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Visual Perception in the Field-of-View of Partial Binocular Overlap Helmet-Mounted Displays

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Because of limitations in the size of the field-of-view (FOV) available in helmet-mounted displays (HMD) using the full overlap display mode, where the entire FOV is binocular, partial binocular overlap displays, which can be convergent or divergent, have been proposed. One consequence of this is a perceptual effect known as luning, which is a subjective darkening in the monocular regions of the FOV, which can in some cases cause fragmentation of the FOV into three regions. A concern is the possible effect on target identification in the monocular regions, particularly in areas affected by luning. We review data we have collected in our binocular vision lab on the effect of display mode on these aspects of visual perception.

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1. BACKGROUND

Artificially small fields-of-view (FOV) can be detrimental to the visual tasks required of military pilots.[1-4] In order to increase the extent of the visual world available to U.S. Army helicopter pilots using helmet mounted displays (HMDs), without incurring increases in size, weight, or loses in central resolution, an unusual method of display---partial binocular overlap---has been proposed. Two flanking monocular regions and a central binocular overlap region constitute the FOV in partial binocular overlap displays, where the display mode may be convergent or divergent (see Figures 1 and 2). Increasing the FOV by this method has been the cause of some concern.[5-18]

One detrimental consequence of the partial binocular overlap display mode is a perceptual effect known as ***luning***, which is a subjective darkening in the monocular regions of the FOV near the binocular overlap borders.[9,11,14,15] Sometimes luning is experienced as a visual fragmentation of the FOV into three distinct regions, where instead of the entire FOV appearing as one unitary visual area, the central binocular overlap region appears to be different than the two monocular side regions. The monocular side regions may appear to lie in a different depth plane, or to be darker than the binocular region.[16] Due to both luning and fragmentation, the monocular regions may appear less substantial and less stable than the binocular region in that they may fluctuate in appearance over time. These effects are due to the binocular rivalry and suppression caused by the dichoptic competition between the discordant stimulation presented to the two eyes. In each of the monocular regions making up the FOV, one eye sees a portion of the FOV and the other eye sees a dark background at the same phenomenal location in space (see Figure 2).

An additional concern is the effect of partial overlap on target detection and identification. The superiority of binocular vision over monocular vision is well known. For example, contrast sensitivity is increased by a factor of 1.4 for binocular vision compared to monocular vision.[19] How does the additional factor of only partially overlapping the binocular display affect perception? How does this affect target threshold in the areas that undergo luning near the binocular overlap border? Is there a difference in the visibility of targets if the partial binocular overlapping FOV is displayed in the divergent as opposed to the convergent display mode (see Figure 2)?

Below, we review our research on the perceptual consequences of partial overlap displays.[15-18] First, we briefly describe our binocular vision lab, then our data, and finally interpretations of our results.

2. BINOCULAR VISION LAB

We designed a binocular vision lab to allow us to present computer controlled images simulating the display modes available in HMDs.[15-17] The equipment consisted of three major components: A Hewlett-Packard HP-98731 Turbo-SRX computer graphics workstation used to generate the visual stimuli; an optical table configuration used to optically direct the visual stimuli from the workstation monitor to a pair of viewing binoculars; and a subject booth, a light proof enclosure where the subject viewed the stimuli via the binoculars and responded via a response keypad. The purpose of the optical table configuration was to allow the independent presentation of two channels, one to each ocular of the binoculars from the same monitor. The equipment is shown in Figure 3. Figure 4 shows examples of the three display modes for presenting the FOV.

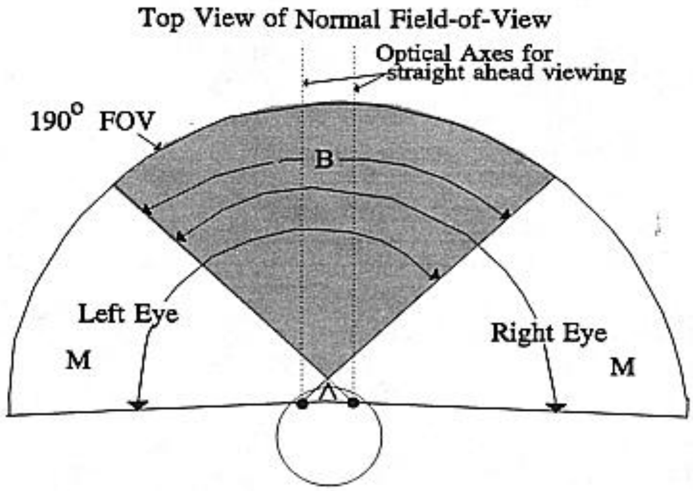


Figure 1. *The unaided FOV is divergent with the right eye's monocular (M) region to the right of the binocular (B) overlap region and the left eye's monocular region to the left. The total FOV is normally around 190°.*

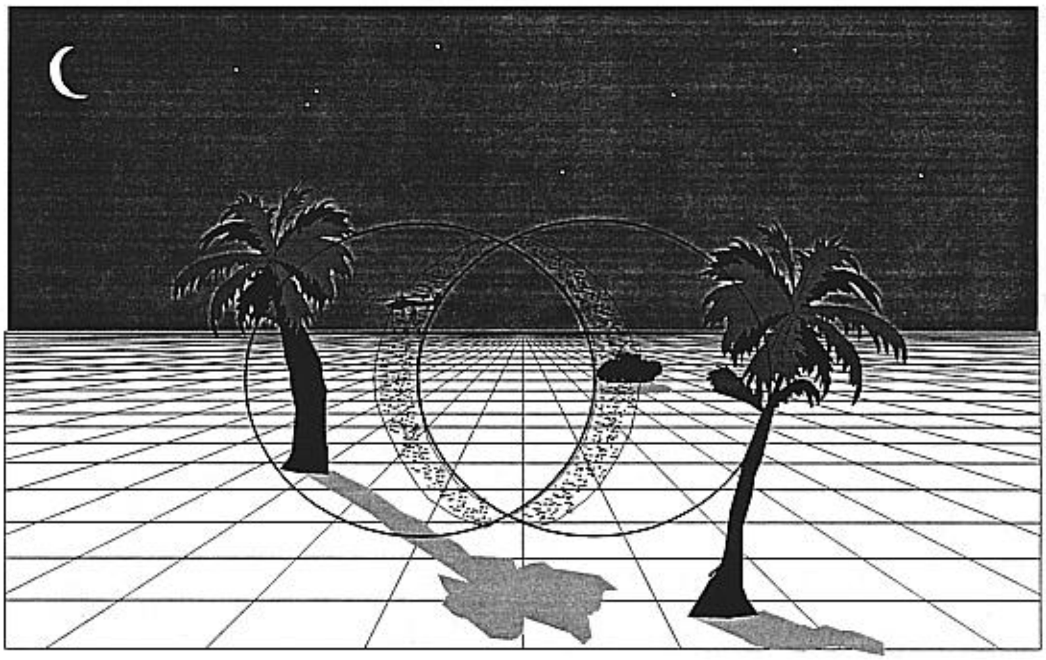


Figure 2. *A helicopter pilot's view of the visual world using a helmet mounted display in the partial binocular overlap display mode, where each eye sees a circular* ***monocular field*** *against a black* ***background****. The central* ***binocular overlap region*** *is flanked by two* ***monocular regions****. If the right eye views the right circular field, the effective* ***field-of-view*** *is in the* ***divergent*** *display mode; if the right eye instead views the left circular field, the mode is* ***convergent.*** *Separating the binocular region and monocular regions are the* ***binocular overlap borders****.* ***Luning*** *refers to the subjective darkening which can occur in the monocular regions near the binocular overlap borders. (A helicopter and an armored personnel carrier are in portions of the monocular regions affected by luning.) Luning can result in* ***fragmentation*** *of the field-of-view into three---two side and one central---phenomenally distinct regions.*

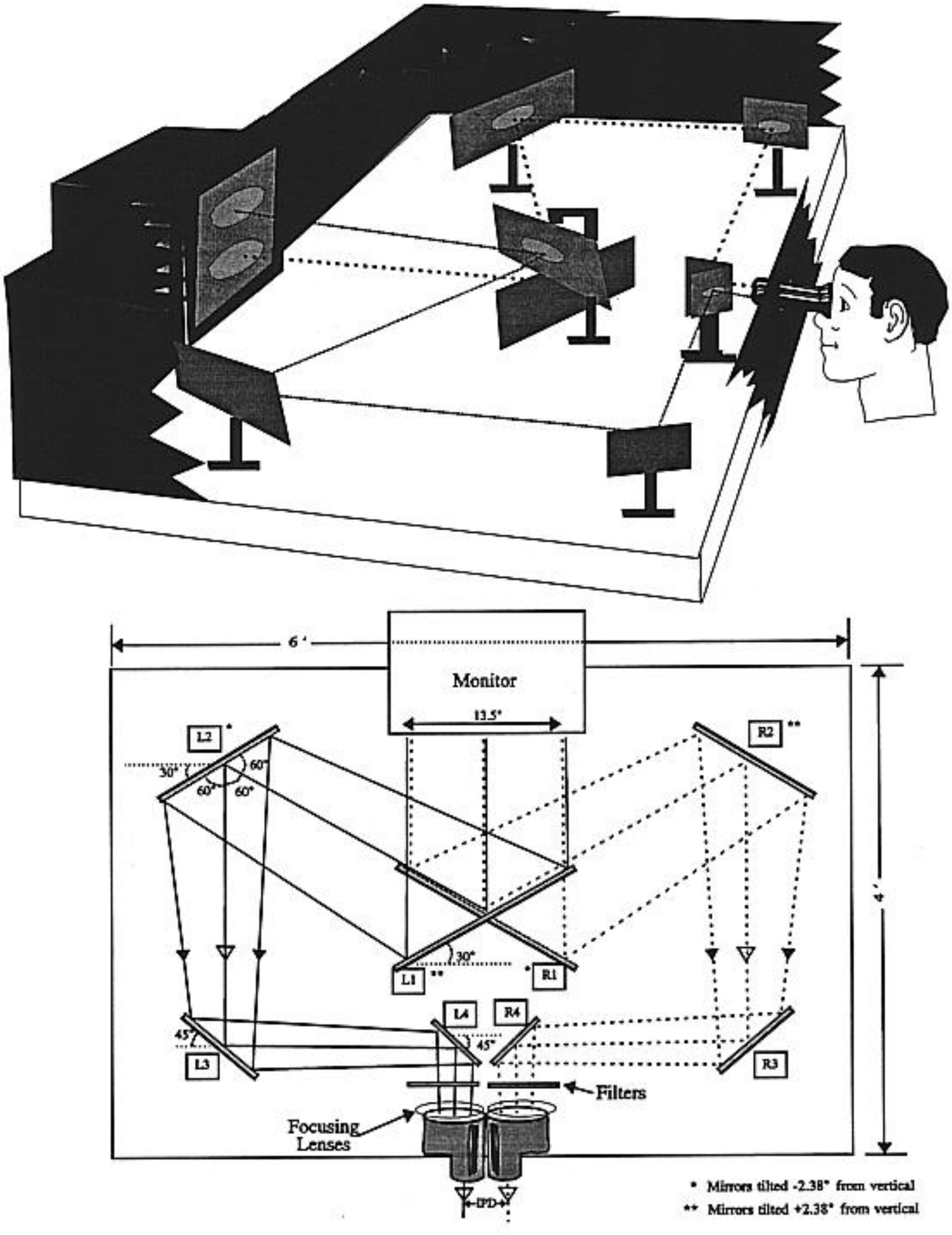


Figure 3. *Perspective and schematic illustrations of the optical table configuration, consisting of the monitor, eight mirrors, focusing lenses and binoculars. The image from the top half of the monitor is directed to the left eye (mirrors L1 to L4), and the image from the bottom half is directed to the right eye (mirrors R1 to R4). The binoculars and movable mirrors, L4 and R4, are set to correspond to each subject's interpupillary distance (IPD). Examples of resulting stimulus displays are shown in Figure 4.*

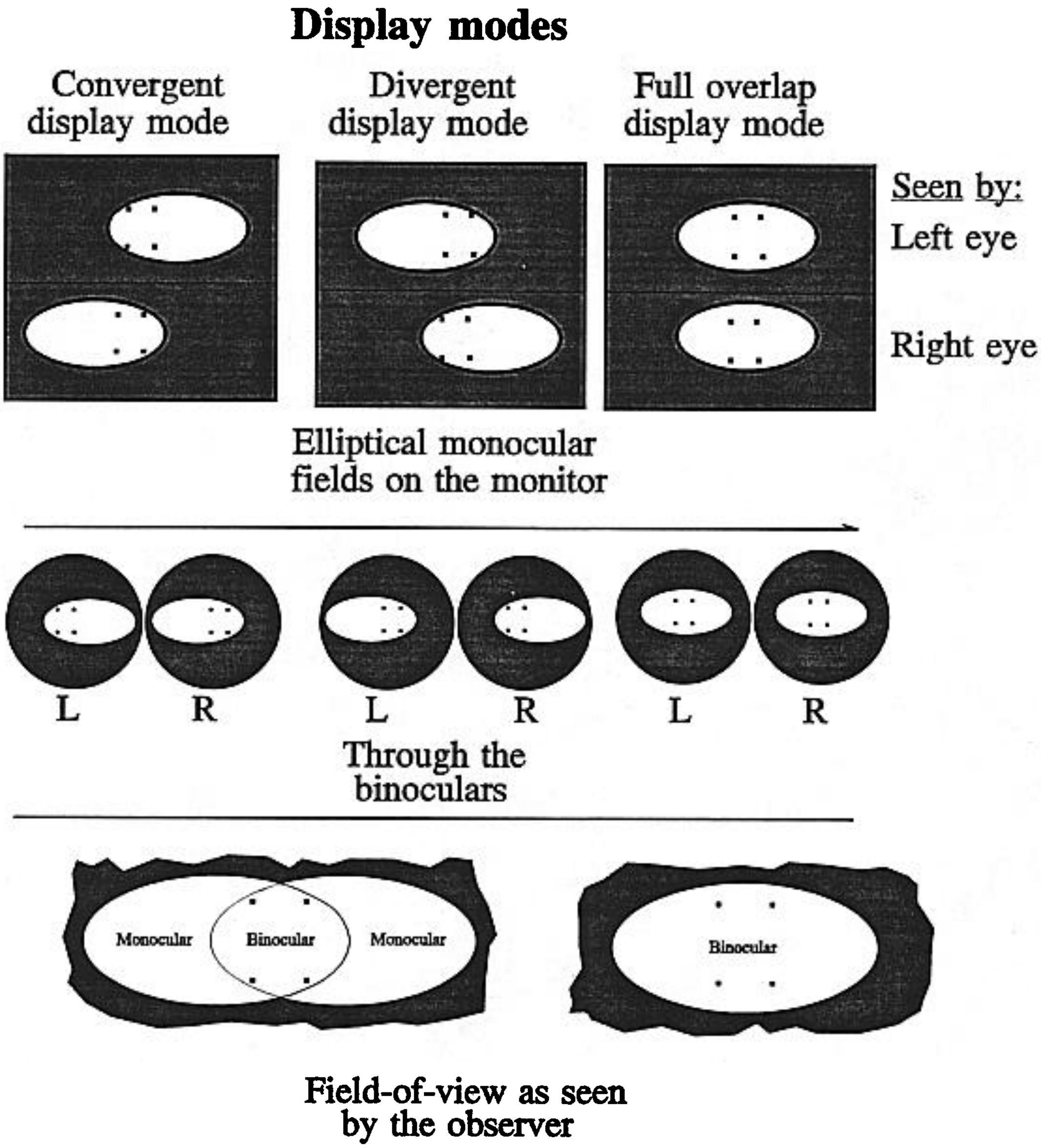


Figure 4. *The **top panel** shows the positions of elliptical monocular fields on the monitor for three display modes. The **middle panel** shows the images of the monocular fields through the binoculars for the right (R) and left (L) eyes for each display mode. The **bottom panel** shows the field-of-view as seen by the observer when the monocular images are properly fused. The image on the right corresponds to the full overlap display mode and the image on the left corresponds to a partial binocular overlap display mode. If the right elliptical field is viewed by the right eye, the partial overlapped FOV is in the divergent mode, and if the left elliptical field is viewed by the right eye, it is in the convergent mode. The small black squares are the fusion locks. Elliptical visual fields were used in the luning and the contrast study.*

3. LUNING IN THE FOV

The effect of a number of display factors on luning were tested. These factors included: (1) convergent versus divergent displays, (2) display luminance level, (3) the presence of either black or white contours or no (null) contours on the binocular overlap border, and (4) lowering or raising the luminance of the monocular side regions relative to the binocular overlap region. The stimulus dimensions of the visual fields are shown on the top of Figure 5. To ensure proper binocular fusion, fusion locks were present in the monocular fields as shown in Figures 4 and 5. If subjects lost fusion and/or experienced diplopia, they could call up a fusion stimulus pattern shown on the bottom of Figure 5. There were 22 stimulus conditions described in Figure 6, which were presented in three blocks. Each stimulus was viewed for 30 seconds during which time the subject was free to scan the FOV. The subject continuously pressed one of two buttons to indicate the presence or absence of luning. Data recording began after the initial 5 seconds of stimulus presentation. The mean percentage of the 25 second data recording time interval that luning was seen was the measure of the amount of luning for each stimulus condition. The stimulus conditions tested are shown on the top and the corresponding results for 18 subjects are shown on the bottom of Figure 6.

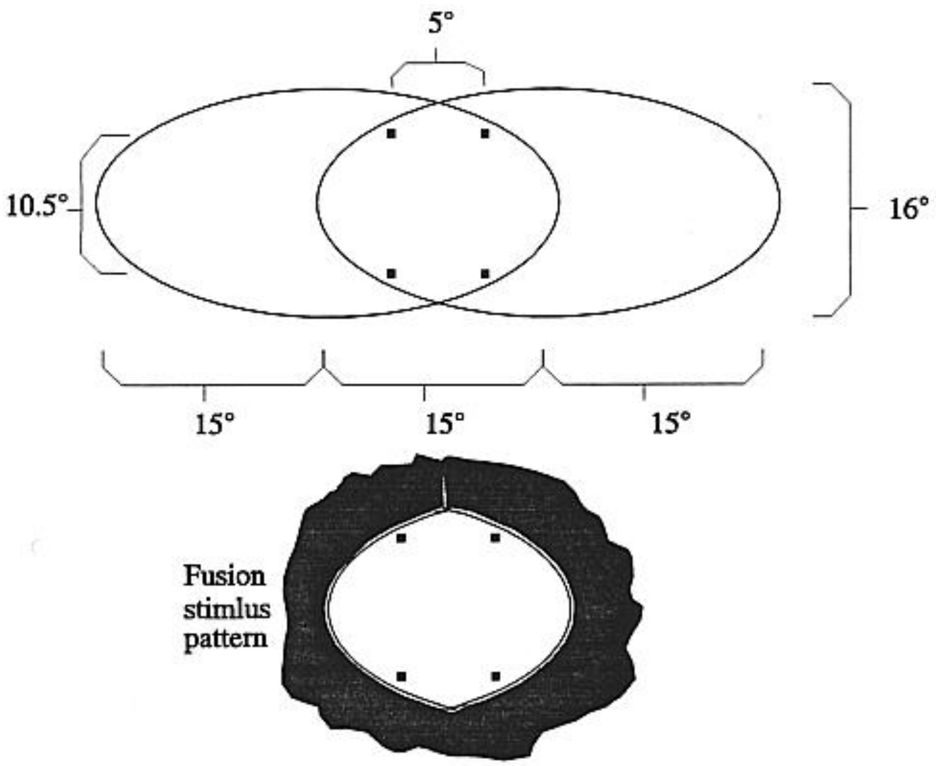


Figure 5. Dimensions of elliptical monocular fields and fusion stimulus pattern. The visual dimensions in degrees of visual angle are given to the right and below the overlapping monocular ellipses. The distances between fusion locks are given above and to the left. The fusion stimulus pattern, in which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

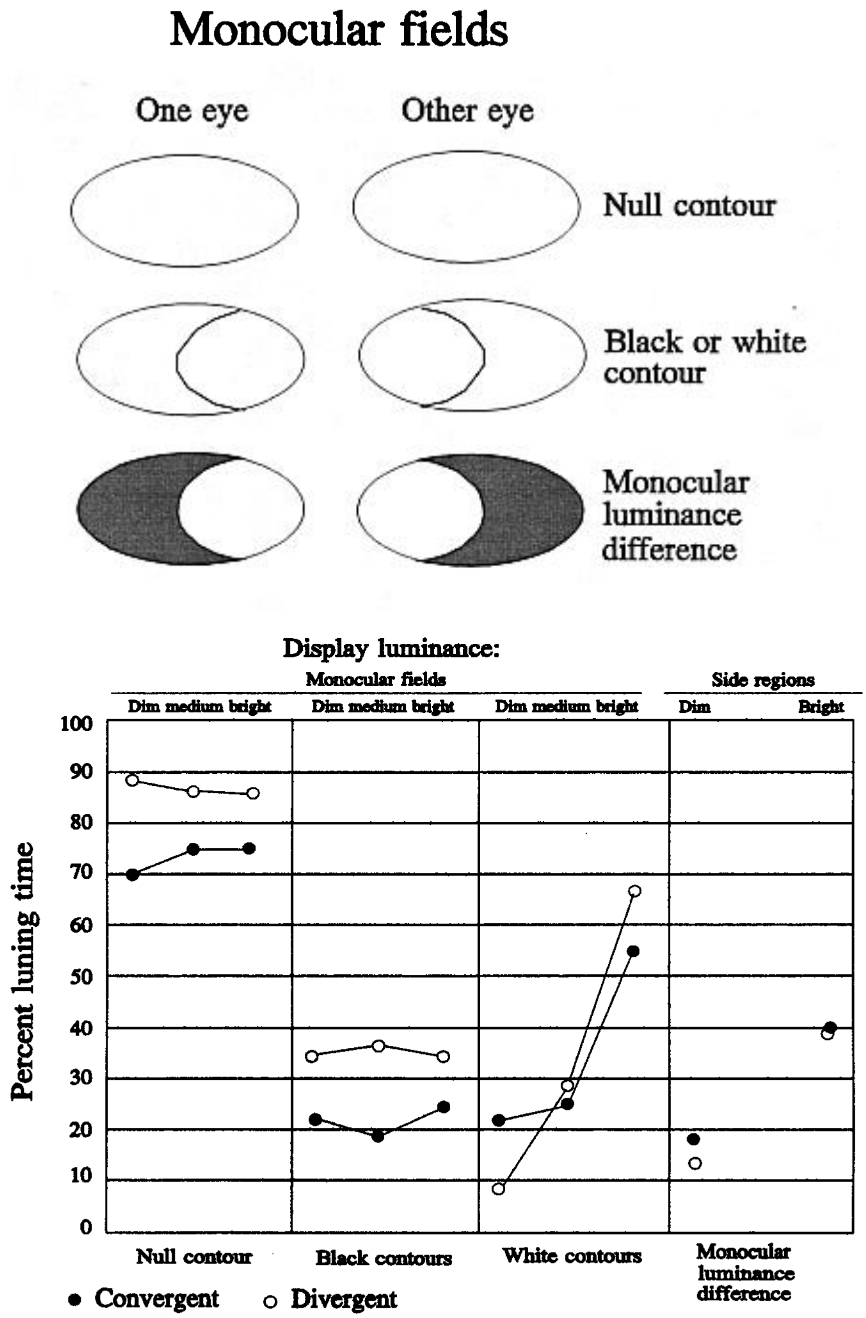


Figure 6. *Top. Stimulus conditions in luning study. Null contour conditions: monocular fields were of uniform luminance against a black background. Black and white contour conditions: contours were added in location of binocular overlap borders. Monocular luminance difference conditions: monocular regions were bright or dim and the binocular overlap region was medium. (Luminance in footlamberts: dim 0.4, medium 2.0, bright 5.0, background 0.02).* ***Bottom.*** *Results. Mean percentage of 25 second stimulus presentation time luning was seen for each condition for 18 subjects.*

The results indicated that the divergent display mode systematically induced more luning than the convergent display mode under the null contour condition. Adding black contours reduced luning in both the convergent and divergent display modes, where the convergent mode retained its relatively lower magnitude of luning: this confirmed previous studies.[11] The display 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 display luminance, where there was less luning for lower display luminance levels. Changing the luminance of the monocular regions (relative to the overlap region) reduced the perceived amount of luning, where a decrease produced more of a reduction than an increase. Also, luning tended to increase over time in that there tended to be more reported luning in the second half of the stimulus interval compared to the first half. These and additional luning data are described more fully elsewhere.[15]

4. CONTRAST THRESHOLD ACROSS THE FOV

We investigated the effect of display modes on visual sensitivity across the FOV. We measured the visual threshold to probe targets across the FOV for three display modes: the full overlap mode, the convergent mode, and the divergent mode. The experimental conditions included four types of position in the FOV: monocular and binocular, each of which could be either near to or distant from binocular overlap border (see Figure 7). All combinations of four spatial frequency (1.06, 2.12, 4.24, and 8.48 cycles per degree; see Figure 8) and four temporal frequency (0, 3.75, 7.5, and 15 Hertz; see Figure 9) probe targets were tested at each of the four positions. The nonzero Hz targets flickered sinusoidally from zero to full contrast. The monocular fields were of the same size and luminance as described previously. The only difference between display modes was the position of the monocular fields as shown in Figure 7.

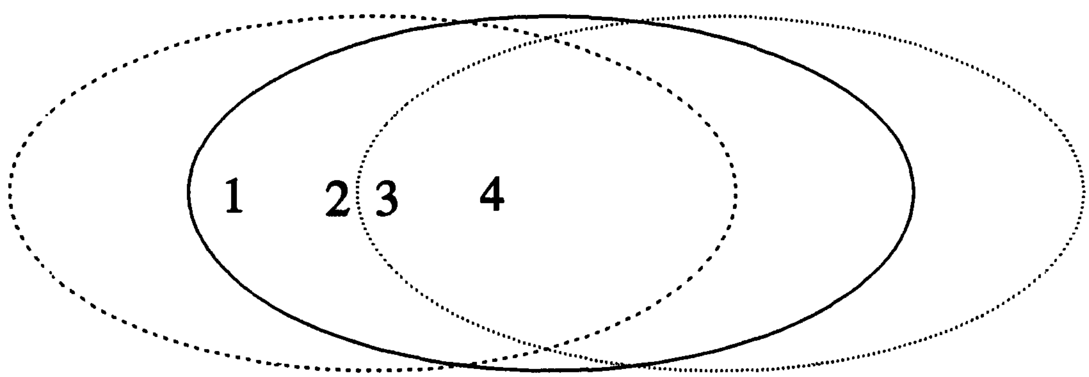


Figure 7. *The four probe positions. The relative positions of the elliptical monocular fields and the four probe positions are shown superimposed. Both eyes saw the ellipse with the solid line in the full overlap display mode. In the divergent display mode, the right eye saw the dotted ellipse on the right, and the left eye saw the dashed ellipse on the left. Conversely, in the convergent mode, the right eye saw the dashed ellipse on the left, and the left eye saw the dotted ellipse on the right. Stimulus probes in positions 1 and 2 are monocular in the convergent and the divergent display modes and binocular in the full overlap display mode. Stimulus probes in positions 3 and 4 are binocular in all modes. In the convergent and divergent display modes, positions 2 and 3 are near (0.08 degrees of visual angle) the binocular overlap border, and positions 1 and 4 are more distant (2.03 degrees of visual angle) from the border. There is no border in the full overlap mode.*

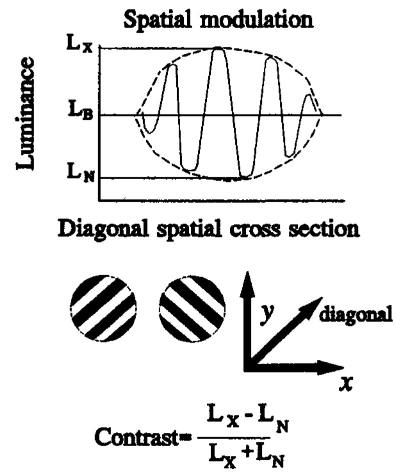


Figure 8. *Spatial modulation of probe stimuli. The probe stimuli were four cycles of a sine wave grating modulated by a circularly symmetric half cosine envelope (dashed lines) of 1/4 the spatial frequency of the sine wave. L_X represents the maximum luminance, L_N the minimum luminance, and L_B the mean (and the background) luminance of the resulting stimulus patch. The phase of the cosine envelope is 0° in the center, and the sine wave is randomly either 0° or 180°. These are modulated with respect to L_B.* ***Top*** *shows a diagonal luminance cross section shown in the* ***middle****. Stimulus contrast defined at the* ***bottom*** *represents the peak contrast for the temporally modulated patterns shown in Figure 9. These probe stimuli are localized in space and have a narrow bandwidth in the Fourier domain.*

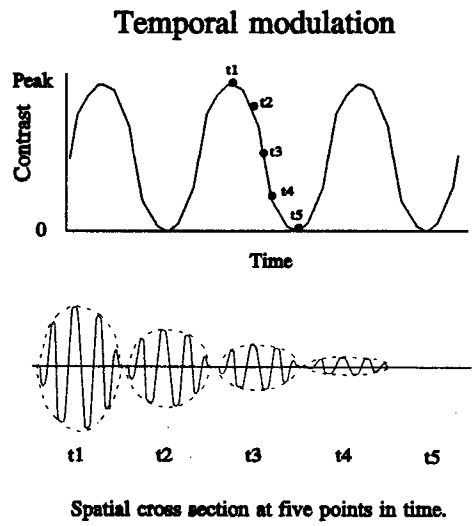


Figure 9. *Temporal modulation of probe stimuli. For the flickering probe stimuli, the contrast varied sinusoidally as shown on the* ***top****. Stimulus contrast is defined by the peak contrast. The* ***bottom*** *shows the luminance profile of a cross section of the probe at five points in time.*

There were 192 experimental conditions, which consisted of the four spatial frequencies x four temporal frequencies x four probe positions x three display modes. These were divided into 16 types of experimental session, where each session presented the four temporal frequencies x the three display modes for one spatial frequency at one position. There were 31 subjects. Each subject took part in from 1 to 16 sessions, and between 15 and 27 subjects took part in each type of session. The 12 stimuli in each session were presented in three blocks.

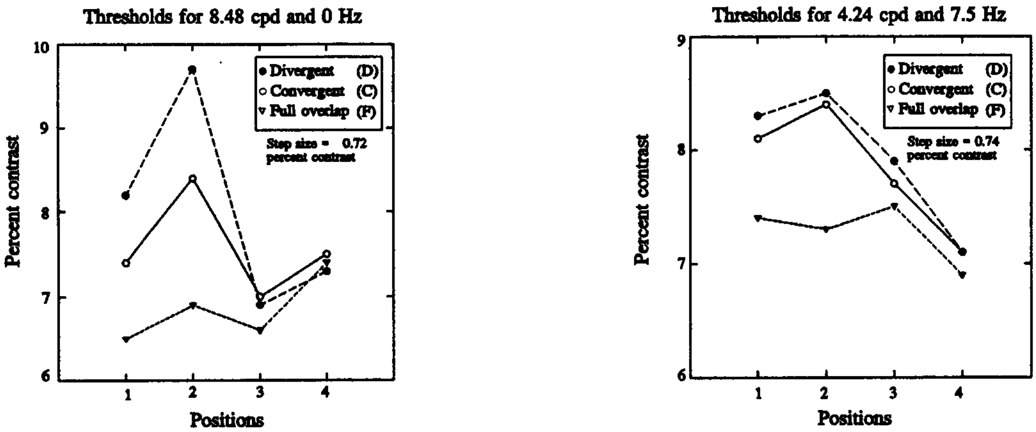
The subject's task for each trial was to fixate the location of the probe stimulus and to set the modulation contrast of the probe, using the method of adjustment, to the lowest level at which the orientation of the probe could be identified. The contrast step size changes were the smallest available for our 256 gray level monitor. The contrast was modulated about a mean luminance level of 2.0 footlamberts. For each trial the contrast of the stimulus probe began at zero. For each change in contrast one of four stimulus versions was presented randomly (2 orientations x 2 phases; see Figure 8). Subjects increased contrast with a button press and could decrease contrast with a button press if threshold was overshot. The data were the mean contrast levels for each stimulus condition.

A sample of results are shown in Figure 10. In general the results indicate that for all spatial and temporal frequencies, the probes in positions 1 and 2 had higher thresholds in both of the partial overlap display modes, where the probes were monocular, compared to the full overlap display mode, where the probes were binocular. This was as expected.[19] We also found systematic increases in threshold for the divergent compared to the convergent display mode for the two highest (4.24 and 8.48 cpd) spatial frequencies, and there was still somewhat of an increase for the next to lowest spatial frequency (2.12 cpd) for position 2. There may still have been threshold differences for the lower spatial frequencies, however, these would have been finer than our ability to measure in the current design.

For the partial overlap displays, thresholds tended to be higher in position 2 compared to portion 1. It appears that the darkening luning phenomenon, emanating from the binocular overlap border, which is greater in the divergent compared to the convergent display mode, is related to this decrement in sensitivity. This is interesting because when any feature is in the FOV, luning is less noticeable, yet, the degree of threshold decrement appears to be correlated with the magnitude of luning in a clear FOV for a display mode. Overall, these differences were more pronounced for the higher spatial frequencies.

In the partial overlap display modes, the reasons thresholds are higher in position 2 near the border compared to position 1 may be as follows: The monocular region is the binocular result of the dichoptic competition of the monocular field of one eye and the dark background of the contralateral eye. The eye contributing the monocular field to the monocular region, the **informational** eye, is a relatively poor competitor compared to the **noninformational** eye containing the border (edge) between the monocular field and background. It is known that edges are strong dichoptic competitors that tend to pull in surrounding areas into the binocular percept.[20-21] This can be attenuated by placing an edge in the informational eye. This will increase its relative dichoptic strength. Also softening the border in the noninformational eye will weaken its strength.[11]

In position 4, where the probe in each of the display modes was binocular and not adjacent to the binocular overlap border in the partial overlap display modes, there were no differences in thresholds for any of the probe targets. In position 3, where the probe in each of the display modes was binocular but was adjacent to the binocular overlap border in the partial overlap display modes, there were some small differences in the thresholds for probe targets at the two intermediate spatial frequencies. Borders in general are known to effect threshold.[22] These data are described more fully elsewhere.[18] All of the above results, with one exception, can be accounted for by known phenomena. The exception, discussed below, is the systematic differences between the divergent and the convergent display modes in terms of both luning and visual thresholds.



t - test	1	2	3	4
C<D	p=.027	p=.003	—	—
F<C	p=.007	p<.001	—	—
F<D	p<.001	p<.001	—	—
ANOVA	p<.001	p<.001	n.s.	n.s.

n.s.= not significant

t - test	1	2	3	4
C<D	p=.202	p=.295	p=.024	—
F<C	p<.001	p<.001	p=.107	—
F<D	p<.001	p<.001	p=.007	—
ANOVA	p<.001	p<.001	p<.05	n.s.

n.s.= not significant

Figure 10. *Sample of contrast threshold results. Spatial and temporal frequency of probe stimulus listed on top. Positions on bottom of graphs correspond to Figure 7. Below graphs are the results of the statistical analyses which test the effect of display mode on contrast threshold for each position.*

5. FRAGMENTATION OF THE FOV

When the informational eye dominates the monocular regions of partial overlap displays, the FOV looks natural and the binocular and monocular regions are both seen as one continuous visual world; alternatively, if the noninformational eye dominates, the FOV appears fragmented into three distinct visual regions, and the two flanking monocular regions appear separate from and/or different than the central binocular overlap region.

We tested the influence of display factors on fragmentation. These included the display mode---convergent versus divergent---and orthogonal to this, the dimensions of the different visual areas. These were the size of (1) the monocular fields, (2) the monocular regions, (3) the FOV, and (4) the binocular overlap region. Rather than ellipses, the monocular fields were rectangles measuring 4 degrees of visual angle vertical and between 11 and 20 degrees horizontal. The positioning and size of the monocular fields determined the size of the other visual dimension factors. The stimulus details are described more fully elsewhere.[16] Thirteen subjects each viewed 25 different pairs of FOVs simultaneously, where the two FOVs differed on either the display mode factor or visual dimension factors. Each subject viewed 200 stimulus pairs consisting of 25 stimulus pairs x 2 positions (top and bottom position in display) x 4 blocks.

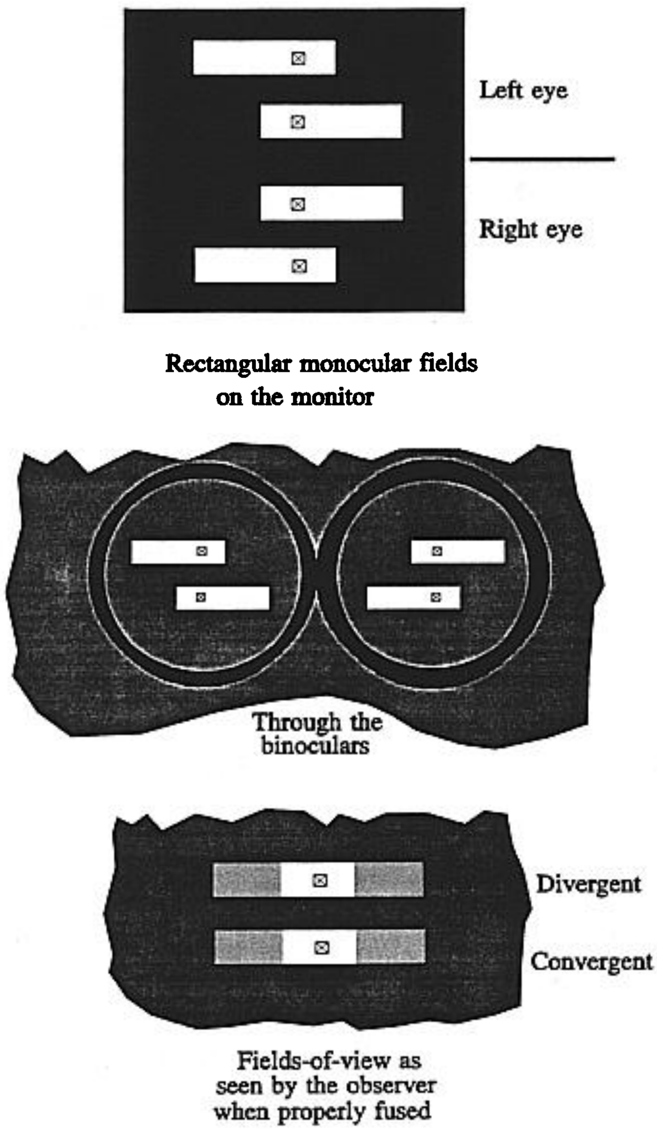


Figure 11. *An example of a pair of stimuli from the fragmentation study, where a convergent and a divergent FOV were present simultaneously for direct comparison. The **top panel** shows the rectangular monocular fields on the monitor and indicates the destination eyes. The **middle panel** shows the monocular fields through the binoculars, and the **bottom panel** shows the two FOVs as experienced by the subject when the display is fused properly. The two display modes indicated in the bottom panel are similar in every respect, except for the regions of the retinas stimulated. The shading in the two FOVs in the bottom panel indicates areas of dichoptic competition which can cause fragmentation of each FOV into three phenomenally distinct regions. For those readers who can free fuse, one can test this by fusing the two images in the middle panel. The crossed squares in the monocular fields serve as fusion locks and fixation markers.*

For each stimulus pair, the subject's task was to indicate, by a button press, which of two FOVs appeared more unitary as opposed to more fragmented. Nine stimulus pairs tested the display mode factor, where the only difference between the two members of each pair was how the FOV was displayed---in the convergent mode or the divergent mode. These nine pairs differed from each other in the dimensions of the visual areas. The results indicated that subjects reported the divergent member as fragmenting significantly more than the convergent member over 90 percent of the trials in each of the nine stimulus pairs. Of the four visual dimension factors tested in the remaining 16 pairs, where each member of the pair was in the same display mode but differed in the dimensions of the visual areas, only one of the four visual dimension factors produced significant results: The FOVs with smaller binocular overlap regions tended to fragment more than the larger FOVs, although, this factor was not as powerful as the display mode factor. In this study, subjects fixated the centers of the different FOVs when making their judgements. The finding that FOVs with larger binocular overlap regions fragmented less may be based on larger overlap regions per se or it may be based on the distance to the binocular overlap border. Informal observations suggest that distance to the binocular overlap border is the important factor, however, further study separating these factors is needed. We have also found that the degree of optical convergence (or horizontal alignment of the optical axes, not to be confused with display mode convergence), is not a factor in these results. Also, the location of the visual blind spots in the nasal retinas is not a factor. These data are described more fully elsewhere.[16]

6. DISCUSSION

In summary, the psychophysical data indicates that there is more luning and more fragmentation and higher thresholds in the divergent mode than in the convergent display mode. This performance decrement for divergence compared to convergence was consistent throughout the three studies despite the differences in method such as free viewing in the luning study, fixation of the probe target in the contrast study and fixation of the center of the FOV in the fragmentation study.[15-18] There are methods to alleviate luning in partial binocular overlap displays such as the placement of black contours in the informational eye as shown in Figure 6, or the smoothing of the binocular overlap edge in the noninformational eye.[11] While the differences in contrast threshold between display conditions were not large in terms of percent contrast (see Figure 10), we still do not know how the placement or smoothing of edges to attenuate luning will effect the threshold of targets in the FOV. This is an important question for research. There are other perceptual factors which we have not considered here, such as stereopsis, and other visual and cognitive factors, such as attentional workload, which need to be tested by additional performance measures such as reaction time.

Analyses in terms of ecological optics suggest that since the visual system has never encountered anything like an HMD in its evolutionary history, the displays are interpreted in terms of possible real world configurations (see Figures 12 and 13).[23-27] Which of the many possible configurations the visual system interprets will presumably determine the visual processing mechanisms brought into play. For example, the convergent display mode may induce less luning because it simulates viewing through an aperture, where the visual system would tend to suppress the occluding portion of the aperture. It has been suggested that this mode is ecologically more valid, closer to a natural viewing situation, than the divergent mode.[10] This, despite the fact that unaided viewing is divergent. More research is needed to investigate this. Another, though not mutually exclusive, possible explanantion for our findings of convergent superiority concerns diplopia suppression. Off-fixation object points in space will project double image points as shown in Figure 14, where each of the double images will be in dichoptic

An ecological interpretation of the convergent display mode

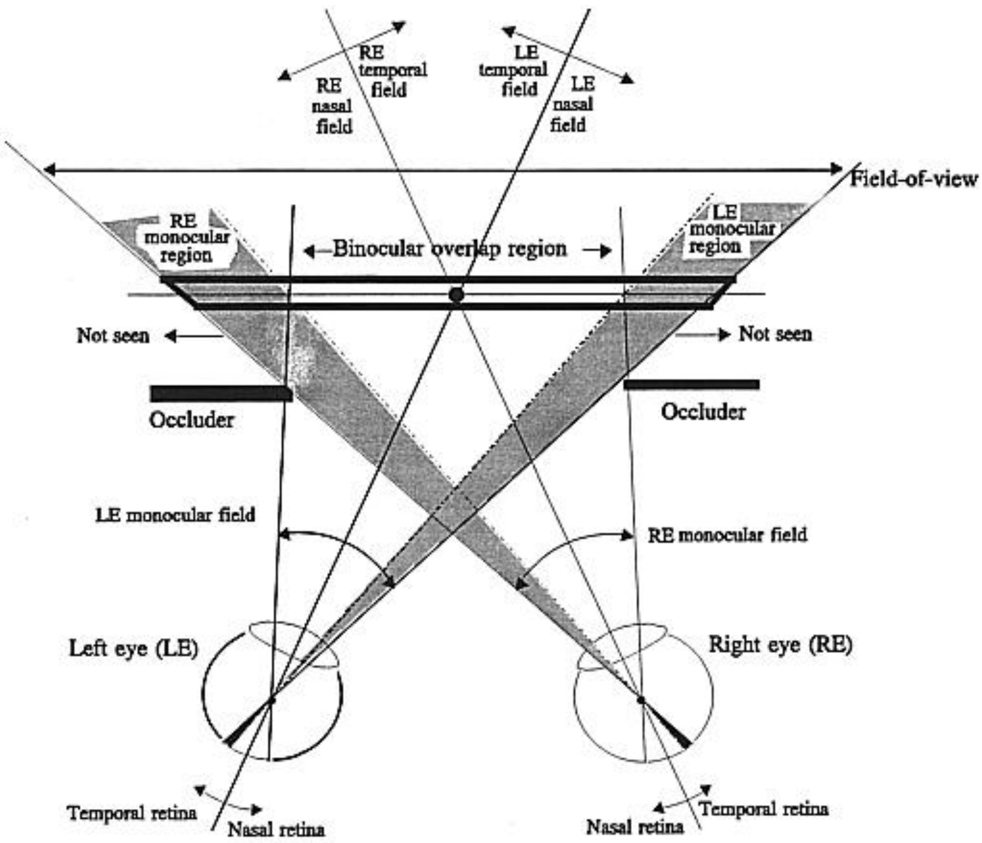


Figure 12. *One of many possible geometric configurations corresponding to the convergent display mode. The background is represented by the occluders. The monocular region portion of the monocular field of each eye falls on the temporal retina, where it is in dichoptic competition with the background falling on the nasal retina of the contralateral eye. This configuration is what would be experienced if one were viewing the world through a small aperture, where the occluders represent the opaque surface around the aperture.*

competition with an unrelated image point in the contralateral eye. Because of the greater importance of near space, the suppression of image points competing dichoptically with projections from near space will be assigned a higher priority by the visual system. The results demonstrating convergence superiority may simply be a byproduct of this mechanism. Recent evidence supporting functional differences between nasal and temporal retina may support this notion; however, it is counterintuitive in light of the reported superiority of nasal over temporal retina.[28-32] This is discussed in more detail elsewhere.[16]

In designing a helmet-mounted display, there are mechanical considerations for partial overlapping visual systems. Most imaging systems could be diverged to increase the total horizontal field of view.

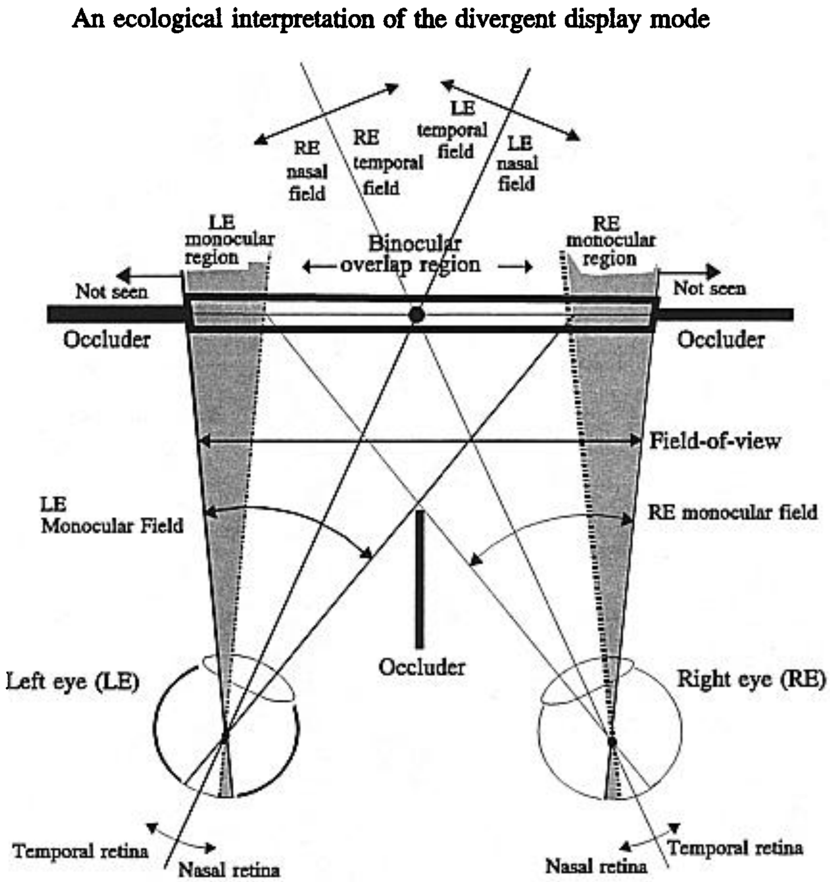


Figure 13. *One of many possible geometric configurations corresponding to the divergent display mode. The background is represented by the occluders. For each eye, the monocular region portion of the monocular field projects onto the nasal retina, where it is in dichoptic competition with the background, represented by the central occluder in near space, falling on the temporal retina of the contralateral eye.*

However, the eyepieces for an imaging system can only be converged within the limits of the eyepiece mounting dimensions and the user's interpupillary distance for a given FOV at a useable eye relief distance. Therefore, all known wide FOV HMDs with partially overlapping fields use the diverging design approach.[33-34] Although the convergent display mode showed a slight advantage over the divergent mode in contrast sensitivity (and luning and fragmentation) in the area of the monocular region near the overlapped region, the performance was always less than the fully overlapped binocular FOV. Whether the larger FOV provided with a partial overlapping HMD will increase flight performance or reduce workload has not been adequately evaluated.

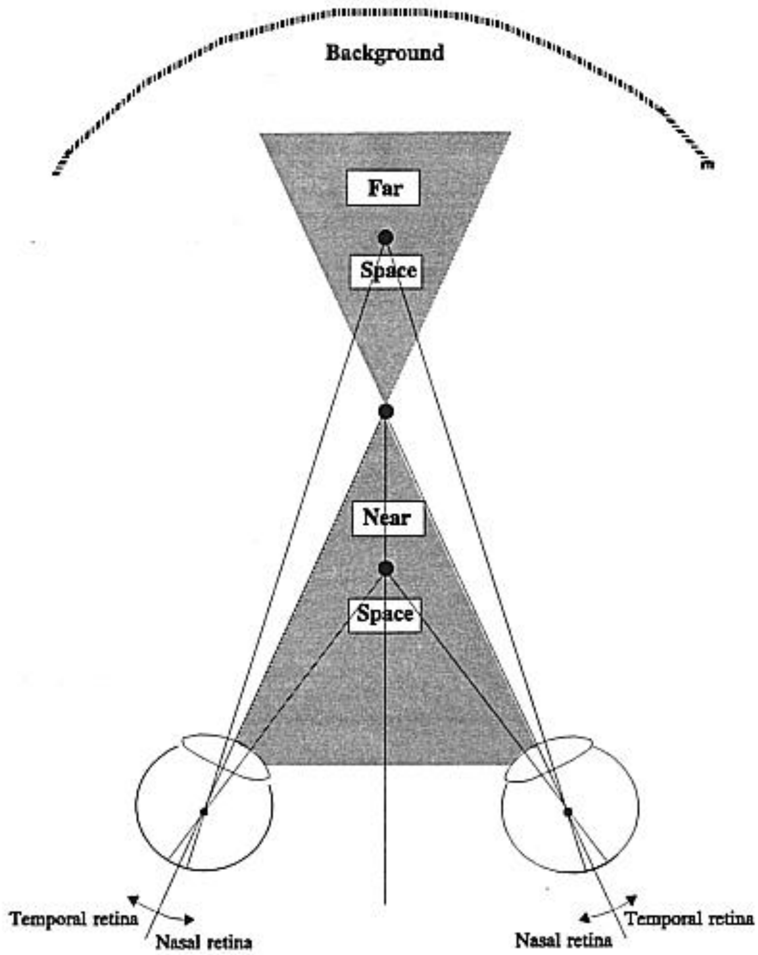


Figure 14. *Retinal projection of non-fixated object points in far space and near space.* ***Symmetrical*** *image points on the* ***nasal retinas*** *representing object points in* ***far space*** *are in* ***dichoptic competition*** *with* ***corresponding*** *points on the* ***contralateral temporal retinas*** *representing the far background. Conversely,* ***symmetrical*** *image points on the* ***temporal retinas*** *representing object points in* ***near space*** *are in* ***dichoptic competition*** *with* ***corresponding*** *points on the* ***contralateral nasal retinas*** *representing the far background.*

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