interpretation and for providing additional information on individual differences in sensitivity to diplopia.

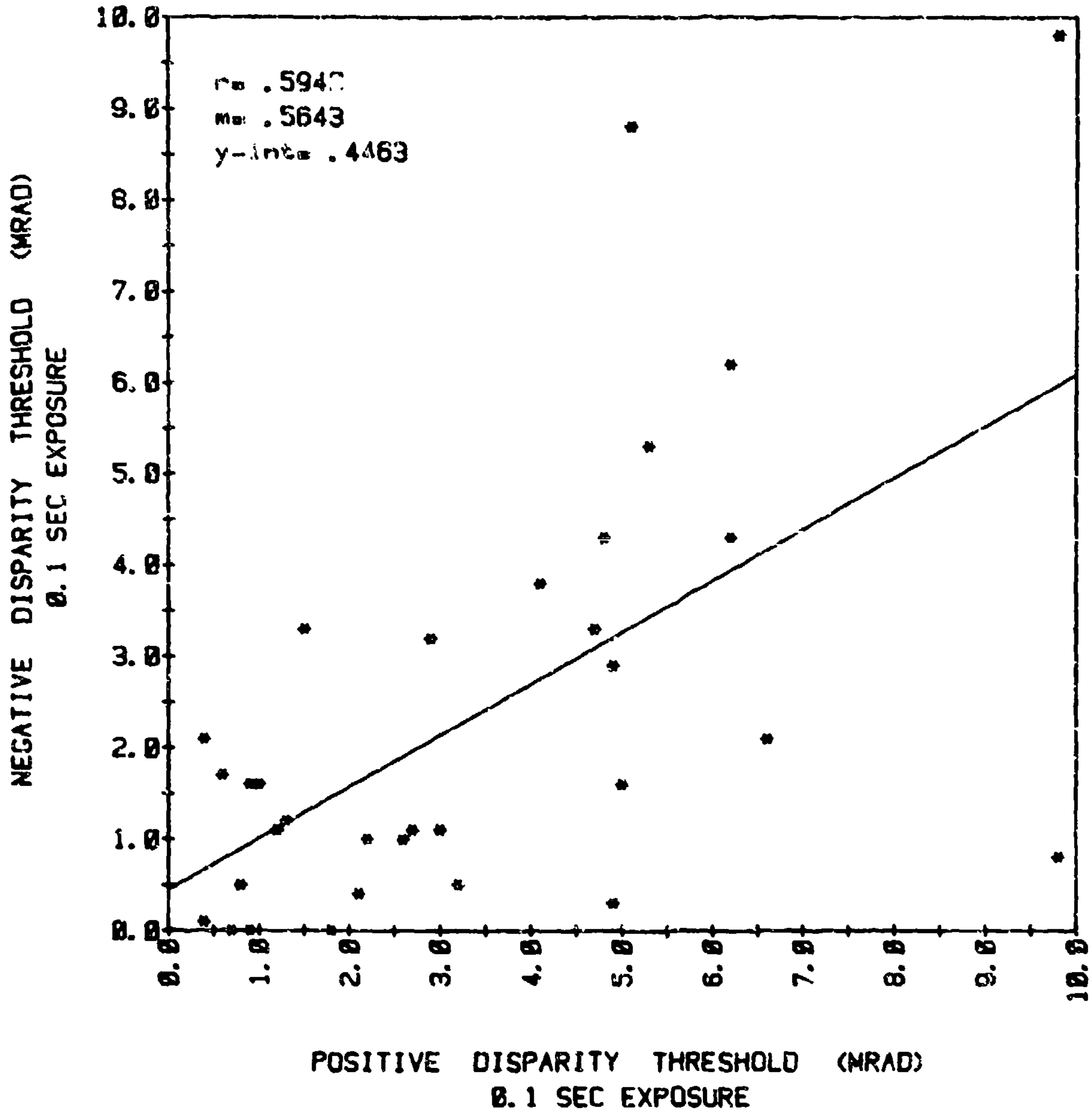


FIGURE 7. Scatterplot: Negative vs. Positive Disparity Thresholds at 0.1 sec Exposure

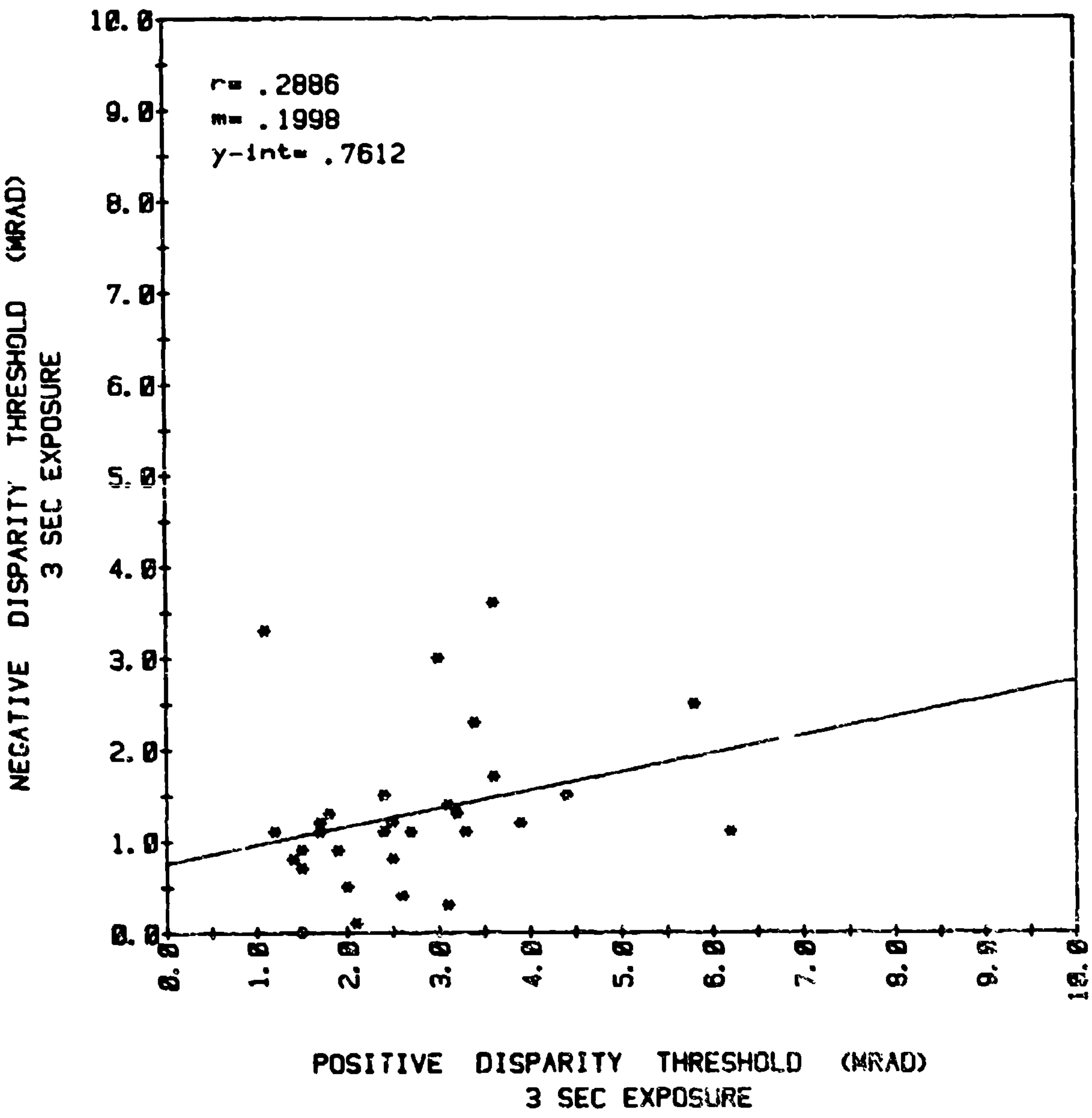


FIGURE 8. Scatterplot: Negative vs. Positive Disparity Thresholds at 3 sec Exposure

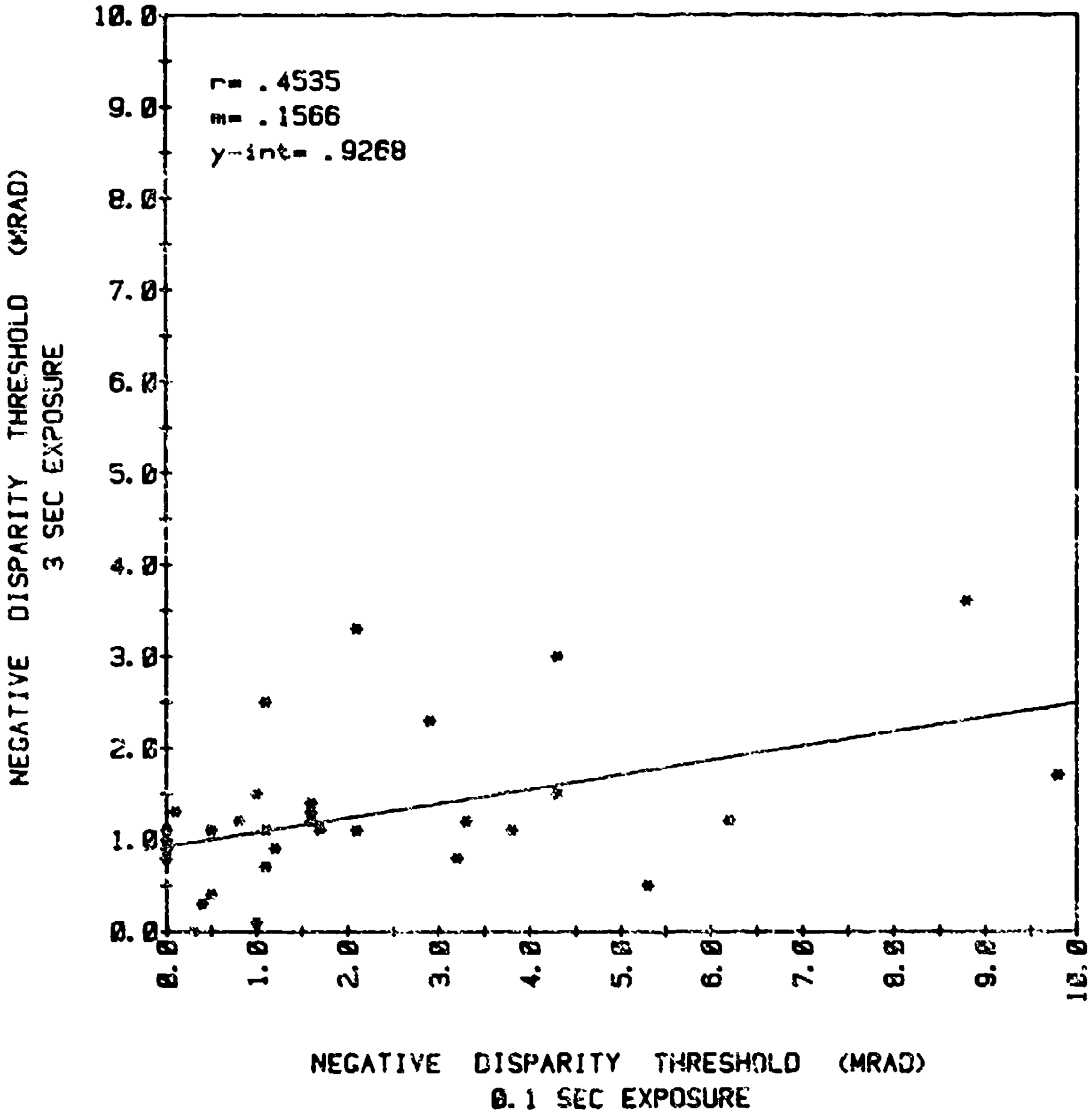


FIGURE 9. Scatterplot: 3 vs. 0.1 sec Exposure Negative Disparity Thresholds

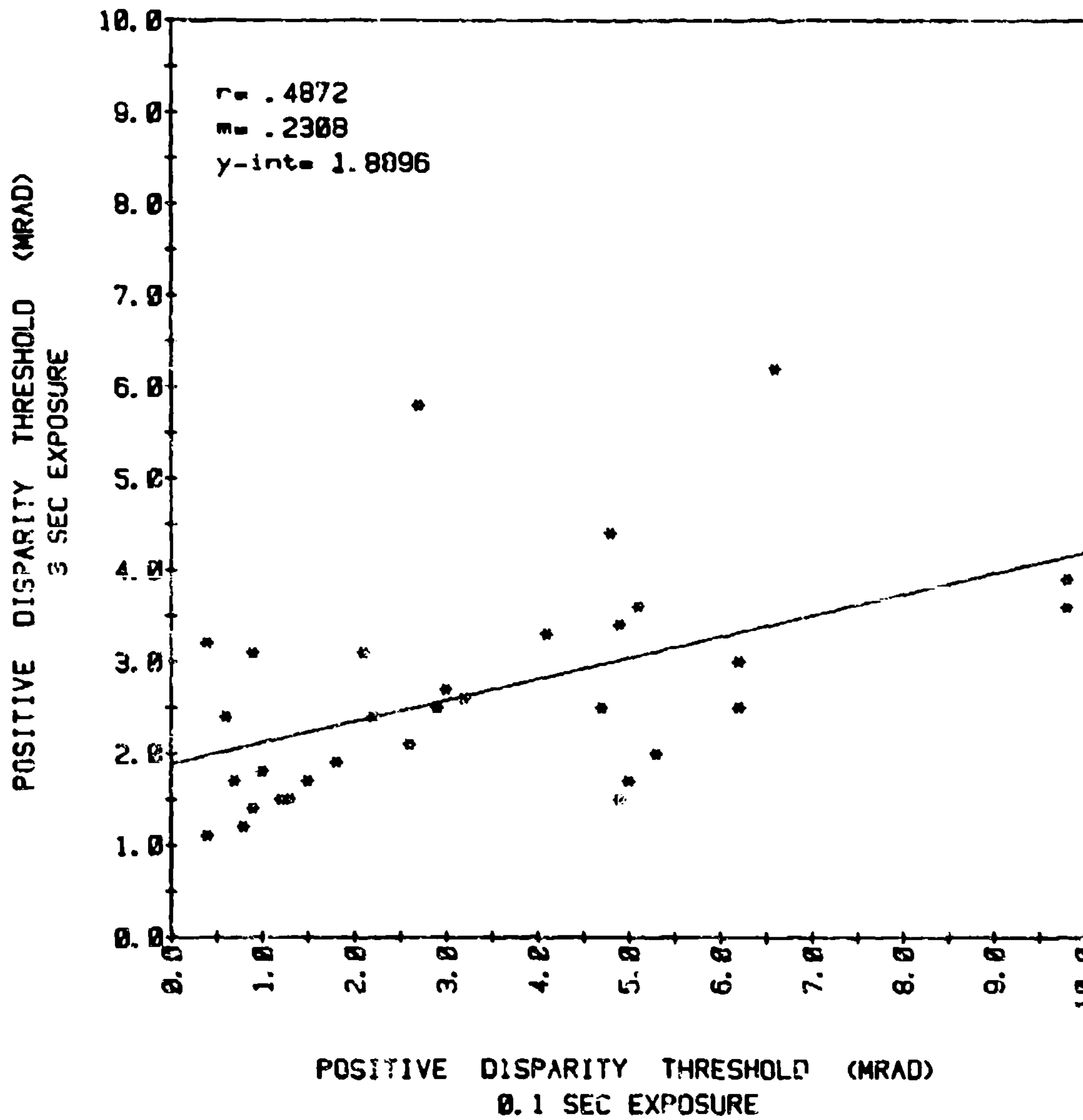


FIGURE 10. Scatterplot: 3 vs. 0.1 sec Exposure Positive Disparity Thresholds

Suppression occurrences

An unexpected finding of this study was the large number of occurrences of suppression. This result was unexpected in that suppression is all but unmentioned in the diplopia literature. A possible reason for the difference is that most studies in the literature use a small (4 or less) number of highly selected and trained observers, whereas this study employs a large number of observers with no prescreening other than good vision. Another possible reason for the difference is that diplopia studies generally use optically simple and uncluttered displays: a minimum number of attention drawing elements set against an otherwise empty or homgeneous field. This study employed an optical scene more likely to occur in aviation: a HUD element superposed over a very cluttered and complex ecological scene.

In order to provide a context for the suppression frequency analysis, the frequencies for single and true double vision are presented first. The following analyses are based on the percentage of trials during a threshold determination which resulted in reports of single vision, true double vision, or suppression.

Frequency of single vision reports. Although the number of trials per threshold determination was 50, the highest frequency of single vision reports would be about half that number since the threshold probing technique was actively seeking that disparity value which would produce a .5 probability of eliciting single vision. In fact, 48.3% of all reports were of single vision which testifies that the PEST algorithm functioned as intended. Further, there were no differential effects of particular disparity directions, viewing times, or their interactions as no cell or marginal percentage differed from the overall percentage by more than 1.3 percentage units.

Frequency of true double vision reports. If there were no instances of suppression, the expected percentage of reports of true double vision would be about 50% by the same argument given for the expected percentage of single vision reports. In fact, the overall percentage of true double vision reports was only 30.0%. Table 6 presents the incidence rates for each of the four disparity direction by exposure duration conditions.

Table 6

Mean Percent of True Double Vision Reports per Threshold Determination

	Exposure (sec)	
Disparity	.1	3.
Negative	34.0	39.6
Positive	20.3	26.1

There were virtually no interaction effects, $F(1, 31)<0.01$, which means that all differences in the cells are due to simple summation of the main effects of disparity direction and exposure duration: Negative disparity produced a larger percentage of true double vision reports than did positive disparity, 36.8% versus 23.2%. This difference is significant, $F(1, 31)=23.58$, $p<.01$, and accounts for 12.3% of the variance. The main effect of viewing duration (27.1% at 100 msec and 32.8% at 3 sec) is also significant, $F(1, 31)=7.12$, $p<.05$, but only accounts for 2.1% of the variance. In contrast to the relatively weak effects of the experimental manipulations, individual differences in observer means (which ranged from 0% to 49.5% true double vision reports) directly account for 53.2% of the variance.

Frequency of suppression reports. During data collection, a distinction was made between left and right eye suppression, but that distinction was dropped after a preliminary data analysis. If there were no instances of true double vision, the expected percentage of suppression reports would be about 50% by the same argument given for the expected single vision percentage. In fact, the overall percentage of suppression reports was 21.7%. (Together with the 48.3% single and 30.0% true double vision reports, all reports are accounted for.) Table 7 presents the incidence rates for each of the four disparity direction by exposure duration conditions.

Table 7

Mean Percent of Suppresion Instances

per Threshold Determination

	Exposure (sec)	
Disparity	.1	3.
Negative	17.4	13.5
Positive	31.0	25.0

The exposure by disparity direction interaction accounts for only 0.1% of the total variance and is not significant, $F(1, 31)=0.33$. This lack of an interaction indicates that the differences in the cell are due to the simple summing of the main effects of exposure and disparity direction:

Positive disparity led to almost twice as many instances of suppreeion as did negative disparity. The difference in the means (28.0% cases per threshold determination versus 15.4%) accounts for 11.1% of the total variance and is statistically significant, $F(1, 31)=19.04$, $p<.01$.

Short viewing exposures led to more suppression than longer exposures. The difference (24.2% cases per threshold determination versus 19.3%) accounted for only 1.7% of the variance which is much less than the 11.1% accounted for by disparity direction, but the effect of viewing time is still significant, $F(1, 31)=6.17$, $p<.05$. Although the reduction in suppression with longer viewing is small, its explanation may be that longer views allow more time for true double images to emerge. Suppresion may yield to double vision and alternate with it.

As in the case of true double vision, individual d fferences in mean suppression rates were large. They ranged from 1.5% to [illegible]% and directly accounted for 53.8% of the variance in suppression rates.

These suppression findings are novel and their full significance remains to be explored. As such, these findings should be considered tentative until they are replicated. A prime variable for study is the complexity versus the simplicity of the scene. Does the visual system prefer to suppress one eye's view rather than permit double images in rich ecologically occurring scenes?

Relation of Thresholds and Vision Reports

A diplopia effect threshold is that degree of disparity which has a 50% chance of producing single vision and a 50% chance of producing a diplopia effect of any kind. We have differentiated between two types of diplopia effect, namely, true double vision and suppresion, and have found wide individual differences in susceptibility to these two vision effects. A reasonable question now is whether these effects, in themselves, correlate with the diplopia threshold. No significant correlation ($r > .349$, $df = 30$, $p < .05$) between the percentage of true double vision reports per threshold and the actual threshold was found for any experimental condition.

With respect to suppresion reports, there was a marginally significant correlation ($r = -.36$) between suppresion rate per threshold determination and the actual threshold value for the condition of postive disparity at a 100 msec exposure. No other suppression correlation was significant. Thus, we conclude that the diplopia effect threshold is reasonably independent of the type of diplopia effect. Since a dependency is not unreasonable, this conclusion is only tentative.

GENERAL DISCUSSION

The main findings of this study are:

(1) Observers are relatively intolerant of negative disparity. In negative disparity, a nonfixated object is optically farther than a fixated object.

(2) Longer viewing is more likely to lead to a diplopia effect than short glances.

(3) Resistance to diplopia effects appears to be an individual trait.

(4) A large proportion of responses involve suppression.

The overall median negative disparity threshold was 1.2 mrad and the overall median positive threshold was 2.6 mrad. These figures compare well with the classic static direction averaged threshold value of 2.0 mrad; but, in addition, provide crucial information of the effects of disparity direction. With respect to practical applications such as setting tolerance specifications for F-16 HUD/canopy combinations, the values of 1.2 and 2.6 mrad are simultaneously more strict and more lenient than the classical value of 2.0 mrad, but the direction information can have a significant payoff in terms of pilot comfort, safety, and acceptance.

For example, tolerance specifications can capitalize on, rather than merely reflect, the asymmetry of Panum's area: The "midpoint" between our limits for Panum's area of +2.6 and -1.2 mrad disparity is +0.7 mrad. This suggests that HUD imagery should be placed at a slightly nearer optical distance than the (fixated) target imagery. Our estimate of 0.7 mrad positive disparity compares well with the 0.38 mrad positive disparity which Gibson recommends as optimal for "viewing comfort."

There is another way to capitalize on the asymmetry: The logic behind Panum's area suggests that diplopia will probably not be noticed if the HUD imagery is as much as 2.6 mrad "nearer" than the target or as much as 1.2 mrad "farther." The question now is "Where is the target?". Contrary to traditional thinking, a distant target is not necessarily at optical infinity. Initial studies at AFAMRL (Genco, 1984; Task, 1983) indicate that F-16 canopy optics can place a distant target at an optical distance of about 3.5 mrad in front of an observer. Thus HUD imagery divergence (eye convergence) could range from (3.5-1.2) to (3.5+2.6) or 2.3 to 6.1 mrad without inducing diplopia.

This range contrasts sharply with traditional goals in two ways: (1) it is not recommended that HUD and target imagery be collimated, but rather that the HUD imagery be optically closer than the target, and (2) neither the target nor HUD imagery are assumed to be at optical infinity.

Another feature of this study is that the number of observers was large enough to yield meaningful standard deviations and threshold distribution functions (Tables 4 and 5). Previous studies were generally limited to reporting a range based on a few observers rather than the standard deviation and full distribution. The following range data are provided only for comparison with previous studies: The range of overall means for individual observers here was 1.2 to 6.2 mrad. The upper limit is similar to Duwaer and Brink's value of 6.46 mrad, but the lower limit of 1.2 is considerably lower than their overall lower limit of 2.18 mrad. This difference is probably due to the much larger number of observers in the present study (32 versus 2).

Actually, exact comparisons of specific values would seem difficult, if not impossible, across different studies due to the large variation in the conditions of each study such as threshold criteria, presentation methods, and exposure durations. These factors, and others such as inherent individual differences and training techniques, are known to affect threshold values. However, in spite of these potential pitfalls, it is the case that our results are reasonably similar to those in the literature. With one notable exception (the suppression findings), the present results confirm, extend, and amplify those of previous studies.

It is well, however, to keep in mind just what the differences between this study and the others are. This study used: (1) a clear distinction between results for different disparity directions; (2) two very different exposure durations; and (3) a large number of observers. These differences are obvious; other more subtle features or differences are the use of: (4) a distant (1 km) fixation point whereas most other studies use a fixation distance of a few meters or less; (5) a complex real-world background (this feature is shared with the other HUD disparity studies); (6) an efficient, high-resolution psychophysical probing technique; and (7) a stringent criterion for diplopia.

This last feature means that some pilots might suffer from a blurring of vision or other diplopia effect at lower disparity levels below the thresholds reported here. A replication using a more lax criterion would show lower diplopia effect thresholds, that is, a greater intolerance for disparity than here. This last point deserves special attention in setting specifications since blurring may lead to discomfort, asthenopia, and reduce target detection range. Recall that the HUD studies of Gold and also of Gibson indicated a discomfort threshold of about 0.8 to 1.0 mrad of negative disparity. Thus, the more generous tolerances apparently indicated by this study might be somewhat artificially high.

For example, although stereopsis effects can be noticed with as little as 0.05 mrad disparity, these effects were not studied. Similarly, the effects of varying disparities across the field of view were not studied. If the central field of view has less disparity than the peripheral field of view, what will happen to comfort and performance?

The most unexpected finding of this study was the near universal and high frequency of suppression as disparity increased. Since suppression due to disparity can also lead to aiming errors, its incidence is by no means irrelevant to pilot performance. The aiming error budget allocated to the F-16 canopy is approximately 3 mrad. If suppression of one eye or the other shifts the target or the pipper image, much of this budgeted amount could be expended on the effects of binocular disparity rather than cyclopean angular deviation. Is suppression frequent under ideal viewing conditions or is it a reaction to disparity? We do not now have the answers and thus recommend a research effort directed at understanding suppression in pilots.

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