Appendix B

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Factors affecting the perception of luning in partial binocular overlap displays

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Abstract

Luning is a detrimental visual effect characterized by a subjective darkening of the visual field in the monocular regions of partial binocular overlap displays. The effect of a number of factors on the magnitude of luning was investigated. These factors included: (1) convergent and divergent display modes for presenting partial binocular overlap field of views, (2) the field of view (FOV) luminance level, (3) the placement of either black or white contours on the binocular/monocular border, and (4) the lowering or raising of the luminance of the monocular side regions relative to the binocular overlap region. Eighteen Army aviators served as subjects in a repeated measures design. The results indicated the following. The divergent display mode systematically induced more luning than the convergent display mode under the null contour (no contours on the binocular/monocular border) condition. Adding black contours reduced luning by a roughly equivalent amount in both the convergent and divergent display modes leaving the convergent mode with less luning. The FOV luminance level had no effect on luning for the null or black contour conditions. Adding white contours, reduced luning by an amount which depended on FOV luminance, where there was less luning for lower FOV luminance levels, but no systematic effect of display mode. Changing the luminance of the monocular regions (relative to the binocular overlap region) reduced the amount of luning, with a decrease in luminance producing more of a reduction in luning than an increase in luminance. When a partial binocular overlap display is needed to present a larger field of view to aviators in helmet mounted displays, the convergent display mode with black contours on the monocular/binocular borders appears to be the most reliable of the ways tested to systematically reduce luning. Additional factors are discussed.

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Introduction

In order to increase the extent of the visual world available to U.S. Army helicopter pilots using helmet mounted displays (HMD), without incurring increases in size, or weight, or loses in central resolution, an unusual method of display--partial binocular overlap--has been proposed. A consequence of this method is a detrimental perceptual effect known as luning (Moffitt, 1989). The purpose of our study is to quantify this perceptual effect under different display conditions, including possible solutions.

First we define a few terms to avoid the ambiguity of the literatures on vision and display systems. In the artificial visual displays described here, **background** is the dark, finite luminance, region surrounding the **visual fields**, which are the intentionally lightened or stimulated visual areas seen by each eye. Access to the visual world is assumed to occur only through these artificial visual fields. Although in our simulations, the visual inputs to each eye are from independent sources, we refer to the visual world that is being simulated, not the method of simulation, which is described in the method section. For example, when we refer to the binocular overlap region, we mean a singular region in the visual world that is seen by both eyes, which we happen to simulate by independent inputs to each eye.

Field-of-view (FOV) refers to the total extent of the visual world that is seen when both eyes are open. It includes what is seen by both eyes together as well as by each eye alone. The portion of the visual world that one eye sees is referred to as its **monocular field**, (note, of course, that in the vision literature the monocular fields include the background; here we use the term to refer to the artificial visual areas intentionally stimulated). The portion of the visual world that both eyes see together is referred to as the **binocular overlap region**, and the portion of the FOV that only one eye sees is a **monocular region.** Thus the FOV may consist of a binocular overlap region and a monocular region for each eye.

A monocular field consists of two areas--the monocular region it sees exclusively and the area which is seen binocularly. Separating these two areas of the monocular field is the **monocular/binocular border** or binocular border for short. This border is akin to an illusory or subjective contour in that it is not physically present in the stimulus; it is delineated simply by the relative positioning of the two monocular fields, and therefore can only be defined in a binocular vision system.

When the two eyes see exactly the same portion of the visual world, the viewing situation is referred to as the **complete binocular overlap display mode.** In this case the FOV consists solely of a binocular overlap region, in which the two monocular fields are coincident and there are no monocular regions. The **partial binocular overlap display mode** occurs when each of the two eyes sees a common portion of the visual world, the binocular overlap region, and each eye exclusively sees a monocular region. All partial binocular overlap displays contain by definition monocular/binocular borders, which in terms of the FOV separate the binocular overlap region and the monocular regions, and in terms of the monocular fields separate the portion exclusively seen by one eye from the portion seen in common with the other eye. In normal unencumbered vision, these binocular/monocular borders, dividing the FOV, are not experienced per se (see Gibson, 1979, for a good discussion), and are only cognitively identified and located with attentional effort. However in artificial viewing situations where the monocular fields are smaller than in natural viewing, these borders are accompanied by a perceptual effect that has come to be known as luning (Moffitt 1989).

Luning is a visual effect characterized by a subjective darkening of the visual field in the monocular regions of partial binocular overlap displays. It was so named (Moffitt, 1989) because of the crescent shapes of the darkened monocular regions adjacent to the circular binocular overlap region. It is strongest (darkest) near the border separating the monocular and binocular regions, gradually fading with increasing distance from the binocular border. The magnitude of luning can fluctuate over time and appears not to be strongly under the influence of attention, see Figure 1.

Luning appears to be related to binocular rivalry and suppression. Binocular rivalry refers to the phenomenal alterations in appearance of the FOV during observations of dissimilar monocular stimuli, in our case the dissimilar monocular fields of a partial binocular overlap display mode. Suppression refers to the phenomenal disappearance of one eye's input due to **monocular dominance** by the other eye. In the partial binocular overlap display mode, of concern here, each eye's monocular region overlaps with the dark background of the other eye. If the background is suppressed the total FOV looks natural, where the binocular and monocular regions are both seen as one continuous visual world. If each eye's monocular region is partially suppressed by the other eye, the dark background will appear in the FOV.

Binocular rivalry and suppression appear to be a common sense first pass explanation of luning. However this does not tell us very much about its nature or solution. For example, Yang, Rose and Blake (1992) point out different varieties of binocular rivalry including piecemeal dominance, binocular superimposition, and binocular transparency, (also see Gur, 1991, on two other phenomena--Ganzfeld fade-out and blackout--which may also be implicated). Since luning is a change in apparent brightness--a darkening--of a region, which can spread or recede over time (see Kaufman, 1963), this particular occurrence of binocular rivalry appears also to be related to the ubiquitous contrast, and color, spreading phenomena (see Grossberg, 1987 for a catalogue and neural net theory of such phenomena), such as neon color spreading (see Nakayama, Shimojo and Ramachandran, 1990). Luning appears to emanate from the monocular/binocular border and is attenuated by monocularly placing physical contours in the location of this border (Melzer and Moffitt, 1991). All these phenomena, thus far mentioned, are modulated by the presence of edges in the visual field, and so this fact does not serve to constrain explanations.

Another, non-mutually exclusive, candidate explanation is what has recently come to be known as DaVinci stereopsis, first studied in depth in modern times by Barrand (1979). Briefly, this refers to binocular occlusion; the fact that an object in one's FOV, such as one's nose, may occlude only one eye's view of more distant objects (see Gillam and Borsting, 1988). Explanations of luning based on DaVinci stereopsis would first analyze the potential visual geometry of the visual world available to the observer in ecological terms (e.g., Melzer and Moffitt, 1991). That is, what real world situation, such as viewing through an aperture or viewing past an object in front of one's face, would correspond to the artificial display mode of the HMD. Then one would incorporate the visual system's natural tendencies to suppress, for the sake of argument say an object such as the foreground region of an aperture. There are a number of potential ecologically salient visual geometric configurations one could evoke; however, to date little work has been done on the visual system's natural tendencies when interpreting a viewing situation in terms of these configurations; however, see Nakayama, Shimojo, and Silverman (1989).

How best to conceptualize the luning phenomenon awaits further empirical work. Non-mutually exclusive candidates include binocular occlusion (Barrand, 1979) also known as DaVinci stereopsis (see Nakayama and Shimojo, 1990; Shimojo and Nakayama, 1990; Ono, Shimono, and Shibuta 1992) based on visual geometry, or a Gestalt explanation in terms of perceptual scission and binocular transparency (see Matelli, 1974), or binocular lustre, or brightness filling-in and color spreading (Grossberg, 1987, in press), or edge effects.

The current investigation is an applied study designed to determine how luning is influenced by display factors, the most important being the way in which the partial binocular overlap display is presented. A partial binocular overlap display can be presented in the **divergent display mode**, where the right eye's monocular region is to the right of the binocular overlap region; that is, the right eye exclusively sees the portion of the visual world to the right of the portion seen by both eyes. Similarly, the left eye's monocular region is to the left of the binocular overlap region. Conversely, in the **convergent display mode** the the right eye's monocular region is now to the left of the binocular overlap region, and the left eye's monocular region is now to the right of the binocular overlap region. This would occur if one were binocularly viewing the visual world through an aperture. Good discussions of the visual geometry ecologically corresponding to these display modes can be found in the Moffitt and Melzer references, and the Nakayama references, as well as in Barrand (1979).

Melzer and Moffitt (1991) have evidence indicating that the convergent display mode induces less luning than the divergent display mode. They also claim that placing black contours in the monocular fields in the location of the monocular/binocular border also attenuates luning. We tested these image manipulations under more general conditions, including the following. We tested the placement of a white as well as a black contour in the location of the binocular border (positive and negative contrast contours). Since luning is a change in apparent brightness, a darkening, of a region, which can spread or recede over time, and may be related to the ubiquitous monocular and binocular brightness spreading phenomena (Grossberg 1987, in press). We therefore, also tested variations in luminance levels. We tested the effect of different FOV luminance levels, and the effect of decreasing and increasing the luminance of the monocular side regions. We measured the effect of each of these factors on the induction of luning for both the convergent and the divergent display modes.

Method

Subjects

Eighteen army aviation student volunteers, seventeen males and one female, took part in the experiment. All had 20/20 unaided or better Snellen acuity. Average age was 25, ranging from 21 to 30. Each subject's vision was tested using the standard Armed Forces Vision Tester. In addition, the accommodative/convergence relationship and the interpupillary distance (IPD) of each subject were measured and recorded. A copy of the exam data sheet is included in Appendix A. Group eye exam data is reported elsewhere.

Equipment

The equipment consisted of three major components: An HP-98731 Turbo-SRX computer graphics workstation used to generate the visual stimuli; a custom made optical table configuration used to optically direct the visual stimuli from the monitor to a pair of (Adlerblick) viewing binoculars; and a subject booth, a light proof enclosure behind the binoculars, where the subject viewed the stimuli via the binoculars and responded via an HP response keypad, or "button-box."

The HP-98731 Turbo-SRX computer graphics workstation consists of a 19" color Trinitron monitor (1280 x 1024 pixels) for presenting visual stimuli, and a computer for generating the stimuli, recording the responses and analyzing the data. Connected to the workstation are the experimenter's terminal to allow the experimenter to run the experimental programs and monitor the progress of each experimental session; an external monitor tied to the HP computer via a scan converter to allow the experimenter to unobtrusively view the experimental stimuli presented to the subject; and the button-box, a 32-button keypad to allow the subject to respond to the visual stimulus presentations.

The optical table configuration consists of a 4' x 6' optical table, the workstation monitor mounted at one wide end of the table, and eight front surfaced mirrors mounted on the table to direct the visual image--the optical train--to a pair of viewing binoculars mounted on the other wide end of the table (see Figures 2 and 3). The purpose of the eight mirrors is to allow the independent presentation of two channels, one to each ocular of the binoculars from the same monitor. Through the binoculars, the image on the top half of the monitor is seen by the left eye and the image on the bottom half of the monitor is seen by the right eye. The 7x50 binoculars are mounted within a fixture which allows IPD to be precisely adjusted for each subject. Affixed on the front of the binoculars are auxiliary focusing lens to focus the magnified image for the optical train viewing distance. A light baffle in front of the monitor between the two optical paths is positioned to prevent cross talk between the two image channels. Filter holders in front of the binoculars allow the placement of optical filters. The two mirrors mounted directly in front of the binoculars, L4 and R4 in Figure 3, are movable to allow adjustments corresponding to the IPD settings of the binoculars. These adjustments, parallel to the table and perpendicular to the optical path to the binoculars, ensure a properly centered image for each IPD setting.

The optical table configuration was designed to allow the horizontal extent of the monitor (1280 pixels) to match the horizontal visual extent of each ocular of the binoculars. The resulting images seen through each ocular of the binoculars were 50° of visual angle with a spatial resolution of 1280 pixels, or 25.6 pixels per degree of visual angle. The temporal resolution, or frame rate of the monitor, was 60 Hz, and the luminance increments were 256 digital grey levels. The 7 x 50 Adlerblick binoculars have a vertex distance of 27 mm, and an exit pupil diameter of 7.14 mm.

The convex cylindrical surface of the monitor (approximately 1.5 meter radius of curvature) results in a focal distance disparity for the center and edges of the display seen through the binoculars. The focusing difference between the center and extreme edge of the image on the monitor, measured with a diopterscope, was approximately 0.75 diopters. To insure a clear image for the test stimuli within the field of view used, the binoculars were focused with the diopterscope to -0.50 diopters (2 meters) for the center of the display. This ensured that subjects could easily accommodate to any part of the visible image.

Covering the optical table and the subject booth is a metal frame covered by black cloth to prevent light leakage and to protect the optical table components. The subject booth is a light proof enclosure in which the subject is seated at an adjustable chin rest affixed in front of the binoculars. Except for the stimuli viewed through the binoculars, the subject is in darkness. Mounted on the end of the optical table in front of the subject is a call switch which rings a buzzer. Mounted within easy access of the subject is the button-box, used to register the subject's responses. Above the subject is an adjustable air vent connected to the air conditioning to allow the subject control of the temperature in the subject booth.

Stimuli

There were 22 experimental stimuli, which can be cross classified into the following categories. There were two binocular display modes--convergent and divergent; three contour types--null, black, and white; and two monocular luminance difference patterns--dimmer and brighter. With respect to monocular luminance differences, the three contour types belonged to the category of same brightness. Glancing forward to the results shown in Figure 7 on page xx should make the stimulus categories clearer. These are described in detail below.

Stimulus duration was 30 seconds with a 5 second delay between stimuli during which time the screen was blank.

Convergent and Divergent Partial Binocular Overlap Display Modes

The visual field of each eye's view through the binoculars consisted of a gray ellipse of dimensions 30° of visual angle (768 pixels horizontal diameter) x 16° (410 pixels vertical diameter) against a black background. In each ocular view through the binoculars, the ellipses were centrally located in the vertical dimension and horizontally located as described below. These ellipses represent each eye's monocular visual field, and the horizontal relationship between them defines the display mode, see Figures 4 and 5.

If the ellipses are each centrally located so that there is complete overlap of each of the monocular fields, the total horizontal FOV is 30°, the same as each monocular field. This complete overlap display mode is designated the baseline position.

If the elliptical field for the right eye is moved 7.5° to the right of the baseline position, and the elliptical field for the left eye is moved 7.5° to the left of the baseline position, the monocular fields remain the same in extent, but the total FOV is increased to 45°, where both eyes see a smaller central binocular overlap region of 15°, and each eye sees a flanking monocular region of 15°. Because the right eye sees the flanking monocular region to the right of the binocular region, and the left eye sees a flanking monocular region to the left of the binocular region, the display mode is **divergent**, which, except for the sizes of the visual fields, is what is seen in normal human vision.

If the elliptical field for the right eye is instead moved 7.5° to the left of the baseline position, and conversely for the left eye it is moved 7.5° to the right of the baseline position, then the display mode is **convergent**, where both eyes will again see the same smaller central binocular region of 15°. The total

FOV will again be 45°, but this time the right eye's flanking monocular region will be to the left of the binocular region, and conversely the left eye's flanking monocular region will be to the right of the binocular region. This can be simulated by looking through an aperture.

Half of the twenty-two stimuli were in the convergent display mode and half were in the divergent display mode.

The grey elliptical fields were presented against a black background, which had a luminance of 0.02 foot-Lamberts (fL). The luminances of the ellipses are described below.

Fusion Locks and Fusion Lock Pattern

Simply shifting the images as described above is no guarantee that subjects will binocularly fuse the images in the way expected, that is overlap the appropriated areas. Subjects need unambiguous stimuli common to both eyes in order to binocularly fuse images properly and to avoid image slippage, which leads to the binocular overlap of inappropriate regions of the two monocular images. To ensure "binocular locking" of the appropriate monocular regions, four fusion locks were always present in each eye's image in the binocular region at the appropriate location in each image. These are the (2 pixel horizontal x 8 pixel vertical) black rectangles located as shown in the ellipses in Figure 5. These were symmetrically located above and below the long axis of the ellipses, and to the right and left of the center of the fused overlap region as shown in the bottom panel of Figure 5.

In the course of the experiment, each subject had access to a fusion lock stimulus pattern, via the button-box, to return fusion in the event it was lost. This stimulus, an unambiguous and easily binocularly fusible pattern is shown at the bottom of Figure 5. It consisted only of the four (for each eye) fusion locks and the binocular overlap region of the elliptical FOVs. This central binocular overlap region is common to both eyes in the two display modes. The luminance of this pattern was 2.0 fL. A subject knew to call this pattern if they became diplopic, or saw more than four fusion locks, which indicated that his or her fusion was out of alignment.

Optical Convergence

Optical convergence and accommodation were both set for 2 meters. Optical convergence here refers to the angle between the optical axes of the eyes and should not be confused with display mode convergence. Since the centers of both the right eye and the left eye images were focused to 2 meters (-0.50 diopters), through the binoculars, the right and left images were also positioned so that the eyes converged to 2 meters. This was for an average subject with an IPD separation of 64 mm. This convergence was induced by shifting each eye's image on the monitor 0.92 degrees of visual angle (22 pixels) in the nasal direction. The range of IPDs for the 18 subjects was 57 mm to 69 mm, with a mean of 64 mm. For this group of subjects, the fixed convergence thus induced convergence demands of from 1.78 meters (for a 57 mm IPD) to 2.15 meters (for a 69 mm IPD), This is less than 0.3 prism diopters (3 milliradians) of residual fusional convergence or divergence required for an image located at 2 meters.

FOV Luminance Level

There were three FOV luminance levels--dim (0.4 fL), medium (2.0 fL) and bright (5.0 fL), where the entire FOV of the stimulus patterns had the same luminance. There were eighteen stimulus patterns of this type; one third at each luminance level.

Binocular Border Types

There were four types of binocular border contour, see Figure 6. In six of the patterns, designated the null contour patterns, no luminance borders were placed on the binocular boundary. In six of the patterns, black contour lines (0.06 fL) were located at the monocular/binocular border and in another six, white contour lines (10 fL) were located there. For these patterns, there were two sided contours, or lines, located at the binocular border. Each of these sextets consisted of three FOV luminance levels for each of the two display modes.

In the monocular luminance difference patterns, the areas of the elliptical fields composing the binocular overlap region was 2 fL and the monocular side regions were either dimmer (0.4 fL) or brighter (5.0 fL), than the overlap region. Thus there was a one sided contour at the binocular border. There was a convergent and a divergent version for both the brighter and dimmer monocular luminance difference patterns.

Procedure

Each subject was required to read and sign the appropriate consent form (in Appendix B) and read the written instructions (in Appendix C), before the verbal instructions were given, explaining the task and the use of the button-box. In each experimental session, each subject was seated in the subject booth, where they viewed the computer generated stimuli through a set of binoculars. The binoculars and movable mirrors, L4 and R4, were individually positioned to correspond to each subject's IPD. Each subject's head and eye were properly positioned by displaying an alignment pattern, a square grid which covered the entire extent of the screen, to ensure that the subject could see the entire FOV through the binoculars. The subject was first given practice in obtaining binocular fusion and in the use of the button box, and was given a brief practice session with four or five stimuli, to make sure the instructions were understood. Each of the subjects had experience with the experimental setup from a previous study measuring visual thresholds.

Experimental Session

For the experimental session, each subject was instructed to continuously press one of the two response buttons during the course of a trial to indicate whether luning was or was not present at any given moment. Each subject was instructed to use only the index finger to press one of the two keys. Experimental sessions lasted approximately 45 minutes. There was a 5 sec. interval between trials during which time the screen was dark. A short warning beep preceded each stimulus onset by 0.5 sec.

The subject was instructed that if at any time during the presentation of a stimulus, he lost fusion, or became diplopic or visually fatigued, he could press the fusion lock button to bring up the fusion lock stimulus to aid in returning fusion. The interrupted trial was restarted only after the subject pressed a release button. After the fusion lock stimulus was released, there was a five second dark interval and then the warning beep before the trial was restarted.

For 25 sec., beginning 5 sec. after stimulus onset, the computer recorded the subject's responses. If the subject failed to respond properly either by failing to press one of the two response keys during either the initial or during the final 12.5 sec. of the data recording interval, or by pressing both response keys at the same time, the following occurred: the trial was terminated; the screen went blank; and a long 5 sec. beep sounded; the trial was restarted after an additional 5 sec. dark interval and the short warning beep.

Design and Data Analysis

The 22 experimental conditions were presented in three blocks for a total of 66 trials. In these 22 conditions, there were eleven stimulus pairs; both members of each pair having the same stimulus luminance characteristics, where one member was presented in the convergent display mode and the other member in the divergent display mode.

Nine of these stimulus pairs were divided equally into three contour classes--null contour, black contour and white contour. Orthogonally crossed with the three contour classes, the nine pairs were equally divided into three FOV brightness levels--dim, medium and bright. There were two additional stimulus pairs, the monocular luminance difference patterns, where the central binocular overlap region was of medium luminance. In one pair the monocular side regions were brighter than the binocular center and in the other pair the monocular side regions were dimmer. In these pairs, the bright and dim luminances of the monocular side regions were respectively the same luminances as the bright and dim FOV levels recited above.

The computer began recording the subject's responses 5 seconds after stimulus onset to avoid data contamination by the initial decision or reaction time. The percentage of time out of the 25 sec. interval that subjects indicated they saw luning by the buttonbox response was recorded for each of the 66 trials. The data for each of the 22 conditions for each subject was the mean response from three blocks. The luning percent times were analyzed by a one-way repeated measures analysis of variance (ANOVA) with 22 treatments, 6 linear trend tests and 12 planned comparisons (Winer, 1971).

At any given moment during the trial, subjects could make one of three responses--luning present, luning absent, or no response. Although subjects were instructed to respond continuously, the amount of time change between responses, or the time to decide on a response means that the total response time, the amount of time subjects gave a luning present response plus the luning absent response, was not a constant sum, (i.e., total stimulus duration minus luning present response time minus luning absent response time equals leftover or decision time). This method is better than simply using an on-off button in that if need be one can examine non-response (decision) time.

Therefore, as a check on the data, we performed two separate analyses of the two response measures as follows: (1) amount of time luning present measured by **luning percent time**; and (2) amount of time luning absent measured by **clear percent time.** Percent time is the percentage of the 25 sec. interval the button was pressed. As the results for luning and clear time were not discordant, we do not report the decision (no response) time as it provided no additional information.

We also report the analysis, where the data for each subject is the median response from the three blocks for each of the experimental conditions. This is analogous to procedures, such as trimming the mean or Winsorization (Tukey and McLaughlin, 1963; Tyler,1991), which remove outliers in order to generate more reliable data. This has the effect of removing any unusual context or other influences (e.g., lack of familiarity initially or boredom finally, etc.) It is done here merely as a check on the stability of the data. We designate this as the trimmed data as opposed to the standard data which uses each subject's mean response in the analysis. Additional analyses are described in Appendix D.

Results

The luning percent time, and the clear percent time, standard and trimmed data, are given in Tables 1 and 2. The standard data is graphed in Figures 7 and 8, which show the mean percent response times, averaged over 18 subjects, where each subject's response for each condition is the mean of three blocks. In the following the results for the clear percent time, confirmed the results for the luning percent time; that is, those conditions which exhibited greater luning time had less clear time and vice versa. Also the analysis of the trimmed data confirmed the analysis of the standard data.

The overall effect of display condition on the percent time luning was present was significant for the standard data, F(21,357) = 23.17, p < .001, and for the trimmed data, F(21,357) = 18.49, p < .001. The overall effect of display condition on the clear time, luning absent, was significant for the standard data, F(21,357) = 20.35, p < .001, and for the trimmed data, F(21,357) = 15.91, p < .001.

Effect of FOV Luminance

Table 3 shows the results of the linear trend ANOVAs for percent luning time and Table 4 shows the results of the linear trend ANOVAs for percent clear time. The linear trend of amount of luning with FOV luminance was not significant under either the convergent display mode, or the divergent display mode, for either the null contour stimulus patterns, or for the black contour patterns. Similarly, the linear trend of amount of clear time with FOV luminance was also not significant under either the convergent or the divergent display modes for either the null contour or the black contour patterns.

However, for the white contour stimuli, there was a significant linear trend of increased luning with increased FOV luminance for both the convergent and the divergent display modes. As expected, in parallel, there was a significant linear trend of decreased clear time with increasing FOV luminance for both the convergent and the divergent display modes.

The difference in FOV luminance results between white and black contours may be related to the fact that the background around the FOV in all the stimulus patterns was black, which matched the black contours and not the white. From a practical point of view, we did not think to test patterns in which the background was white, as this would be visually detrimental to the pilot. Whether this asymmetry in luminance relations between the contours and background is related to the differential effect of FOV luminance for white and black contours, is a question for further research.

Effect of Convergent and Divergent Display Modes

The results of the planned comparisons are given in Table 5 for the luning percent times and in Table 6 for the clear percent times.

The convergent display mode had significantly less luning and more clear time than the divergent mode for the null contour and for the black contour stimulus patterns (comparisons 1 and 2 in Tables 5 and 6). The difference in clear time only marginally failed to reach significance ($p = 0.05$) for the trimmed data for the null contour. There was no effect of display mode for the white contour patterns, or the monocular luminance difference patterns (comparisons 3, 8 and 9 in Tables 5 and 6).

Effect of Adding Black or White Contours to Binocular Border

For both the convergent and the divergent stimulus sets, luning was significantly reduced by adding black contours or by adding white contours; and as expected, in parallel clear time was significantly increased by adding the black or white contours (comparisons 4-7 in Tables 5 and 6).

Effect of Monocular Luminance Difference

The condition with dimmer monocular side regions had significantly less luning than the condition with brighter monocular side regions, and each of these had significantly less luning than the condition in which the side regions were of the same--medium--luminance (null contour condition) as the central region; these differences were confirmed for the clear time (comparisons 10-14 in Tables 5 and 6).

As noted above, the difference in luning, and in clear time, between convergent and divergence displays was not significant for either the brighter or dimmer monocular luminance difference patterns.

Fusion Lock Pattern Calls

The computer recorded the number of times that each subject called the fusion lock pattern. Only six out of the eighteen subjects called the fusion lock pattern. Of these, four called the fusion lock pattern more often during the divergent display mode and two more often during the convergent display mode. In total, the fusion lock pattern was called 16 times for divergent stimuli and 7 times for convergent stimuli. This is anecdotal evidence that our subjects had comparatively more difficulty with divergent than with convergent binocular overlap.

Caveat on the Method and Additional Data Analysis

While this method of recording the percentage of time a percept is present, in our case the presence or absence of luning, is widely used to measure the strength of alternative perceptual responses with perceptually ambiguous or fluctuating stimuli, such as binocularly rivalrous patterns (e.g., ref.; Melzer and Moffitt, 1991) and figure-ground patterns (e.g., Klymenko and Weisstein, 1986), what is often overlooked are the additional related influences of experimental context and the subject's criterion bias. Experimental context here refers to the complete set of patterns, in our case the twenty-two stimulus patterns. During a trial, the subject is required at every given moment to make a categorical response--yes, luning present, or no, luning not present--to a stimulus effect which can vary continuously in magnitude. Where the subject decides to set his cutoff point, his criterion, for present or absent is likely to be largely determined by the set of stimuli he has seen--the experimental context--as well as personal idiosyncratic factors. For instance, if only very weakly luning patterns, or only very strongly luning patterns were present, the subject is likely to make finer discriminations between stimuli and set his criterion accordingly. Conversely, if extreme anchor points are present in the set of stimuli, then subjects are less likely to systematically make finer discriminations between similar stimuli.

A way around this, which was not possible in the current context, is to have the subject make direct comparisons between pairs of stimuli, where the stimuli are presented simultaneously (see Klymenko, Verona, Martin, Beasley, and McLean, in preparation). We point this out only to alert the reader that the results, being based on different subjects with different and shifting criterion points, while legitimate for indicating the relative differences in luning magnitude between stimuli, should not be interpreted as indicating the absolute percentage of time luning is always present or always absent (cf., Fox and Check, 1972).

We report data for smaller temporal intervals in Appendix D to provide additional information on the differences between the stimuli.

Discussion

For the null contour and the black contour conditions, the results showing a reduction in luning for the convergent display mode compared to the divergent display mode, and a reduction for the black contours compared to the null contours confirm Melzer and Moffitt's (1991) findings. The average reductions in luning from the divergent mode to the convergent mode was about the same for the null contour conditions (13.5 sec.) and the black contour conditions (14.3 sec), which supports the independence of the effect of display mode and the effect of black contours on luning. Thus with respect to the attenuation of luning, the convergent display mode with black contours appears to be the best display condition. How target thresholds are affected near the contours, or the binocular border, is another question (see Klymenko, Verona, Beasley and Martin, 1993; also see Fox and Check, 1968).

The results for the white contours appear less stable in that there is no systematic effect of display mode on luning, and the luning effect varies as a function of FOV luminance level; the brighter the FOV background, the greater the prominence of luning. This is likely due to the lower contrast between the white contours and the bright FOV, than between the white contours and the dim FOV. Since limiting FOV luminance to low levels is operationally unrealistic, white contours are not recommended for HMDs. In addition, it is plausible that there would be a deleterious effect on threshold in the vicinity of high contrast white contours. An alternative explanation is that with the dim FOV, the luning was less noticeable near the high contrast white edges; even so, small proximate targets might suffer the same effect.

The fact that there was less luning with the dimmer monocular luminance difference patterns compared to the brighter monocular luminance difference patterns may be related also to noticeability, or it may be because there was less rivalry between the dim monocular region and the background. In any case, the low luminances in the dimmer monocular luminance difference patterns, do not make them good candidates for HMDs. It is however interesting to note the effect of the one sided contour of the monocular luminance difference patterns compared to the two sided contours of the black and white contour patterns; and of course compared to the illusory contour type binocular border of the null contour patterns.

It is interesting that the black contour conditions did not show the same effect of FOV brightness as the white contour conditions. Either the contrast effect of the black contours reached their peaks or floors, outside of our FOV luminance testing range, or the direction of the contrast of the black contours, negative compared to the positive contrast of the white contours, was important. Or the fact that the black contours (which had a finite luminance) matched the luminance of the background region outside the FOV, while the white contours did not, may have played a role in the different results. This latter case might entail a Gestalt type of explanation: the visual system interprets the black contour as being a border between the visual field and the background which is also black, thus there is less ambiguity and less rivalry, the background is more thoroughly either suppressed or perceptually scissioned into a different depth plane (see Matelli, 1974). A large number of factors are known to affect binocular rivalry (e.g., Hollins, 1980; O'Shea and Blake, 1986). Currently there is not enough information to settle on a perceptual theory. A larger future study might independently vary the contrasts (or colors) of the contours, the FOVs, and the background.

While there are no doubt several possible perceptual level theories, which one experiment can not constrain, before closing, two other notions are worth briefly mentioning: naso-temporal retinal physiology, and blindness denial and virtual persistence. We have found anecdotal evidence that the fragmentation of a partial binocular overlap display is influenced by not only the display mode, but also where one is fixating (Klymenko, Verona, Martin, Beasley, and McLean, in preparation). This is related to the functional and physiological differences of the nasal and temporal retina (see Blakemore, 1969), and how the visual world maps onto these retinal regions in the convergent and divergent display mode. Briefly, fragmentation is the severe effect of the FOV, corresponding to luning, when the visual angles of the monocular fields are small. As here, it is much more pronounced in the divergent partial binocular overlap display compared to the convergent mode. However, when one is fixating at or beyond the binocular border, in a monocular region, this is no longer the case, due possibly to the different retinal areas being stimulated. This may be directly related to physiological factors such as the large differences in ganglion cell density in the two retinal hemifields (Curcio, and Allen, 1990).

Blindness denial and virtual persistence is another more cognitive factor, which should always be kept in mind when coming to conclusions based on subjective phenomenology. Subjects in our and other experiments report less luning in the convergent than in the divergent display mode; that is, they see less darkening, the FOV looks more natural or clear. However, though implausible at first glance, without testing with objective methods, we don't know for certain that failure to see luning is not due simply to failure to see per se, accompanied by perceptual filling-in, or virtual persistence and blindness denial. While, more often thought of in clinical terms, such as the nonawareness of severe visual scotomas (see McGlynn, and Schacter, 1989), this lack of awareness also occurs in normals, the most common example being the blind spot. The existence of the blind spot is never noticed per se; even the most complex textures and dynamic environmental patterns are "filled-in". We mention this only as a caveat about phenomenal appearances.

To summarize, small FOVs are detrimental to the visual tasks required of military pilots (Osgood and Wells, 1991; Wells, Venturino, and Osgood, 1989). Increasing the FOV by the partial binocular overlap display mode has introduced luning and other potential problems (see Alam, Zheng, Iftekharuddin, and Karim, 1992; Edgar, Carr, Williams, and Clark, 1991; Kruk and Longridge, 1984; Landau, 1990; Moffitt, 1989). Of the conditions that we investigated, the convergent display mode with black contours appears to be the best method for reducing luning. How the advantages tradeoff with the disadvantages in HMDs depends obviously on a number of factors including the visual tasks required (Farrell and Booth, 1984).

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Appendix D

Additional Data Analysis

Below we examine the same set of data in terms of smaller temporal intervals. The following analyses are not orthogonal with the analyses of the larger temporal interval in the main text, and are presented merely as a source of additional information.

Temporal Intervals

In the main text, we reported the data for the total 25 sec. stimulus duration interval (excluding the initial 5 sec. of stimulus presentation). The data from the first half and from the last half of that 25 sec. interval--the initial 12.5 sec. and the final 12.5 sec.--were recorded separately and thus are also available for analysis. This data is of some interest in that it gives us some idea as to whether the differences in the magnitude of luning are more pronounced upon initial viewing, or after some time has passed.

Data Tables

[to be added; also, decision time data, if of interest]
[Note: change "clear time" to "natural time" or other name:?]

Manufacturer's List

HP Computer and Trinitron Monitor

Adlerblick Binoculars

Table 1
Luning Percent Time

Condition	Standard Data		Trimmed Data	
	Mean	SD	Mean	SD
Null contour; Divergent;				
Dim	87.6	10.8	89.6	6.5
Medium	86.5	22.1	87.5	22.3
Bright	85.8	22.9	88.7	22.3
Null contour; Convergent;				
Dim	70.1	26.1	70.8	28.7
Medium	74.8	23.3	80.7	23.9
Bright	74.6	23.0	76.1	27.9
Black contour; Divergent;				
Dim	35.4	30.9	30.5	35.8
Medium	37.0	31.7	37.3	43.0
Bright	34.9	33.9	36.1	39.9
Black contour; Convergent;				
Dim	22.0	27.3	20.2	31.1
Medium	18.7	26.9	16.0	28.8
Bright	23.8	29.6	21.4	34.0
White contour; Divergent;				
Dim	8.5	19.0	7.3	21.9
Medium	28.7	28.5	24.1	30.3
Bright	66.9	32.2	58.3	34.9
White contour; Convergent;				
Dim	21.1	27.8	20.2	29.4
Medium	25.7	26.9	25.2	35.4
Bright	54.7	32.2	58.3	34.9
Monocular Luminance Difference; Divergent				
Dimmer	12.8	20.1	13.9	28.3
Brighter	39.1	31.4	44.3	38.1
Monocular Luminance Difference; Convergent;				
Dimmer	17.5	22.0	10.9	24.4
Brighter	40.4	32.0	40.8	39.3

Table 2
Clear Percent Time

Condition	Standard Data Mean	Standard Data SD	Trimmed Data Mean	Trimmed Data SD
Null contour; Divergent;				
Dim	3.9	9.5	1.2	2.9
Medium	6.2	22.2	5.9	22.3
Bright	7.1	22.5	5.2	22.1
Null contour; Convergent;				
Dim	18.1	25.1	16.4	28.1
Medium	15.3	23.1	8.6	23.5
Bright	14.4	22.1	14.1	26.6
Black contour; Divergent;				
Dim	51.2	32.1	53.2	35.6
Medium	50.8	31.6	50.7	42.5
Bright	51.1	31.7	49.0	37.8
Black contour; Convergent;				
Dim	64.7	28.0	67.1	33.3
Medium	69.6	28.4	72.0	32.2
Bright	64.0	30.9	66.3	34.2
White contour; Divergent;				
Dim	77.1	24.7	79.0	26.2
Medium	57.4	32.3	59.3	38.1
Bright	23.3	30.7	22.5	35.1
White contour; Convergent;				
Dim	68.1	30.7	68.8	33.2
Medium	62.2	30.5	64.1	38.3
Bright	31.8	34.5	25.8	39.0
Monocular Luminance Difference; Divergent				
Dimmer	75.1	22.0	73.4	28.4
Brighter	44.6	33.0	41.1	39.6
Monocular Luminance Difference; Convergent;				
Dimmer	69.0	25.5	71.7	30.3
Brighter	44.8	33.1	44.3	39.7

Table 3

Liner trend tests for luning percent time as a function of FOV brightness:

Condition	Standard Data		Trimmed Data	
	F(1,357)	p	F(1,357)	p
Convergent, Null Contour	0.33	NS	0.33	NS
Divergent, Null Contour	0.06	NS	0.01	NS
Convergent, Black Contour	0.06	NS	0.02	NS
Divergent, Black Contour	0.00	NS	0.36	NS
Convergent, White Contour	19.01	<.001	16.90	<.001
Divergent, White Contour	57.37	<.001	43.19	<.001

Table 4

Liner trend tests for clear percent time as a function of FOV brightness:

Condition	Standard Data		Trimmed Data	
	F(1,357)	p	F(1,357)	p
Convergent, Null Contour	0.23	NS	0.06	NS
Divergent, Null Contour	0.17	NS	0.19	NS
Convergent, Black Contour	0.01	NS	0.01	NS
Divergent, Black Contour	0.00	NS	0.20	NS
Convergent, White Contour	21.99	<.001	21.18	<.001
Divergent, White Contour	48.37	<.001	36.54	<.001

Table 5

Planned comparisons for differences in luning percent time:

Comparison	Standard Data F(1,357)	 p	Trimmed Data F(1,357)	 p
1. Null Contour: Convergent v Divergent	9.14	<.005	5.66	<.05
2. Black Contour: Convergent v Divergent	10.31	<.005	8.33	<.005
3. White Contour: Convergent v Divergent	0.04	NS	0.06	NS
4. Convergent: Null Contour v Black Contour	134.76	<.001	112.22	<.001
5. Divergent: Null Contour v Black Contour	130.44	<.001	101.75	<.001
6. Convergent: Null Contour v White Contour	78.13	<.001	59.58	<.001
7. Divergent: Null Contour v White Contour	136.06	<.001	107.16	<.001
Monocular Luminance Difference;				
8. Brighter: Convergent v Divergent	0.03	NS	0.04	NS
9. Dimmer: Convergent v Divergent	0.05	NS	0.03	NS
10. Convergent: Brighter v Same	19.92	<.001	18.49	<.001
11. Divergent: Brighter v Same	37.78	<.001	21.71	<.001
12. Convergent: Dimmer v Same	55.21	<.001	56.63	<.001
13. Divergent: Dimmer v Same	91.31	<.001	63.02	<.001
14. Brighter v Dimmer	20.33	<.001	21.16	<.001

Note: Same = Null Contour at Medium FOV.

Table 6

Planned comparisons for differences in clear percent time:

Comparison	Standard Data		Trimmed Data	
	F(1,357)	p	F(1,357)	p
1. Null Contour: Convergent v Divergent	5.19	<.05	2.73	NS
2. Black Contour: Convergent v Divergent	11.41	<.001	10.52	<.005
3. White Contour: Convergent v Divergent	0.10	NS	0.02	NS
4. Convergent: Null Contour v Black Contour	126.67	<.001	105.73	<.001
5. Divergent: Null Contour v Black Contour	103.15	<.001	75.57	<.001
6. Convergent: Null Contour v White Contour	73.05	<.001	54.70	<.001
7. Divergent: Null Contour v White Contour	110.29	<.001	84.20	<.001
Monocular Luminance Difference;				
8. Brighter: Convergent v Divergent	0.00	NS	0.03	NS
9. Dimmer: Convergent v Divergent	0.06	NS	0.02	NS
10. Convergent: Brighter v Same	14.61	<.001	14.65	<.001
11. Divergent: Brighter v Same	24.61	<.001	14.20	<.001
12. Convergent: Dimmer v Same	48.32	<.001	45.70	<.001
13. Divergent: Dimmer v Same	79.51	<.001	52.20	<.001
14. Brighter v Dimmer	25.09	<.001	20.41	<.001

Note:, Same = Null Contour at Medium FOV.

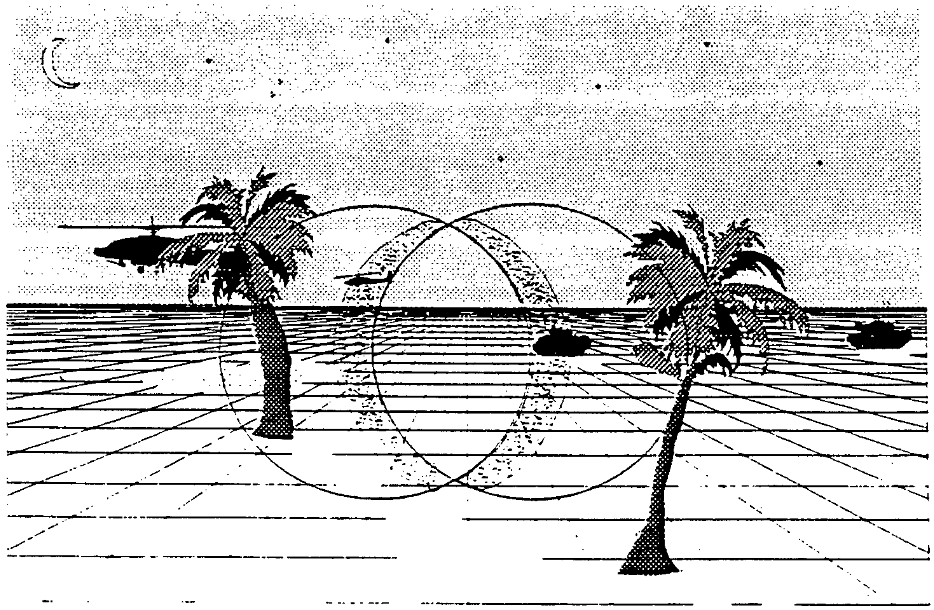


Figure 1. A helicopter pilot's view of the visual world using an HMD in partial binocular overlap display mode. The helicopter in the left visual field and the armored personnel carrier in the right visual field are each in monocular regions near the monocular/binocular border, where luning occurs, as indicated by the shading. If the right eye is viewing the circular region containing the armored personnel carrier, the display mode is divergent. If instead, the left eye is viewing this region, the display mode is convergent. Luning has been reported to be more severe in the divergent display mode.

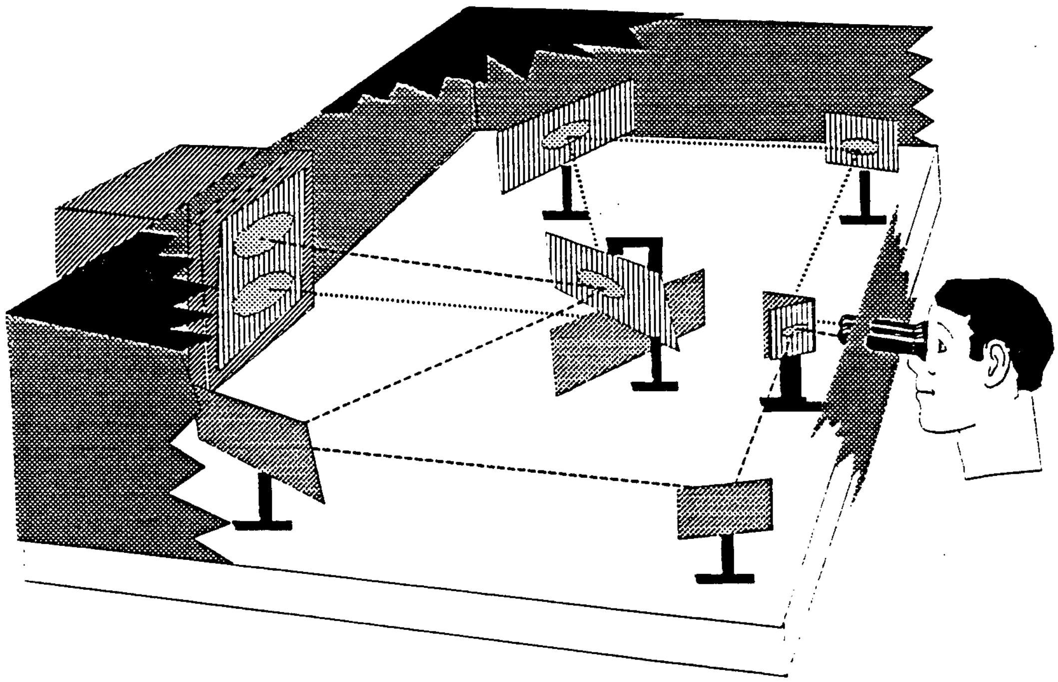


Figure 2. Perspective view of the optical table configuration, consisting of the monitor, eight mirrors, and a pair of binoculars (not to scale). The image from the top half of the monitor is directed to the left eye and the image from the bottom half is directed to the right eye. Additional equipment, not shown, include a light baffle in front of the monitor between the two optical paths, focusing lenses attached to the binoculars, and filter holders in front of the binoculars.

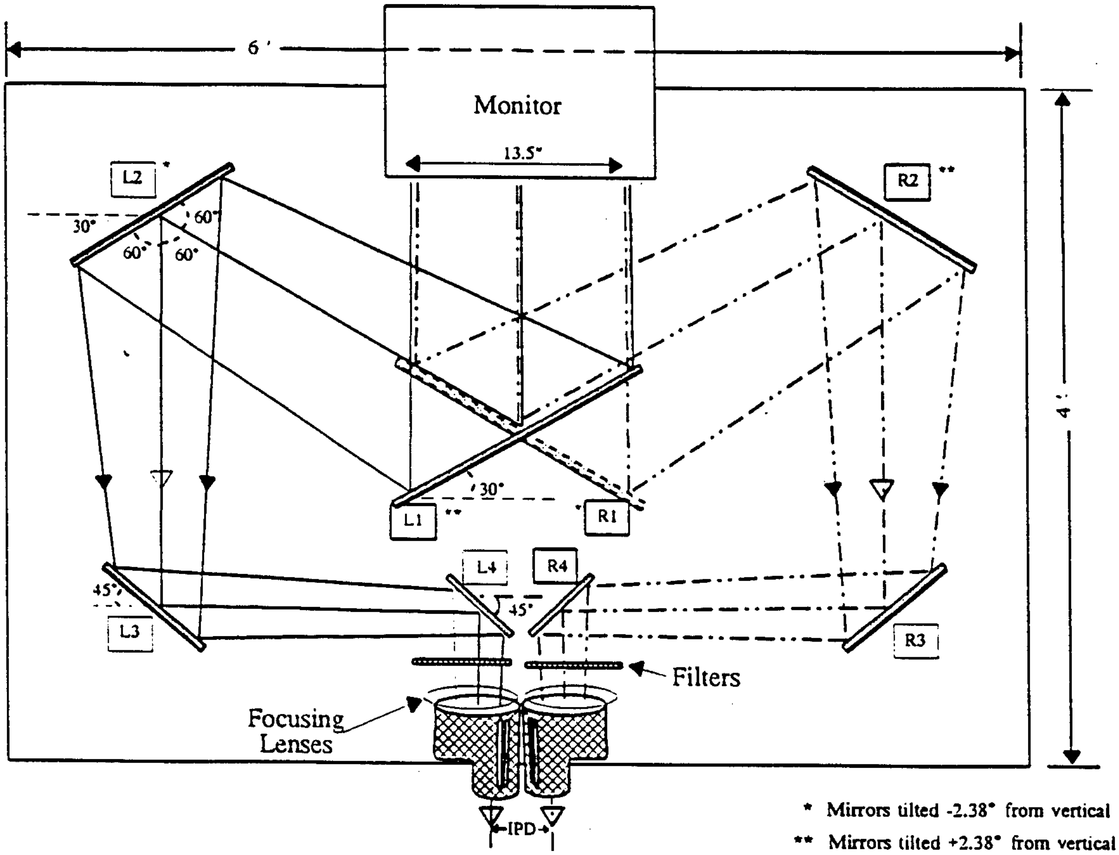
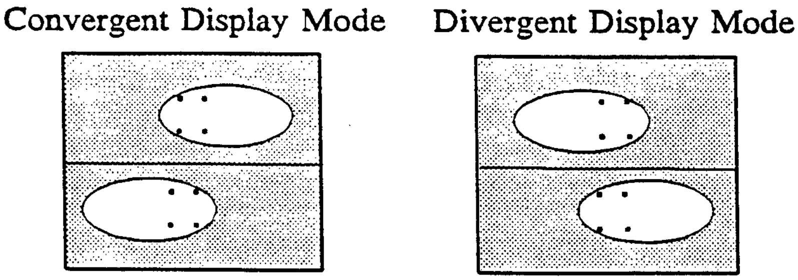
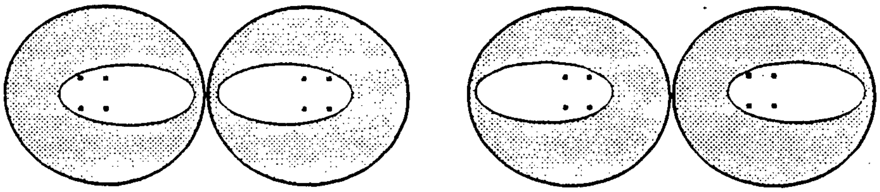


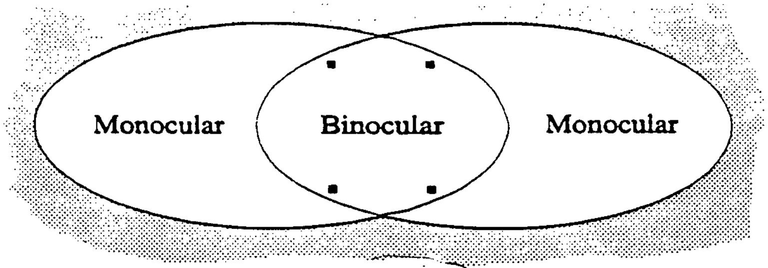
Figure 3. Top view of the optical table configuration. The image from the top half of the monitor (solid rays) is reflected down from mirror L1 to L2, and then parallel to the surface of the table, from mirrors L2 to L3 to L4 to the left ocular of the binoculars. Similarly for the right channel, the image from the bottom half of the monitor (dashed rays) is reflected up from mirror R1 to R2, and then parallel to the surface of the table from mirrors R2 to R3 to R4 to the right ocular of the binoculars. The binoculars and movable mirrors L4 and R4 are preset to correspond to each individual subject's IPD. The resulting stimulus is shown in Figure 4.



Elliptical monocular fields
on the monitor



Through the
binoculars



FOV regions as seen by
the observer

Figure 4. The top panel show the elliptical monocular fields on the monitor for the convergent and the divergent display modes. The middle panel shows the monocular fields through the binoculars and the bottom panel shows the FOV as experienced by the subject when the images are properly fused. In the bottom panel, the right eye sees the right ellipse and the left eye sees the left ellipse in the divergent display mode, and vice versa in the convergent display mode. The purpose of the four black rectangles in each image is to serve as a stimulus for binocular locking and to prevent image slippage during binocular fusion.

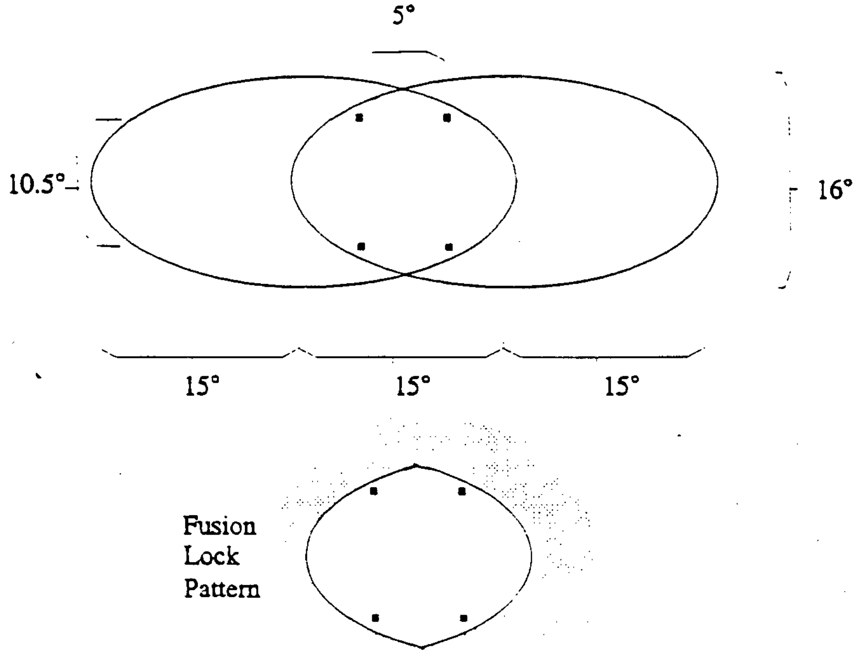


Figure 5. The visual dimensions in degrees of visual angle are given to the right and below the overlapping monocular ellipses. The distances between fusion locks are given above and to the left. The fusion lock pattern, in which the same image is presented to both eyes, is shown below the ellipses. This pattern consists of the fusion locks and the binocular overlap region.

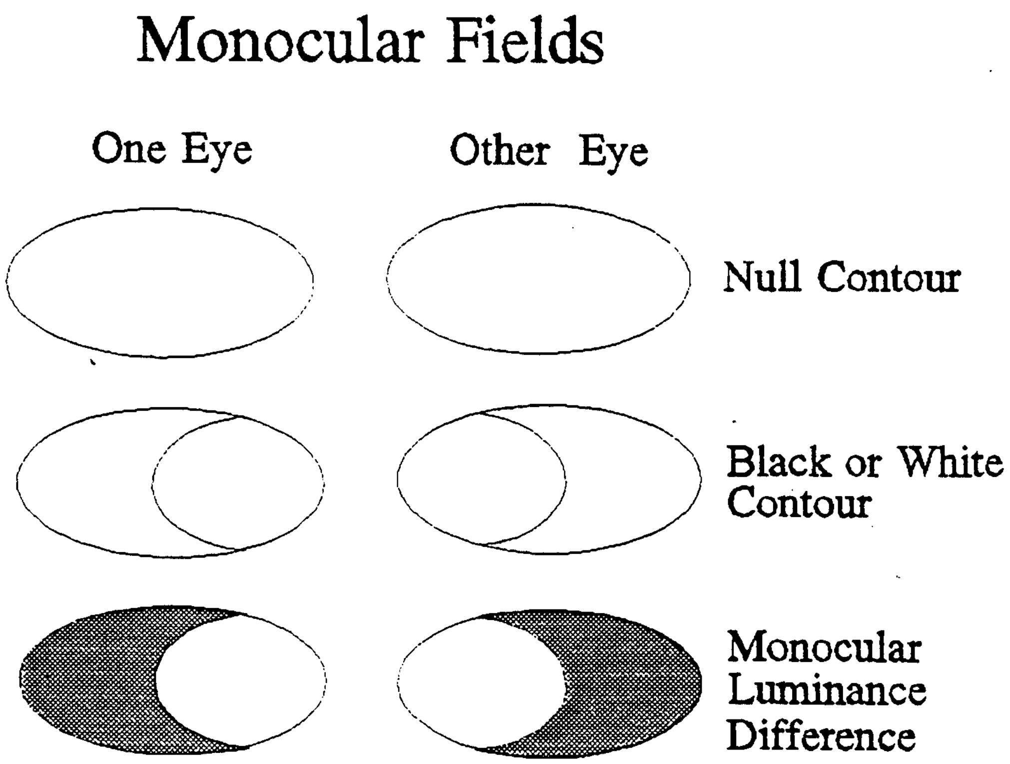


Figure 6. In the null contour stimulus conditions, the elliptical monocular fields were of uniform luminance. Contours were located on the two monocular/binocular borders indicated by a black line in the black and white contour conditions. The monocular regions indicated by shading were brighter or dimmer than the binocular overlap region in the monocular luminance difference conditions.

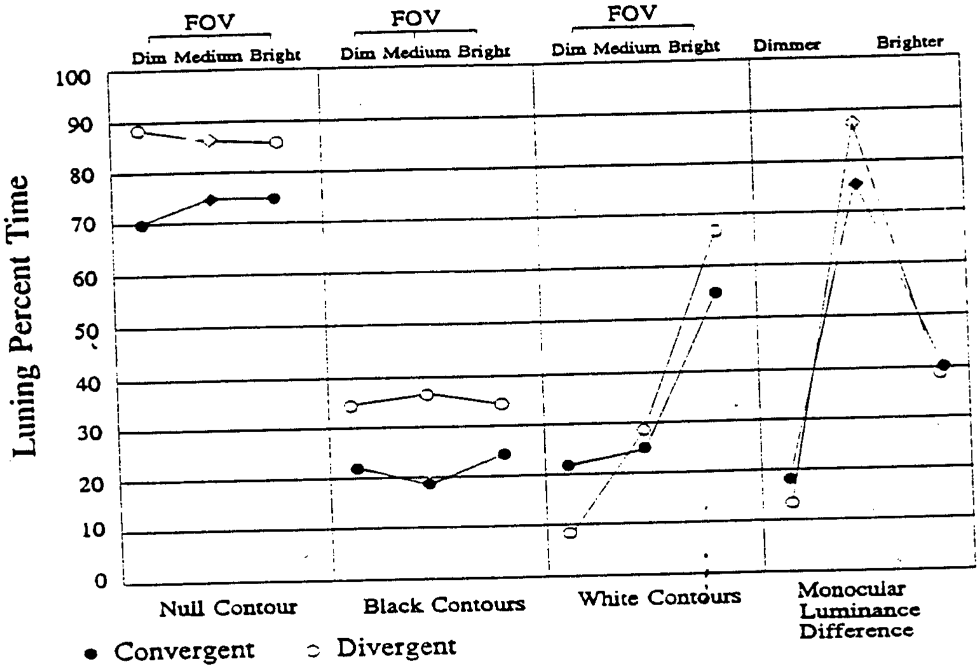
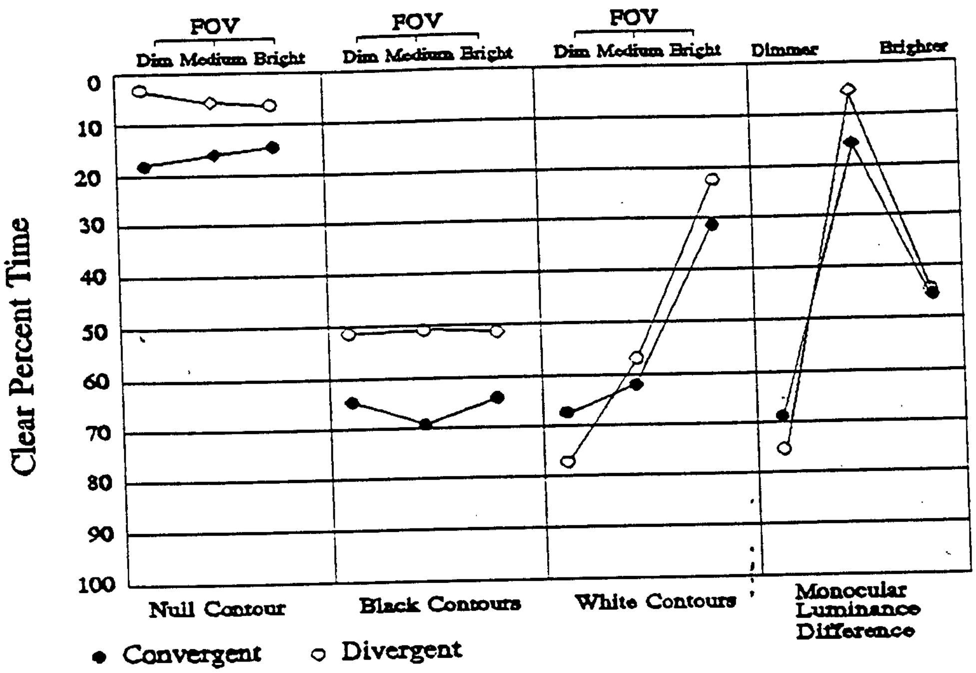


Figure 7. Mean luning percent time. (Diamonds indicate data points reproduced twice for comparative purposes).



Note: Ordinate reverse numbering for easier comparison with Figure 7.

Figure 8. Mean clear percent time. (Diamonds indicate data points reproduced twice for comparative purposes).