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Eye Controlled Simulation of Scotomas on the Retina

Annual Report

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<p>→ Loss of central vision was simulated during a simple monitoring task while the adaptive eye fixation responses were measured in normal subjects. A circularly symmetric simulated scotoma of 2.6 degrees was stabilized on the fovea of 5 normal observers while they attempted to maintain a 20 minute target in clear view. Eccentric eye positioning developed within 2 minutes of viewing time with most subjects. Cumulated fixation positions showed that the edge of the scotoma was positioned next to the target and that mean eccentricity was optimum. All subjects reported that they found an upper right position relative to the target easier to maintain as an eccentric vantage point and fixation maps showed that the majority of fixations were located there. Fixation durations became longer during eccentric viewing practice indicating rapid improvements in fixation stability. <i>Keywords:</i></p>			
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SUMMARY

This report describes some of the studies performed during the second year of a project whose purpose was the development and experimental test of systems to simulate the loss of the central area of the normal human retina. The scotomas were generated in normal subjects using various forms of eye controlled displays. Human eye movements made during visual performance tasks were used to move an obscurant or mask to display areas corresponding to the fovea. These real-time, eye controlled scotoma movements eliminated central vision and compelled the subjects to adapt by using peripheral vision and eccentric fixation.

Adaptation to the simulated scotomas was evaluated by measuring changes in the eye fixation duration, saccade length and the eye position relative to instructed targets. The eccentric eye positions were

analyzed to determine if the subjects optimized the location of the scotoma edge by bringing it near the target to maintain visual input on an area of retina with the highest receptor density. Optimization was defined by eccentric eye positions which put the scotoma edge within a few minutes of the target. During and after adaptation, the presence of a simulated scotoma caused grossly distorted eye fixation patterns when compared to normal fixation control. Abnormal patterns were reduced as subjects became more experienced with the simulated visual losses. The effect of the visual loss is dependent on the size of the scotoma, the length of the adaptation period and the visual demands of the task.

The general method of scotoma simulation is useful for evaluating the potential effects of visual loss or disruption because it allows testing the size, position and shape of scotomas in normal subjects under complete safety.

FOREWORD

For the protection of human subjects the investigator has adhered to the policies of applicable federal law 45CFR46. Any mention of commercial products is

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CONTENTS

Summary	1
Foreword	1
Introduction	3
Methods	4
Results	5
References	10
Distribution List	12
Illustrations	
Figure 1. The scotoma simulator, raster display and grid.	4
Figure 2A. Composite topographical mapping of eye position samples.	6
Figure 2B. Percentage of correct eccentric fixations.	6
Figure 2C. Fixation eccentricity from fixation target - free viewing.	6
Figure 2D. Fixation duration during free viewing practice.	7
Figure 3A. Percent eccentric fixations at each viewing position.	7
Figure 3B. Fixation eccentricity from fixation target - instructed viewing.	7
Figure 3C. Fixation duration at each instructed viewing position.	8
Figure 3D. Bivariate area for each viewing position.	8
Figure 4A. Fixation position for background grid on and off. Subject A	8
Figure 4B. Fixation position for background grid on and off. Subject B	9

INTRODUCTION

The purpose of this project was to widen and detail the application of a simulated scotoma technique for use in examining the effects on visual performance and oculomotor activity of loss of central vision. The simulated loss can be accurately placed at any point on the retina and adjusted to produce different levels of loss. The simulated scotoma effects can be measured during the adaptation period to investigate the plasticity and time course of changes in oculomotor timing and performance.

The degree of impairment from central visual loss might be quite different depending on the demands of the visual task. A large scotoma in the periphery might not be very noticeable if the task demands only low levels of acuity. In contrast, however, even a relatively small scotoma in central or foveal vision might produce a large impairment in visual performance, especially if the task involves the use of detail vision.

Simulated central scotomas or stabilized retinal masks have been used to investigate the functions of peripheral versus central retinal inputs to various visual processes: contrast sensitivity thresholds (1), the motor component of convergence and divergence responses (2, 3), reading rate and eye fixation duration (4). Recently Bertera (5, 6) used a simulated scotoma to examine the effects of loss of central vision on visual search time, eye fixation duration and saccade length. The results showed that a 10 or 20 minarc scotoma could seriously disrupt search performance when it was in the fovea. Both search time and eye fixation duration increased significantly.

Whittaker (7) compared fixation stability and eye movement velocity and direction in a patient population with the same variables in a group of normals with a simulated scotoma. An eye position controlled shutter eliminated a projected central target when the target was touched by a computed scotoma boundary. Reductions were found in the normals in fixation stability with the computed scotoma but no systematic changes in drift velocity towards the target. Earlier, Kertesz and Hampton(2) and Boman and Kertesz (3) showed that fixation stability was not impaired until the scotoma was larger than about 10 degrees.

The factors which may control a preference in the eccentric viewing position used by patients with loss of central vision has been given increasing attention. Timberlake (8) using a scanning laser ophthalmoscope (SLO), identified acuity isopters around vari-

ous visible abnormalities on the retina and these isopters were then related to the PRL (the preferred retinal loci) used by patients for eccentric viewing; they were positioned near the scotoma boundary but not always in the area of best acuity. Whittaker(7) demonstrated that about 60 % of the patients showed a stable PRL which remained within a 3X3 degree area and the larger the scotomas the more likely the subjects were to have multiple eccentric viewing locations.

The use of eccentric looking strategies may be a major adaptation to disease related foveal loss in patient populations (9). No studies have been done which measured the immediate effects of loss of central vision in subjects who have no previous experience with eye movement recording or with the effects of a scotoma. Stable eccentric fixation control may be considered to be a basic requirement for good performance in a search task. Holding the eye steady during a prolonged fixation could be one way to compensate for loss of central vision by improving opportunities for input of less detailed images from peripheral vision. Besides stable fixation control, positioning the scotoma should be optimized so that a candidate target is just outside of the scotoma area; but as near to the fovea as possible to maximize acuity, particularly for targets with fine detail.

Visibility of the scotoma edges may vary depending on the source of the scotoma. Both positive and negative scotomas are equally effective in blocking visual information. In a positive afterimage scotoma the subject sees a bright spot floating with the eye movements in central vision. The afterimage from a photoflash best exemplifies this effect. A strong negative afterimage is less familiar except to some of those who have eye disease. This may take the form of a black or grey hole floating in the central area (or elsewhere), or, a less visible area of distortion may be present which makes reading or visual search very difficult. The edges of the scotoma are often not clearly visible in macular diseases, partly because of perceptual filling in and because the periphery of the retina has less resolution than the central area, especially with larger scotomas. In the case of a positive afterimage, when the scotoma image is the same perceived brightness as the background, the scotoma edges are invisible except when viewing densely placed targets. When the scotoma image is either brighter or dimmer than the background there is a distinct edge between the scotoma and the background. This report describes in part

the effect of background imagery which made the outline of the scotoma visible compared with a background which was at the same luminance as the scotoma. It was reasoned that a visible scotoma edge would allow more exact placement of the scotoma edge and improve eccentric eye control.

In the present study naive subjects were exposed to a 2.6 degree circularly symmetric scotoma and were free to look wherever they chose in order to obtain a clear view of the target. The development of their eccentric viewing skill was monitored from the beginning of the loss of central vision. An obvious asymmetry was detected in the PRL chosen by these subjects and so a second experiment was performed in an attempt to find the source of this asymmetry: the subjects to held their fixation at instructed positions around a target. The tasks involved sufficient space around the fixation target to allow specificity in determining the degree of eccentricity. When search elements are too close together it is difficult to determine whether any one eye fixation position is a fixation on target A or an eccentric or adaptive fixation to a more distant target B.

METHODS

Subjects.

The 6 subjects selected through local advertisement had no previous experience in vision studies or eye movement recording. They had normal uncorrected vision, aged 18-25 years old and were in good health. The purposes and procedures of the study were explained and written informed consent was obtained.

Apparatus

Horizontal and vertical analog eye position outputs from an SRI dual Purkinje tracker (10) were used to control the scotoma position. The analog outputs representing horizontal and vertical eye position were low pass filtered, digitized at 200 Hz and stored. Placement of the scotoma was accurate to 5 min of arc or better. The right eye was used to position the scotoma since the tracker only records from the right eye. The subjects steadied their heads with a dental mold to insure accurate eye movement recordings. Calibration targets were used to relate eye position voltages from the Purkinje tracker to the display screen coordinates.

The use of CRT and raster technology supports specific contract objectives to enlarge the scotoma size

(SOW 3.12.c), to develop a scotoma with graded edges (SOW 3.1.1), to attempt to grade visibility through the scotoma (SOW 3.1.c), and to generate multiple scotoma patterns (SOW 3.1.c).

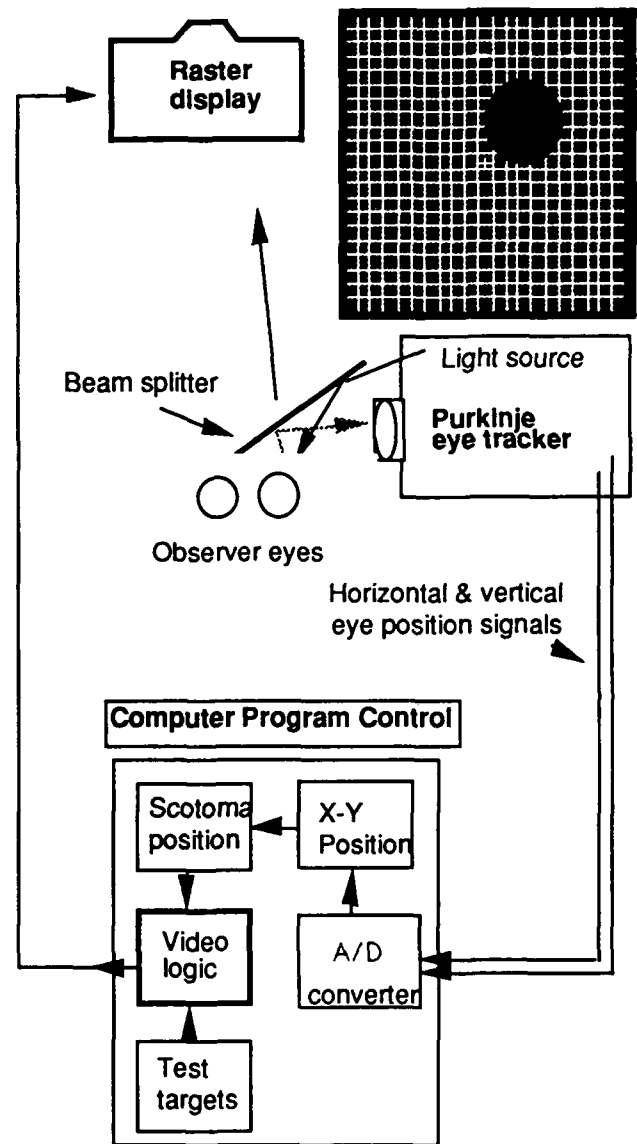


Figure 1. The scotoma simulator consisted of the Purkinje Tracker, computer control elements and raster display. Analog outputs representing horizontal and vertical eye position are used to move the scotoma image (shown upper right) around the display, accurate to within 5 minarc. The grid lines make the scotoma continuously visible since they are intercepted by the scotoma even when it is not obscuring the fixation target. The maximum delay between an eye movement and a scotoma movement was 16 msec.

The scotoma together with the fixation target were presented on a raster display 9 degrees wide placed 79 cm directly in front of the subject (Figure 1). The scotoma was a disk 2.6 degrees in diameter, centered on the fovea. The edge of the scotoma was therefore 77 min from the normal fixation point. The scotoma position was updated at 60 Hz. The central target used for the fixation task consisted of a cross 20 min wide positioned in the display center.

A set of grid of lines was presented on the video display so that the edge of the scotoma was highly visible. The grid lines were white on black and separated by 20 min arc. The contrast was approximately 95%. The luminance of the dark scotoma and the background between the lines was 0.07 cd/m² and the luminance of the grid lines was 1.9- 3.0 cd/m² depending on screen position.

Procedure.

In the free viewing condition, a series of 10 -30 scotoma trials were presented lasting approximately 30 seconds per trial. This was done to assess the immediate adaptation effects to the scotoma because pilot work had shown that some eccentric eye control developed quickly. The subjects were told to position their eye so that the central cross was "as clear as possible". The instructions did not indicate where or how the subjects should do the task. After free viewing all subjects then proceeded to the instructed viewing condition. For each trial the subjects were instructed at which of eight positions around the target to hold fixation. For example, at the beginning of a trial the subject was told "upper left" or "lower right," or "straight up". Two or three fixation trials lasting 30 sec were given at each display position. Two subjects are reported who were compared with the grid on and off. In the grid off condition the scotoma edges were not visible until the scotoma crossed the target whereupon the target was replaced with the background. A further exploration was made in a substitution scotoma condition. When the computed mask boundary crossed a target the target was replaced with a marker which continued to identify its spatial location but deleted the identity (SOW 3.1.c).

Data Analysis.

Data were discarded if there were any large head movements or track losses. The location of blinks and track losses in the data were marked and data samples which were taken 250 msec before and after the mark were discarded. The eye position samples were stored

on disk in x and y arrays along with duration readings. They were then preprocessed in preparation for analyses of dispersion, eye fixation duration, saccade length and spatial distribution (SOW 4.1.c)

RESULTS

Spontaneous Preferential Viewing

Eccentric fixation position.

All the subjects learned within the first 6 trials (about 120 seconds) that they had to maintain an eccentric fixation position in order to "uncover" the target. During the initial trials all of the subjects generally preferred an eccentric fixation position which was up and right relative to the target position (See Figure 2A), but, the subjects tended to look around more as practice proceeded beyond asymptotic performance. The percentage time for eccentric fixation within each quadrant showed that the upper right quadrant was used most with 48%, next was the upper left with 15%, and then the lower left and right with 6% and 9%, respectively. Upon debriefing as to why they had looked up and right rather than anywhere else, all subjects said that it seemed easier but none could give a specific reason for this preferential looking position with the simulated scotoma.

The subjects tended to make errors by fixating the target with the scotomatous retina (fovea) only in the early phase of adaptation. The percent time spent in eccentric viewing (greater than 1 degree from the target) is shown in Figure 2B. These correct eccentric fixations increased rapidly from about 40% to 95% during the first six trials.

The average eccentricity from the target is shown in Figure 2C, along with the average saccade length. The upward slope in eccentricity for trials 1-4 represents rapid learning. Good eccentric viewing would position the eye away from the target approximately the radius of the scotoma plus the added distance of the target itself or 87 min of arc (the radius of the scotoma, 77 min, plus the target radius of 10 min). The subjects come quite close to the optimum eccentricity of 87 min which positions the scotoma edge just next to the target. The leveling off of eccentricity shows that nearly the optimum performance had been reached by the 6th 30 sec epoch.

Fixation duration and saccade length.

There is an increase in the median fixation

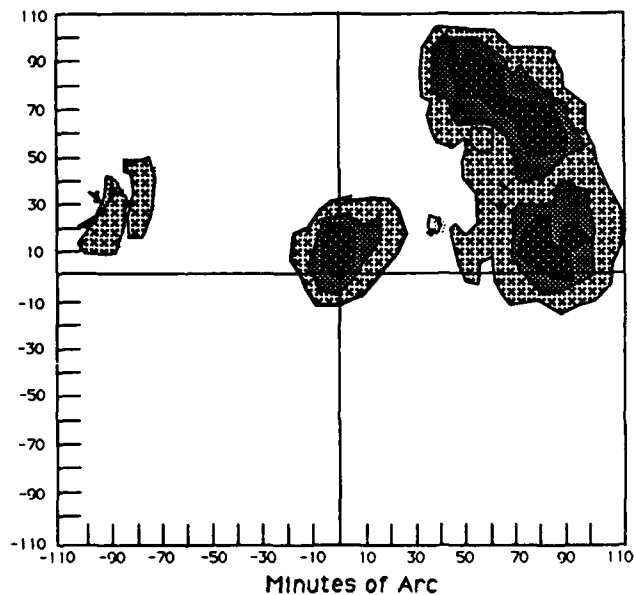


Figure 2A. Composite topographical mapping of eye position samples for six subjects. The subjects attempted to keep a central target cross (located at intersection of dashed lines) in clear as possible view for a total of about 300 sec with a 2.6 degree simulated scotoma across their fovea. An asymmetry is obvious in the scatter of eye positions which were freely chosen by these naive subjects. All subjects claimed that the upper right fixation position "felt" easier than anywhere else. Clusters of eye positions near the center represent the most common error: fixating the target with the scotoma.

duration for trials 1-9 shown in Figure 2D. Thereafter the durations are more variable but are generally longer than in the first few trials.

Figure 2C shows that saccade length initially rises and then generally declines during practice.

Instructed viewing condition.

Eccentric fixation position.

The instructed study showed good performance in maintaining eccentric fixation positions. The percent eccentric fixations are shown in Figure 3A for the eight instructed fixation positions. Positions 1, 2, 4 and 8 are all close to 100 percent eccentric fixations, ie. very few fixations were made in the target area where the scotoma would cover part or all of the target. Some

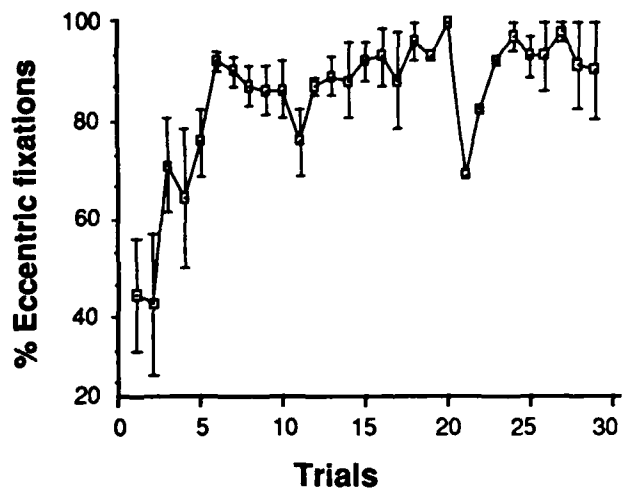


Figure 2B. The adaptation to the scotoma is shown as a rapid development in the % of eccentric fixations. As practice progressed subjects stopped almost completely emitting the most common error, ie. fixating the target with the scotoma. Standard error in brackets.

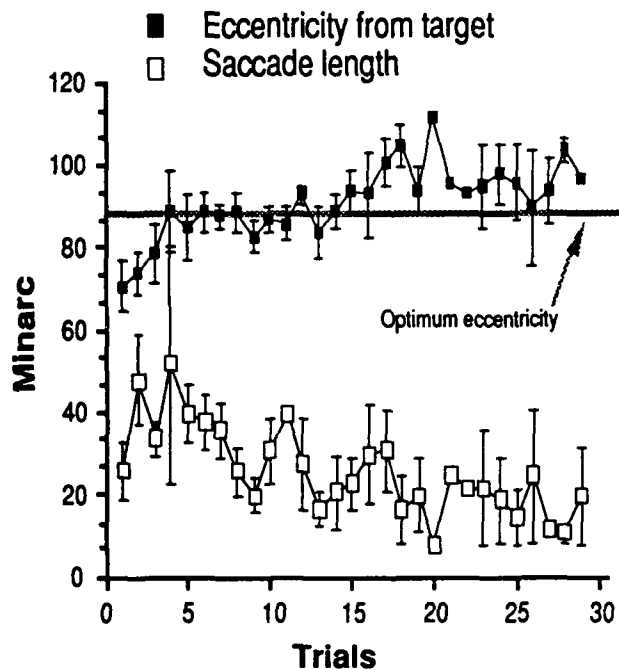


Figure 2C. Fixation eccentricity from the target increased to an optimum level during practice. Within about 2 minutes of practice subjects had achieved enough fixation control to position the scotoma (and their fovea) away from the target so that it was uncovered from the scotoma just enough to see it in peripheral vision. Standard error in brackets.

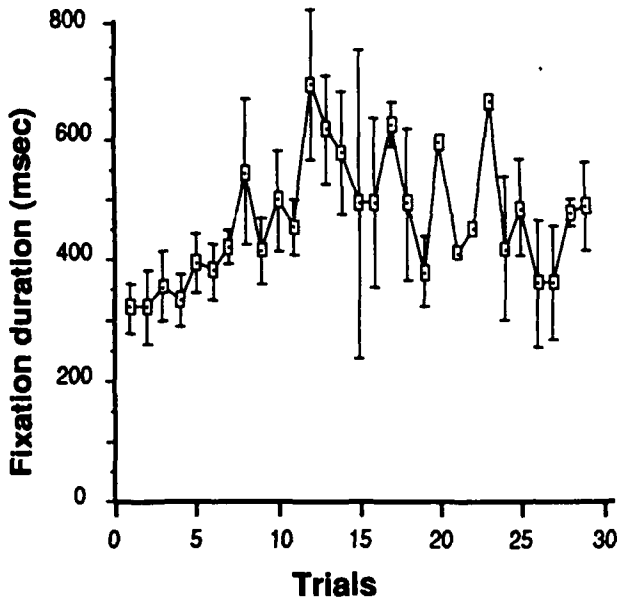


Figure 2D. Fixation duration increased during the free viewing practice. The steady rise in duration means that the fixation is becoming more steady. The greater variability and decrease in duration around trial 12 is due to increasing exploratory movements.

of these positions (1, 2, 8) were also associated with the preferred looking positions from the free viewing condition. However, the differences in percent eccentric fixations among the positions were not significant.

The mean eccentricity from the target center is shown in Figure 3B and the closest approximations to optimum eccentricity are found at locations 1, 2, and 8, again close to the preferred scotoma position from the free viewing condition. The worst average eccentricity performance is found at instructed location 7. However, the differences between locations were not statistically significant ($F=0.276$, $df=7,14$, $p=0.953$).

Fixation duration, saccade length and bivariate areas.

The most prominent feature of the pattern of fixation durations (Fig 3C) is an increasing and then decreasing trend from position 3 to 7. Position 2 has the longest duration closely followed by 8. But, the differences again were not statistically significant ($F=.767$, $df=7,14$, $p=0.624$).

The saccade length measure seemed generally unremarkable, although position 5 showed the longest saccades.

The bivariate areas for each instructed position are shown in Figure 3D. Positions 1, 2 and 8 produced the smallest bivariate areas indicating tighter eye fixation control, followed by positions 6 and 7. However,

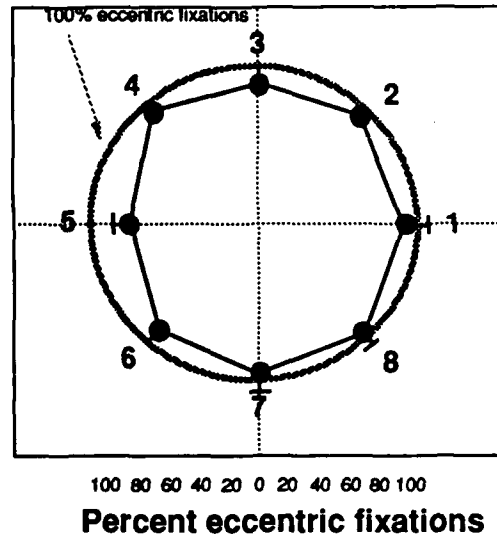
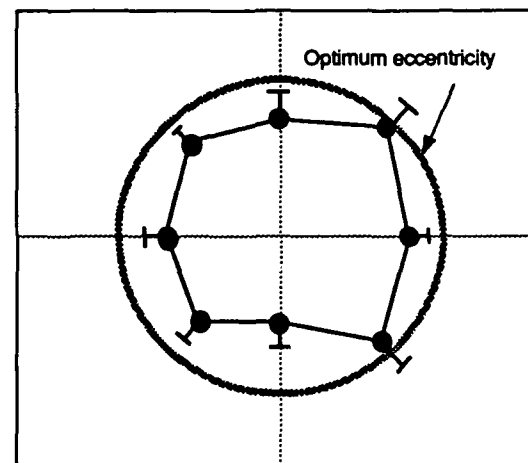


Figure 3A. Percent eccentric fixations are shown at each of the instructed viewing positions. Standard error in brackets.

the differences among the bivariate areas were not significant ($F=1.248$, $df=7,14$, $p=0.342$)

Scotoma Edge Visibility

The subtraction of the background grid did not produce a clear response eye fixation behavior. The scatter of eye position samples in Figure 4A and Figure 4B show differences in the pattern of fixations from the free



Eccentricity (minarc)

Figure 3B. Average eccentricity from target for each instructed position. Optimum eccentricity is approximated for each position. Although the subjects are slightly better near the preferred positions from the free viewing condition, the differences are not significant. Standard error in brackets.

viewing to the instructed viewing conditions, but, the effect of better edge visibility with the grid on appears to be minimal under these conditions.

DISCUSSION

There was rapid development of eye control sufficient to move the scotoma to an optimum eccentric position relative to the target. If the occasional fixations with the scotoma are subtracted, the subjects all established eye control approaching normal fixation stability with 10 minutes of training. The main error in their eye control seems to be this tendency to fixate the target with the scotoma. If these errors are subtracted, their eccentricity was also close to optimum and developed within two minutes of practice.

The strong preference for moving the scotoma up and right relative to the target appeared to be present from the earliest trials and was maintained for the practice period, although, as practice continued, the subjects tended to look around more in the free looking condition. Four of the six subjects claimed it seemed easier to look to the upper right but were no more specific about the reason for this preference.

Several possibilities to explain this rather strong asymmetry in performance can be mentioned. It could be speculated that the upper right position was preferred in free looking and produced less errors in in-

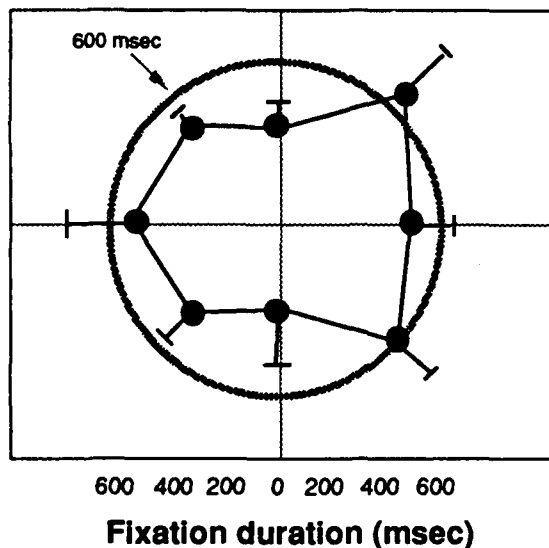
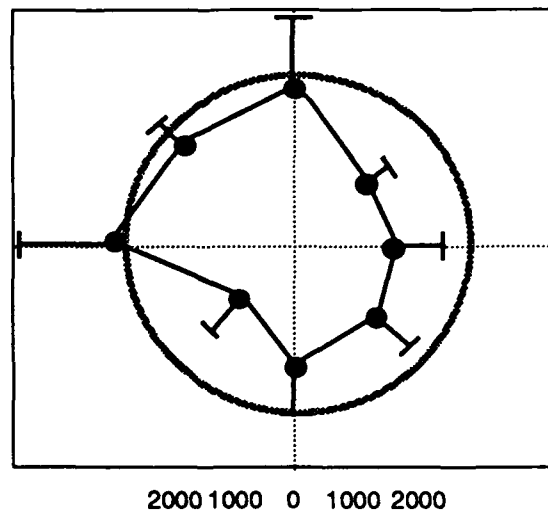


Figure 3C. The average fixation duration for eccentric fixations at each instructed viewing position. Longer fixations for the upper right positions suggest increased fixation stability for the preferred eccentric fixation positions which subjects spontaneously selected in the free viewing condition. Standard error in brackets.



Bivariate area (sq. minarc)

Figure 3D. The bivariate contour ellipse area for eye fixation samples at each instructed viewing position. The bivariate areas show a tendency to be smaller at positions 1, 2, and 8 which were close to the preferred areas for eye fixations in the free viewing condition. However, the fixation durations were not significantly different. Standard error in brackets.

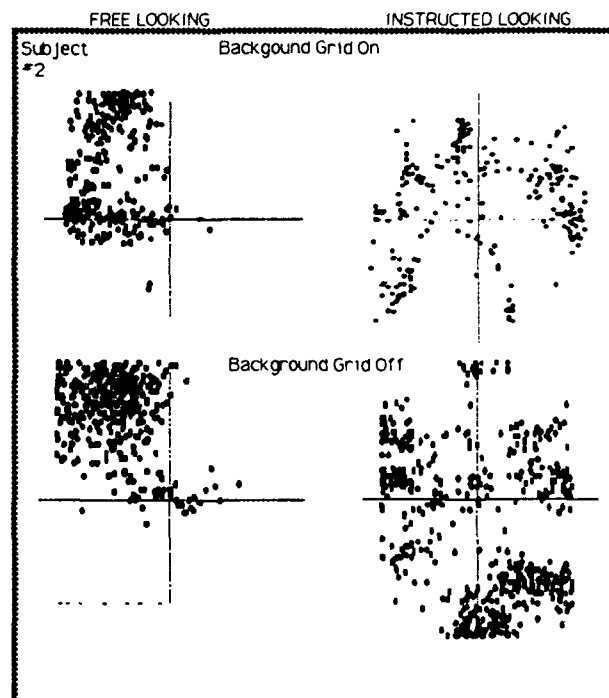


Figure 4A. Fixation positions for background grid on and off. Subject A. The grid on and off conditions are not clearly different. The asymmetry in the free viewing condition is opposite to that observed in the larger group of subjects in Fig. 2C.

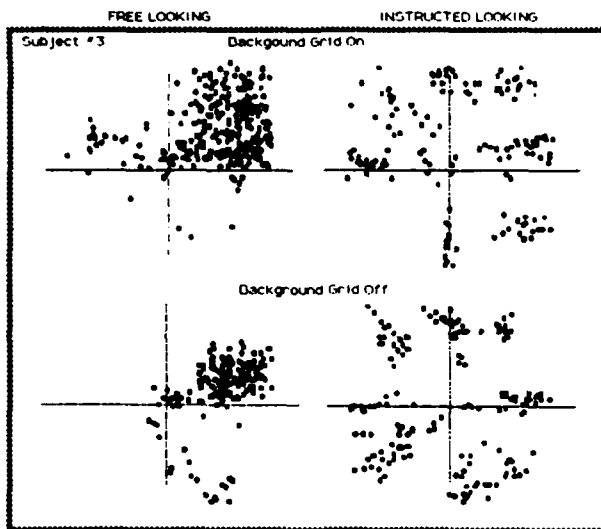


Figure 4 B. Fixation positions for background grid on and off. Subject B. Lower left data in grid on were lost to tracking errors. Closer packing of the fixation positions with the grid off is apparent. The asymmetry in free viewing in Fig. 2C is seen in both conditions .

structed looking because of some habitual, mechanical or neuro muscular process. For example, since reading habits are left to right in English, eye movements in the opposite direction may be better inhibited or less likely. In the instructed study the lowest percentage of errors occurred in the right to left direction (Position 1) where a reading scan habit might inhibit such errors, and the highest percentage of fixation errors (ie. the lowest percent correct eccentric fixations) occurred for Position 5 where a reading scan habit would provoke such errors. However, it should be noted that few errors were also found in positions 4 and 8.

Another potential explanation for the preference for the upper right eccentric position may be that the eye muscles are relatively larger supporting the UR eccentric position, there may be some mechanical properties which reduce oblique error fixations from right to left. It is also possible that some combination of mechanical and habitual factors combine to yield a stereotyped tendency to fixate to the right of the target.

An asymmetrical eccentric fixation pattern could be related to an optimizing sensory process. The explanation begins with visual suppression due to the presence of the scotoma in the non-dominant eye (the left eye in these subjects). If the left eye image were suppressed the subjects may optimize their eccentric fixation for the right eye. Since the right eye blind spot projections on the visual field would be to the right side of the target, the best fixation position might be to the

right. Such eccentricity places the blindspot and the scotoma on the same side of the target. By comparison, if the subject chose a left side eccentric position, the scotoma and blindspot would straddle the target and could interfere with the functional monocular view. This speculation assumes that the subjects would include the presence of the blindspot "scotoma" in developing their eccentric viewing strategy even though the edge of the blindspot is some 10 degrees away from the edge of the scotoma.

Since 3 of the 6 subjects asked if their looking position was adequate or if they should look around (the display) more, it seems reasonable that a voluntary strategy might have played a role in the asymmetrical looking patterns. That is, the subjects were aware that their looking was asymmetrical and may have considered how they might best accede to the experimental objectives. Such eccentric fixation position biases might be maintained for extended periods because maintaining a strategy is better than developing a new strategy under ambiguous rules.

The asymmetrical looking pattern found with a simulated scotoma in this study at least partly follows a clinical observation. Patients complain much more when therapeutic laser lesions are placed on the superior retina where there may be much more useful information for daily activities like navigating and coordination. The superior retina corresponds to positioning the simulated scotoma above the target. Whether the present finding of an upward bias in the eccentric fixation position is related to this clinical observation requires further study.

The relationships between the scotoma, the background and the foreground images may be a factor in the adaptation to loss of foveal vision. A dark scotoma with a distinctive edge seen on a lighter background (assuming the background does not fill in) would supply relatively more feedback about the scotoma position (and eye position). Under such conditions the distinctive scotoma boundary may be a stimulus for controlling the fixation stability and fixation eccentricity. On the other hand, if there is little or no background the absolute dark scotoma will be invisible to the subject until the computed scotoma boundary crosses the target and obscures it. The movement of the scotoma would supply relatively less feedback about eye position than with a background grid, and, therefore, less information is available for the development of adaptive eye behavior.

Under the scotoma edge visibility conditions in the present study little effect was observed. The target position was known and fixed, however, and this

spatial certainty may have reduced the usefulness of the scotoma edge information. Further, sufficient information must have been gained under these conditions from the disappearance of the target as the scotoma edge passed over it to allow good control of the eccentric fixation to develop. Whether fixation control would be improved by increased edge visibility for larger scotomas remains to be seen.

Some of the eye fixations observed under simulated scotoma conditions may represent exploratory behavior, partly because exercising the eye controlled scotoma may help the subject to anticipate the best strategy for search, and partly because the eye linked scotoma is a novel form of feedback with some esthetic appeal. It seems worth pointing out that because we did not instruct our subjects to suppress such behavior it is likely that some of their fixations were evaluative and exploratory rather than directly related to maintaining a clear view of the target image. Upon debriefing all subjects reported some exploratory behavior in this study, as well as in an earlier study of visual search with a simulated scotoma (6).

These stereotyped eccentric looking strategies found with normal subjects using simulated scotomas may tell us something about the basic nature of adaptive processes which might be employed as a countermeasure in cases of central visual loss from laser exposure or macular disease. Until now, the different spatial characteristics of scotomas in patient populations has precluded analysis of preferences in eccentric looking positions. Eventually, the added experimental control offered by simulated scotoma techniques may shed some light on the problem of why reading is impaired in patients with macular disease despite adequate peripheral resolution.

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