Eye Controlled Simulation of Laser Damage on the Retina

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An eye controlled brightspot or scotoma was used to simulate the after effects of focal laser exposure on the foveal retina during a visual search task. Search time, eye fixation position and duration, and saccade length were measured while human observers searched displays of increasing difficulty. Search time increased by 90% to 110% with foveal scotoma sizes of 10 and 20 min arc and eye fixation duration increased by 15%. Adaptations in eye behavior during recovery from simulated laser exposure - eccentric eye fixations and changes in fixation duration - were also measured during simulated decay of laser induced scotomas.

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SUMMARY

A scotoma or blindspot was generated in human subjects using an eye controlled computer display to simulate retinal effects of accidental laser exposure. Visual search time and eye behavior were measured during search for acuity targets while a simulated brightspot or scotoma afterimage blocked the foveal visual information. This simulated laser aftereffect impaired visual search performance 90%-110%. Comparisons of impairments produced by a 20 minarc versus 10 minarc scotoma showed that deficits were still potent with the smaller simulated scotoma. Eye fixation durations also increased after simulated laser exposure and appeared to be an indicator of task difficulty. Simulated foveal scotoma deficits were still present when target size, search element density and display brightness improved peripheral visibility. The simulated scotoma probably required subjects to employ the unaffected peripheral retina for target recognition and may have caused disturbances in eye fixation programming.

A technique was also developed for simulating the slow decay of a laser induced afterimage. The intensity of the computer controlled brightspot was slowly reduced during search, and eye behavior was measured to determine how functional ability might be restored after a laser exposure. Important developments in the technique included computer control of the brightspot intensity, automated methods for analyzing the changes in eye behavior as a function of afterimage fading and description of subjects' eccentric viewing in dealing with the decaying afterimage. Preliminary data suggests that the subjects tend to look left relative to their normal eye fixation position in order to bring the search target to an area of retina just outside the site of simulated laser exposure; the tendency appeared to be reduced as the simulated scotoma faded.

Development of the simulated scotoma technique to evaluate the effects of laser exposure on visual performance in human subjects shows promise because the size, intensity and position on the retina of the simulated exposure can all be controlled with complete safety. The method may have application for demonstrations and training which might serve as countermeasures to the impairments in visual performance caused by central scotomas.

FOREWORD

For the protection of human subjects the investigator has adhered to the policies of applicable federal law 45CFR46.

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Part I. INTRODUCTION Scotoma Simulation

The widening use of lasers for sighting, range finding and communications poses a threat to human vision in the form of permanent retinal laser injuries and temporary debilitating visual loss due to accidental exposure. Visual performance in tasks requiring rapid target detection, tracking and recognition, or reading of instrument displays may be impaired by even weak laser aftereffects which cause relatively small losses in acuity or brief periods of visual dysfunction. The studies performed under this contract show that small afterimage scotomas of 20 and even 10 min seriously impair visual search performance and eye fixation durations and that the percentage impairment is significant even for relatively simple tasks or display conditions.

The purpose of this project was the development of methods that safely simulate the effects of focal laser exposure on the foveal retina of human observers and measurement and analysis of resulting visual performance deficits. These exploratory studies were also designed to develop methods for examining adaptations in eye movements and visual search strategies which observers may use to compensate for the laser induced visual losses. In the simulation the observer sees a brightspot that follows his gaze as he searches, reads instruments or inspects a visual scene. The brightspot or simulated afterimage follows the subject's eye movements so closely that it creates a simulated central scotoma which blocks the acquisition of information from the foveal retina.

The immediate effects of accidental laser exposure can be tested using the simulated afterimage technique with control over the retinal position of the simulated injury, its size, and period of persistence. Clinical reports of various forms of scotomata resulting from accidents have been described by Boldrey (1) and reviewed by Wolfe (2). Most of these reports measured acuity level after some recovery had taken place. It has not been possible to measure and interpret impairments immediately after an injury because of the nature of the injuries, the variable recovery periods from widely varying levels of severity, and because ophthalmoscopic visibility may not indicate functional loss at the time of injury, due to repeated exposures or in the long term (3a). A major advantage in these present simulations is that both weak and strong laser aftereffects can be simulated in complete safety since the human observer is never exposed to any laser light or intense light sources of any kind. Therefore, the simulated scotoma conditions can be maintained for extended periods simulating strong laser exposure aftereffects, and, since there is no potential for injury, it is possible to simulate repeated exposures without diminishing the effects.

The degree of impairment in visual performance may be quite different depending on the size, retinal location and intensity of the central scotoma and the characteristics of the visual display and the visual search task. Simulated scotoma brightspots of 50 and 100 microns were chosen to correspond to areas of retinal damage resulting from a single exposure based on the spot size of fielded laser systems (3b). However, it should be noted that an ophthalmoscopically or histologically visible abnormality of 100 microns on the retina after laser exposure may be an underestimate of both the true area and severity of dysfunction at the time the exposure took place. It was assumed that a worst case position for the scotoma would be the central fovea. The same size injury in the fovea is likely to produce greater deficits than in the peripheral retina since the retinal cone receptors which are concentrated mainly in the fovea provide the maximum visual acuity. Dysfunction in foveal cells may produce loss of central acuity, accommodation control, and pupillary control. By comparison, the same size injury in the periphery may not produce any detectable deficits.

A second main factor controlling the degree of impairment in visual performance will also depend on whether foveal resolution is demanded for efficient processing of the salient aspects of the search field. The present studies were designed to examine visual search behavior using target sizes and display conditions requiring a range of foveal demand for processing. Displays with densely packed small targets of low contrast require more foveal vision compared with displays with dispersed, larger, higher contrast search elements. In general, visual noise or clutter causes tunnel vision and reduces the effectiveness of peripheral processing (4,5,6,7), thereby increasing the requirement for foveal vision.

Previous studies have tested the effects of foveal visual loss on contrast sensitivity with grating test fields. Kelly (8) used a horizontal moving, eye linked, blank stripe, 3 degrees wide, which reduced sensitivity by a factor of 3. Higgins, Carusso, Coletto and de Monasterio (9) stabilized a 3 degree scotoma along with a grating field, to examine contrast sensitivity with gradual versus abrupt onset of the grating field. In a reading task, Rayner and Bertera (10) used a horizontal eye linked mask and found that eye fixation duration rose as mask size increased. However, no studies of free visual search have been done using both horizontal and vertical scotoma movements while recording eye behavior and search time.

The dependent variables in the present studies included search time, and eye movement behavior measures: fixation position and duration, the saccade length and the total number of fixations needed to find a target. Eye fixations are pauses of variable duration occurring at the rate of about three per second during which the eye extracts detail information from a scene. They are followed by a high velocity saccadic movement which directs the fovea to a new position in the visual field. The total number of eye fixations required to find any one target may vary from one fixation up to tens to search a simple display, or, even hundreds of eye fixations may be required for a target detection during monitoring tasks or in complicated or cluttered displays.

In general, longer fixation durations and altered sacccade lengths (the distance the eye travels from one eye fixation position to the next) along with increased numbers of fixations have been associated with increasing difficulty in the characteristics of visual displays. These eye movement measures change depending on the display element density, background clutter, color highlighting, or size of the search field (eg. 11-17). It has been generally found that longer eye fixation durations are associated with increasing task difficulty.

It was expected that the foveal blockade produced by the simulated scotoma afterimage in the present studies would cause detectable distortions or adaptations in the observers eye behavior. Peripheral visual capability may take over the foveal requirement increasing the search time and there may be some adaptation in the pattern of eye behavior (eg. longer fixation durations, eccentric fixation positions or altered saccade lengths). Alternatively, there may be some completely covert adaptations or re- organizations in the way the visual information is processed which overcome any potential impairments.

Another major thrust of this project was to develop methods for testing the processes involved in restoration of visual function due to the interplay between recovery of retinal cells from the laser exposure (an essentially passive process) and other active adaptations, eg. changes in eye movement patterns. The recovery of retinal cell functioning was simulated by fading the brightspot afterimage during several search tasks. Major developments in this part of the project included the computer techniques, interfacing and program development to control the fading and the methods to analyze the associated oculometric responses. More details on this problem are presented in Part II.

METHODS (Study #1-#3)

Subjects. The subjects, selected through local advertisement, all had normal uncorrected vision, were aged 18-25 years old and in good health. The purposes and procedures were explained and the informed written consent was obtained.

Apparatus. The eye movements were measured using a dual Purkinje tracker (SRI International, Menlo Park, CA). The horizontal and vertical analog outputs of the tracker were used to control the position of the simulated scotoma over the search field using a microprocessor which recorded and updated the eye controlled scotoma position every 5 msec. The scotoma was produced by the beam of a CRT X-Y display (P31 phosphor) 55 cm directly in front of the subject (Figure 1). The search array was presented on a video monitor optically superimposed on the scotoma display by a beamsplitter and aligned so that the imagery on each matched point for point and the scotoma and search elements appeared in the same focal plane. The brightness of the scotoma was adjusted to 9.2 cd/m, so that the bright spot or scotoma completely masked the search element(s) over which it was positioned, simulating an absolute positive scotoma. Scotoma brightspot diameter was adjusted to either 10 or 20 min of visual angle.

The search displays consisted of a matrix of small bright squares, 20 min on a side. One element in each display, the target, had a gap of either 3 min of visual angle (small target) or 6 min of visual angle (large target), similar to a Landolt C acuity target. Two display densities were studied: a high density of 100 squares or a low density of 25. The search elements were separated by 0.9 degrees of visual angle in the high density condition and by 1.8 degrees of visual angle in the low density condition (Figure 2). Display contrast was adjusted to either 30% or 70%, in study #1 and #2 with a background luminance of 0.14 cd/m. In study #3 the background brightness of the display was increased to 3.46 cd/m and the contrasts were adjusted to maintain a task which was graded in difficulty: either 12% or 30%.

Target search difficulty was varied by using combinations of the 3 min and 6 min gaps with high and low display contrast and high and low element density which provided four levels of descending difficulty (for each gap size) as determined by preliminary tests. The most difficult level was designed to require foveal fixation and the least difficult display type could be searched using non-foveal vision. The levels of difficulty are summarized below ranked from most to least difficult based on preliminary tests:

Level of Difficulty	Display Parameters
	3 min target gap
4	High density, Low contrast
3	High density, High contrast
2	Low density, Low contrast
1	Low density, High contrast
	6 min target gap
4	High density, Low contrast
3	High density, High contrast
2	Low density, Low contrast
1	Low density, High contrast

Procedure. Subjects were told that search time was the major variable in the study and that they were to search each array and find the target as fast as possible, signalling by a button push. They were not given any specific instructions as to the best method of search. If subjects asked they were told that it was up to them to search freely and find the best method. The observer was dark adapted for approximately ten minutes and given some practice trials to demonstrate the shape of the targets and the structure of the search arrays. The observers steadied their heads with a dental mould to insure accurate eye movement recordings. The subject was shown calibration targets to relate the eye position voltages to the screen coordinates and to set the output levels for controlling the scotoma position on the CRT display. Rest breaks were given every five minutes and as needed.

Designs. The designs for the first three studies were the same except for the area of the simulated scotoma and the brightness of the display. The major control was a no scotoma condition in which the observer searched the displays without the presence of the simulated scotoma brightspot. This no scotoma control was given for each of the target sizes and levels of difficulty. For each of the 8 combinations of target gap size and level of difficulty 8 trials or displays were presented for the scotoma and no scotoma conditions yielding a total of 128 trials for each subject (16 conditions X 8 trials each). Thus, a direct comparison of scotoma and no scotoma conditions was possible for each subject in each condition of these three studies. The conditions were presented grouped by target size, half the subjects in a study received the small targets first and half received the larger targets first. Half the subjects were given the no scotoma control trials first the other half received the scotoma trials first. The four levels of difficulty were presented in a random order within each of the two target size conditions.

In study #1 it was determined that a 20 minarc scotoma across the fovea was effective in disrupting visual search performance. Therefore, study #2 was performed using a 10 minarc scotoma, again, positioned centrally on the fovea. This smaller scotoma size was also effective in producing deficits. Study #3 was performed to test the effect of the larger 20 minarc scotoma under conditions of higher display brightness. This was done to further evaluate modifications in the scotoma effect which might follow increases in peripheral acuity associated with a brighter display. The increase in brightness caused data losses and prevented some subjects from participating due to pupillary constrictions. In these cases the observer was brought back for another session, or the data were discarded.

Data Analysis. During the search period, time to search in seconds was measured along with eye fixation position and duration in msec. An eye fixation was defined by movements which remained within 20 min of visual angle for a minimum of 90 msec. Less than 5% of such fixations are under 100 msec in duration (23). The saccade length was calculated in degrees of visual angle from one eye fixation position to the next and the number of eye fixations during search of each display were counted. Trials were discarded if there were any large head movements, accidental button pushes by the observer or track loss states from the Purkinje Tracker. Such discards accounted for less than 6% of the trials. For each observer a mean value was then calculated for the dependent variables within each of the 16 conditions and summary statistics were generated which represented the group of subjects in each study.

Below are summarized the main variations in the experimental designs used in the first three studies:

Study #1. Scotoma size equaled 20 minarc. N=12

Study #2. Scotoma size equaled 10 minarc. N=5

Study #3. Brighter display with 20 minarc scotoma. N=11

RESULTS (Study #1-#3)

In all experimental conditions, the simulated scotoma seriously impaired visual search performance and altered eye fixation duration. The impairment produced by the scotoma is illustrated in the following figures by the percentage increase in search time over the no-scotoma control condition. The percentage impairment or the increase in scotoma values relative to the no scotoma control was calculated in order to compare across the three studies.

The effect of the scotoma on search time is shown in Figure 3. Search time was impaired 110% with the 20 min scotoma and 89% with the 10 min scotoma. Increasing peripheral target visibility using a brighter display with the 20 min scotoma still produced deficits in performance of around 90%. The display difficulty variable had little effect on the percent impairment in the three studies. The large target gaps showed slightly higher impairments overall than the small gaps.

Eye fixation durations increased by up to 15% due to the presence of the simulated scotoma (See Figure 4). The 10 min scotoma showed smaller increases than the 20 min scotoma studies. Larger scotoma percentage effects are seen for the easier display conditions. The large target gaps showed a higher percentage increase than the small target gaps in the 20 min scotoma studies.

The number of eye fixations was highly correlated with the search time variable and provided redundant information to search time. The measures of saccade length did not present a systematic picture of significant deficits. Across the three studies, 14 of a possible 24 conditions with the scotoma showed shorter average saccade lengths, and 9 conditions showed longer average saccades.

The detailed results are presented next for search time, fixation duration, number of fixations and saccade length, in the first three studies. Of principal importance are the results for the search time and fixation duration variables.

Study #1: 20 Min Scotoma. The search times and oculometric variables for the scotoma effects at four display difficulty levels are presented in Figure 5. The largest scotoma effect for the 3 min target gap is found in the most difficult, level 4, condition (high density, low contrast), the two middle levels of difficulty are similar and a smaller scotoma effect is present for the lowest difficulty level. For the 6 min target gaps the scotoma effect declines with level of difficulty, but even the easiest level 1 conditions, with control levels around 1 sec for search time, show relatively large scotoma effects. All the display difficulty conditions showed significant scotoma effects for search time (F tests, $p<.05$).

The eye fixation durations (Figure 5b) also increased at all of the difficulty levels with the scotoma. In the 3 minarc condition, the scotoma effects at the two mid levels of difficulty were not statistically different, with 8 of 12 and 9 of 12 subjects showing greater fixation durations with the central scotoma. Level 4 and level 1 showed significant scotoma effects. However, in the 6 minarc condition all the scotoma effects for fixation duration were significant (F tests, $p<.01$).

There were large increases in the number of eye fixations with the scotoma at all four levels of difficulty in both the 3 minarc and 6 minarc targets due to the high correlation between the search time and number of eye fixations. All scotoma effects were significant except for the second level of difficulty in the 6 minarc condition ($p=.073$).

The saccade lengths (Figure 5d) did not fluctuate systematically with the presence of the scotoma or with display difficulty level and remained around 1.1 degrees of visual angle. None of the scotoma effects were significant. Of the 12 subjects who participated in this study, 5 showed a decrease in saccade lengths in the presence of the scotoma, and, 7 subjects showed an increase in saccade lengths, for the 3 minarc condition. The proportions were just reversed in the 6 minarc condition.

Study #2: 10 Min Scotoma. The methods and analysis for this study were identical to Study #1. The 20 minarc scotoma was replaced with a smaller scotoma of 10 minarc across the fovea.

The average search times and oculometric variables for the scotoma effects at the four display difficulty levels are presented in Figure 6. The smaller scotoma effect was significant for the third difficulty level in the 3 minarc condition (F tests, $p<.01$), borderline for the fourth level ($p=.068$), and not significant for the two easiest display levels. A similar pattern emerged for the 6 minarc condition - the two higher difficulty levels showed significant scotoma effects (F tests, $p<.05$), but the easier levels did not.

The fixation durations for the scotoma effects at four display difficulty levels are also presented in Figure 6. Almost no scotoma effect is present for the two higher difficulty levels in the 3 minarc condition while the scotoma effects are significant for the two easier levels. In the 6 minarc condition, scotoma effects for duration were again present for the two easiest displays where 4 of the five subjects had longer average fixation durations for the scotoma cells, but, none were significant (F tests).

The pattern for the number of fixations is similar to that for search time (again because of the high correlation between search time and number of fixations) wherein the scotoma effect is present at each display level, but, only the third level is significant (F test, $p<.01$), the first borderline non significant ($p=.080$) and the easier two levels show no significant differences. Turning to the 6 minarc condition a similar trend can be seen in the close relationship between search time and number of fixations. Only the highest display difficulty level shows a significant scotoma effect, although the other mean differences are all positive.

The saccade lengths again did not change consistently with the presence of the scotoma or with display difficulty level. They remained around 1.2 degrees of visual angle. None of the scotoma effects were significant, although level 2 was borderline ($p=.062$) in the direction of longer saccades. The other three levels had small but shorter saccade length scotoma effects.

Study #3: 20 Min Scotoma with Brighter Display. The methods and analysis for this study were identical to Study #1. The 10 minarc scotoma was replaced with the original 20 minarc scotoma use in Study #1, and the display brightness was increased over the level used in the first study.

The brighter display produced generally faster search times and somewhat diminished scotoma effects. The average search times and oculometric variables for the scotoma effects at the four display difficulty levels are presented in Figure 7. The smaller scotoma effect was significant for the fourth and second levels of difficulty in the 3 minarc condition (F tests, $p<.05$), borderline for the third level ($p=.079$), and not significant for the first. For the 6 minarc condition, the lowest level of difficulty was not significant but all the higher levels did show significant scotoma effects (F tests, $p<.05$).

For the eye fixation durations in the 3 minarc condition only the second and fourth levels were significant (F tests, p<.05) although positive effects are present at all levels. In the 6 minarc condition, scotoma effects were again all positive. The first two levels were significant (F tests, p<.05) but the third and fourth levels were not significant (p=.053; p=.079, respectively).

The number of fixations for the scotoma effects at four display difficulty levels are also presented in Figure 7. In the 3 minarc condition, all the scotoma effects were significant (F test, p<.05). Turning to the 6 minarc condition, the third and fourth levels of difficulty were significant (F tests, p<.05), but the two easiest levels were not.

Again, the saccade lengths did not change consistently with the presence of the scotoma or with display difficulty level. The two highest levels of difficulty showed only a nominal increase in saccade length and all the others were negative, that is, the saccade lengths became shorter with the scotoma, although only the second level in the 6 minarc condition was significantly shorter (F test, p<.05); the first level (6 minarc) was borderline (p=.080).

Part II. INTRODUCTION Recovery of Function Studies

This section describes the development and testing of methods for studying restoration of visual function that might occur during fading of an afterimage produced by laser exposure to the fovea. Long term recovery was simulated with a fixed level of simulated afterimage intensity. Short term recovery was simulated by fading the brightspot from full brightness (absolute scotoma) down to zero (no scotoma control) within 30 seconds. One objective of the development of these techniques was to provide information about the contribution of retinal recovery versus central compensation to restoration of visual function

Visual recovery is the improvement in performance as the afterimage fades and normal retinal cell functioning returns. It is essentially a passive process. As the afterimage fades, foveal visual information which was blocked becomes accessible once again and normal levels of acuity and target recognition return. For the present exploratory studies and technique development it was assumed that retinal recovery would be a linear improvement.

Restoration of visual functioning after a laser exposure may also be associated with central compensation. For example, the foveal requirement for information acquisition or target recognition may be substituted with peripheral vision. Another centrally mediated compensation may be reprogramming of motor patterns for eye fixation position or fixation durations or both. For example, the eye may fixate longer at each position to gather peripheral information about target detail or the fixation position may be changed to bring the desired target to a retinal position outside of the scotoma area.

Retinal recovery and central compensation may interact during the restoration of visual functioning. However, in a case with irreversible retinal tissue loss or with a very long lasting afterimage, central compensation will be the only mechanism supporting a restoration of visual performance.

To study long term restoration a fixed level of simulated scotoma brightness was presented during the visual search task over several sessions. To study short term recovery, the scotoma luminance was gradually reduced while the observer performed the search task.

METHODS (Study #4-#7)

Subjects. The subjects were the same type as described above for Study #1-#3. Some had participated in previous studies of simulated scotomas in visual search.

Apparatus. The techniques used were the same as previously described with the following additions. An analog signal was sent to the CRT display for controlling the brightness of the simulated scotoma. The maximum scotoma brightness was governed the sensitivity of the eye position sensor to pupillary contractions. A bright central scotoma causes pupillary contractions at its onset seriously affecting the eye tracker. Various levels were tested in a pilot study (#4) to find a maximum brightness level which would be usable with all subjects rather than finding a maximum level for each observer. Too many pupillary contractions occurred at 20 cd/m and at 15 cd/m, therefore, the maximum scotoma level was reset to the 9 cd/m used in the first three studies.

In studies #5 and #6, the fixation position criterion was increased from 0.3 degrees to 0.6 degrees to reduce noise which developed in the analog eye position conversion system. This resulted in an increase in the magnitude of the fixation durations and average saccade lengths compared to the first three studies, but it was present over all of the experimental conditions within studies #5 and #6.

The most difficult displays (level 4) were used along with the 3 minarc target gap size for the fixed and variable scotoma intensity studies and were used in order to potentiate any deficits in visual search.

Fixation position eccentricity was addressed in study #7 by reducing the display elements to eight in number, and, requiring the observer to sequentially fixate the elements. The targets were arranged around a square with an inter-character distance of 3.75 degrees (See Figure 2). The larger inter-character distances were used to make eccentric fixations easier to detect and interpret during fading of the afterimage.

Designs. In the fixed scotoma brightness study (#5) three levels of scotoma brightness were used along with a no scotoma control: Level 3, 9 cd/m (an absolute block), level 2, 4 cd/m (dimmer but still a complete block) level 1, 1.2 cd/m, (see through), level 0 (no scotoma control). At each level 32 trials were presented to 5 subjects in each of two sessions. The second session was used to establish reliability and check for practice effects. The levels were presented randomly to each subject.

In the fading scotoma study (#6) the brightspot slowly became dimmer during each trial until it faded completely, leaving the display in the no scotoma control state. Thirty-two trials were presented to each of 9 subjects. The rate of fading of the scotoma was 0.45 cd/m/sec. From first onset to complete fading of the scotoma/afterimage required 25 sec. The search period was analyzed in five sequential levels of brightness. - level 4 being the most bright or maximum scotoma brightness and level 0 being the control condition. The search elements were weakly visible at level 2 and were in the clear at level 0. Therefore, the largest effect would be expected from level 4&3 to level 0, with level 2&1 in the middle. The target was withheld until level 1 or 0 to maintain search behavior during scotoma fading.

In the sequential search study (#7), the instructions were to look at each element in turn moving around the square in a clockwise or counter- clockwise direction (counterbalanced) until the target (a 3 minarc gap) was located. The subjects were told that the target gap would only be presented intermittently and that their best chance of detecting the target would be to search as fast as possible. The scotoma faded at .45 cd/m/sec. The target was withheld until the end of the fading in order to maintain searching behavior.

The designs for each of the restoration of visual function studies are summarized below:

Study #5. 20 Minarc Blocked Scotoma Intensity. N=5
Study #6. 20 Minarc Fading Scotoma. N=9
Study #7. Sequential Search with 20 Minarc Fading Scotoma. N=4

Data Analysis. The oculometric data were reduced within each scotoma brightness level by averaging the fixation durations and saccade lengths, and accumulating the number of fixations.

Study #5: 20 Min Blocked Scotoma Intensity. The search time and oculomotor variables for the fixed scotoma brightness study are presented in Figure 8, separated by sessions. The two highest intensity levels produced a positive scotoma effect for search time in the first session with a slight downward trend. In the second session, search time was only slightly higher for the three scotoma intensity levels when compared with the no scotoma control or 0 level. The eye fixation duration measures are higher for the scotoma than no scotoma conditions, but do not decline for the three intensity levels. In the second session the fixation durations are irregular in magnitude. The number of fixations is also irregular over intensity. The saccade length measures show a slight downward trend in the first session only.

Study #6: 20 Min Fading Scotoma. The average fixation duration for each fading epoch is presented in Figure 9 and shows a downward trend. Fixation durations dropped by 65 msec (13%) from level 4 to level 3, with a much smaller change from level 3 to level 2.

The scotoma light level was faded during each search trial and the target was withheld until the 0 level. Therefore, the 0 level data are artifactual and search time was not a variable in this study since the target was always found during this epoch. Some targets were also occasionally presented in epoch #1, therefore, the effect of scotoma fading should be a trend in the dependent variables over levels 4, 3 and 2.

The number of fixations first rises and then falls from levels 4 to 2. The mean saccade lengths for each dimming interval are also presented in Figure 9. The saccade lengths held at 1.9 degrees of visual angle for the three brighter dimming intervals, and, as the scotoma faded, the saccade length increased from 1.9 to 2.1 degrees at level 1.

Study #7: Sequential Search with Fading 20 Min Scotoma. The use of sequential search was designed as a control over the free search which caused ambiguities in identifying the exact position in the display from which information was being extracted by the observer. The target, as will be recalled, was not turned on until the last epoch (no scotoma control) began, therefore, the search time was not a dependent variable in this study. The expected scotoma effect in this study should be some trend from level 4 to level 1 in scotoma brightness. The data from level 0 are artifactual.

The fixation duration first falls and then rises from level 4 to level 2, shown in Figure 10. Total number of fixations shows an increase from level 4 to level 3, then decreases in levels 2 and 1. The sharp decrease in number of fixations in the no scotoma control (level 0) was due to the fact that the target was found almost immediately after its onset. The saccade length measures about 2.75 degrees over the four relevant conditions with a slight fall in saccade length from level 4 to level 3. This compares rather poorly with the true inter-target distance of 3.75 degrees, but, it can be accounted for as due to inaccurate fixation.

These data were analyzed for fixation deviation or eccentricity while accepting that the data contained fixation inaccuracies due to the task requirements. A sample of the fixation positions for the eight targets is shown in Figure 11. The fixation eccentricity from target center was calculated for each of the four dimming intervals and is shown by the solid line in the upper panel of Figure 12. The same data are shown by target location or sector in the lower panel and it is apparent that the deviations for target location are much larger than the deviations associated with the dimming intervals.

The composite of the eccentric fixations for over 15,000 eye position samples is pictured relative to the size of the scotoma in Figure 13 for each brightness level. These data must be interpreted only as a preliminary attempt to assess eccentricity effects with the simulated scotoma because the accelerated sequential search produced some inaccurate fixation patterns. The brightest scotoma (level 4) produced fixations below and to the left of the target center. The dimmer scotoma levels are all clustered together (levels 3-1), and, while the no scotoma control (level 0) is closest to the true target center, it is still eccentric probably due simply to the inaccurate fixations generated by the sequential search task.

DISCUSSION and CONCLUSIONS

The large visual search impairments found in these studies were due to the presence of a simulated afterimage scotoma designed to approximate the immediate aftereffects of accidental laser exposure. The first three studies showed that search time could be doubled by a foveal scotoma even with a relatively small size or under easy display conditions.

The results of the first three studies also showed that eye fixation duration increased under scotoma conditions, although the effects became somewhat weaker under less difficult conditions of scotoma and display. Why are the observers making longer eye fixations? What is the exact nature of this adaptation to the foveal loss produced by the simulated scotoma? Two factors may be important: an information processing factor which is related to the area of the scotoma, and, a general interference factor which retards eye movement programming independent (to some lower limit) of scotoma size.

The eye may be guided by pattern analysis of the search elements or a simple spatial location of a peripheral element. If pattern analysis is used some criterion level of confidence must be reached before an eye fixation is spent in verifying that the target is present. Foveal losses may demand longer fixations because more pattern analysis is being performed peripherally on each target. The larger the scotoma the less resolution in the remaining retina and the longer the processing required to find peripheral targets. If the observer uses only the spatial location of targets to program subsequent eye movements then processing for recognition must be done foveally. Under normal search conditions it is possible that the searcher selects some combination of such foveal-peripheral strategy depending on many factors such as past experience, the size or visibility of the targets, recent feedback, perception of what is expected as good performance, payoff or penalty for slower search or errors, to name only a few.

Disruption in programming for eye movements may accompany the foveal scotoma independent of the area of the scotoma. The fact that the deficit did not drop very much when the scotoma was reduced in size and when easier display conditions were introduced suggests that the mere presence of the central scotoma may add a fixed amount of processing time to the eye fixations. Analyzing the effects of smaller scotomata in the range of 5 min to 60 min across the fovea seems reasonable therefore to determine the extent of this motor disruption. This will demand measuring smaller eye movements, too, coinciding with the smaller scotoma sizes. This will produce larger volumes of eye position data and will require more computer memory and low noise, high stability analog signal acquisition. The advantage will be more information about the role of the scotoma in disrupting motor programming and about the role of eccentric fixations with small scotomata.

It has been shown in patients with new macular scotomas that there is a tendency not to eccentric fixation but attempts to continue to fixate using the scotomatous area of the retina. This compulsive fixation tendency is a counterproductive strategy in overcoming the effects of foveal loss since it positions the target on an area of the fovea which is totally or relatively unresponsive to light. The effort to overcome this tendency may also account in part for the longer eye fixation durations.

One of the limitations with the simulated scotoma is that these techniques are in no way alarming to the subject. In this respect the simulation is a departure from the high levels of activation and alarm which might be expected from an actual injury if a foveal exposure results in even temporary loss of acuity or accommodative functions (perhaps especially if the exposed observer believes the losses will be permanent). It could be concluded, then, that the losses seen in these studies may be an under-estimate of the visual impairment due to actual injuries. The simulated scotoma is also limited in fidelity because a bright light flash bleaches the photochemical pigments and the photolytic products diffuse on the retina and create complicated aftereffects, at least for white light stimuli (18-21).

Improvements in the eccentricity analysis can be made by including smaller sets of target locations in tasks which do not require speeded sequential monitoring. This will help to analyze the eccentricity of fixations without causing inaccurate fixation positions because of a simplified or accelerated task. Some of the subjects in the sequential search task indicated that they were not, in fact, accurate in their fixations because the task was monotonous. Study #1 showed that each eye fixation could serve to detect 2 or 3 targets. With so much less processing required per fixation in this sequential search study, it is understandable that the subjects would not need to be as accurate as they might have been in fixating the targets.

The eccentricity analysis illustrates the examination of fixation locations relative to targets over conditions of differing scotoma intensity. Eccentric viewing may be the main method of compensating for a scotoma if restoration of retinal cell functioning is not possible. Whether these eccentricities for different brightness levels will generalize to other visual display sets or different search instructions remains to be examined. However, the method appears to be a promising way of repeatedly examining adaptations in visual function during the period immediately following accidental laser exposure in human subjects.

The intensity of the brightspot afterimage was limited by the pupillary constrictions and these studies established some boundaries for the study of the central bright spot. It is not a new finding that variability in autonomic activation and pupillary sensitivity is great both within and between subjects. This is not considered to be a serious limitation, however, since more advanced sensors are less sensitive to pupillary noise. Also, the conditions under which recordings are very good represent some of the worst case conditions for visual performance described by O'Mara (22), ie. an absolute positive afterimage on the fovea with displays of low luminance along with low contrast targets. Further studies will employ a limbus tracker in addition to the Purkinje tracker used in the present work in order to explore the possibility of expanding the range of brightspot intensities without problems from pupillary constriction or the use of mydriatics.

The fixed and variable scotoma brightness studies illustrate two methods of estimating the impairments which result from foveal losses. They may be considered converging operations for the purpose of checking the results of one method against another. Scotoma effects seen in session 1 of the fixed scotoma brightness study were not seen in session 2. This may be due to practice effects. Practice effects in adaptation to the scotoma are the topic of study in a follow-on contract now underway.

The following conclusions based on the experimental outcomes are important:

1) Small afterimage scotomas of 20 and even 10 minarc across the fovea seriously impair free visual search. Impairments are easily detectable in both search time and eye fixation duration measures.

2) The percent impairment from the simulated laser aftereffect is significant even for relatively easy search tasks, but deficits are strongest for difficult search fields, eg. small targets, dense arrays and low contrast.

3) Controlled fading of the simulated afterimages shows promise as a method for examining the mechanisms of restoration of visual function.

4) The evaluation of eccentric viewing strategies by computer analysis of eye fixation position data bases appears to be a useful development in the analysis of restoration of visual function.

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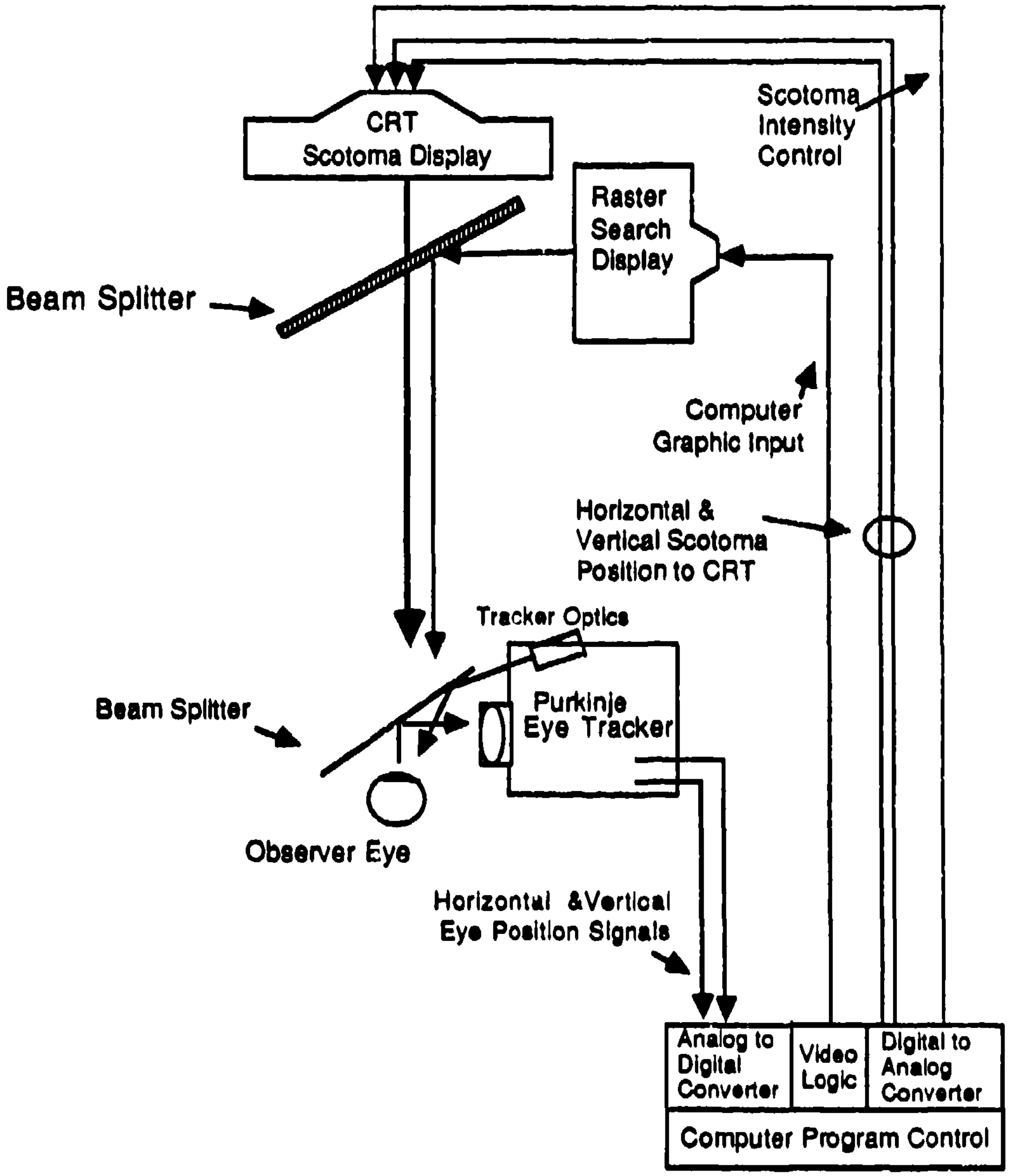


Figure 1. The scotoma simulation system is diagrammed with the Purkinje Eye Tracker, visual displays, computer and control lines. The observer eye is shown in the path of both the CRT afterimage display and search display through the beamsplitter. Analog signals for horizontal and vertical eye position exit the eye tracker and are converted and stored in RAM memory. Scotoma position control signals exit the computer to move the CRT image under eye control. Video ligic output to the raster monitor controls the search display, target position, gap size and target onset. The delay from eye position movement to scotoma movement was 5 msec.

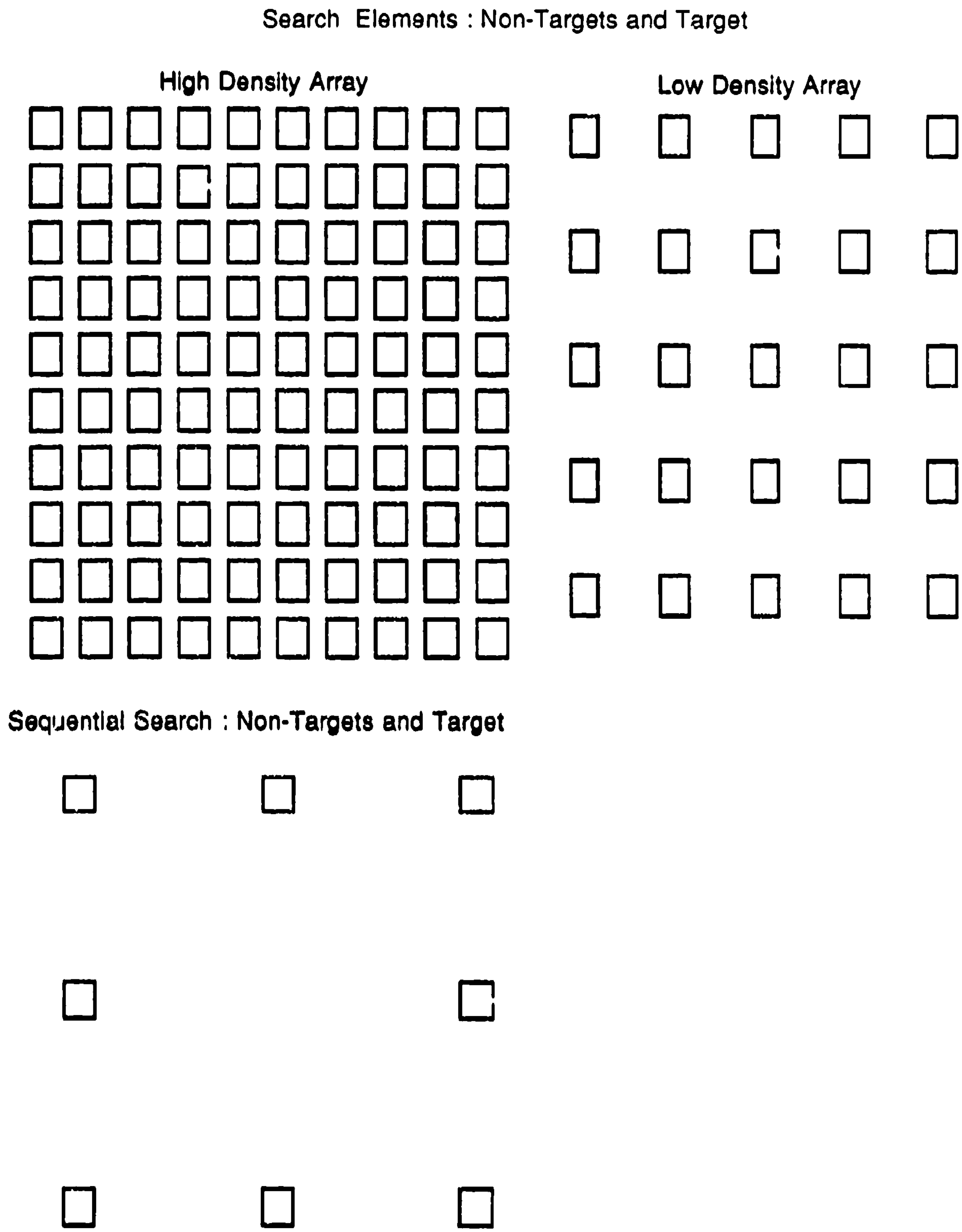


Figure 2. Configuration of visual search displays for high and low density arrays which were used in studies #1- #6, and, the 8 element search array used in the sequential search task (study #7). The eig sectors used in the eccentricity analysis correspond to the eight target locations - centered on the targe

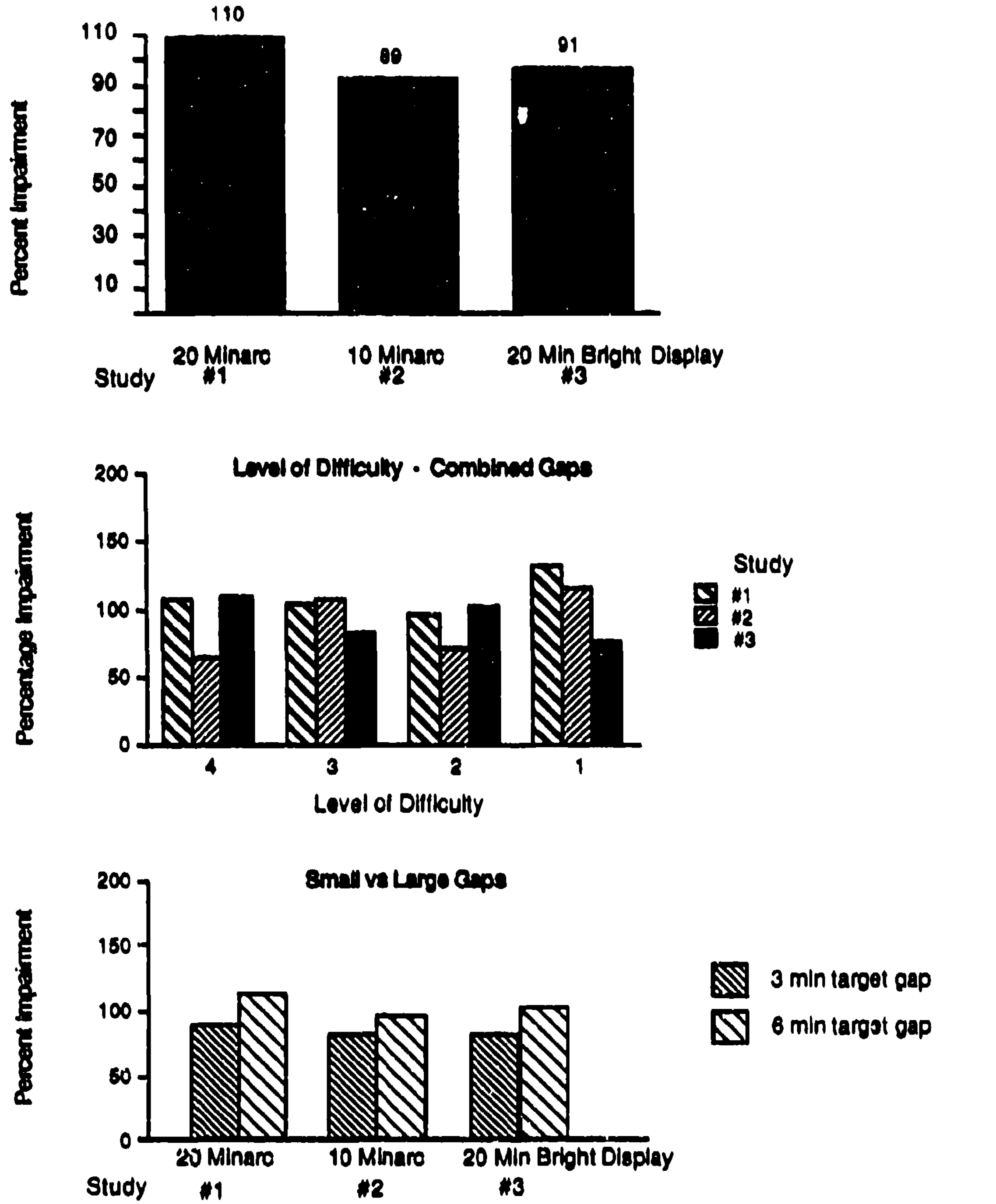


Figure 3. Summary of percentage increases in search time due to the simulated scotoma or afterimage. Percentage increases are comparable across studies with 20 and 10 min scotoma sizes and with a brighter display, even though absolute values in seconds of search time changed considerably. Percentage impairment for level of difficuty and gap size are also similar. These dificits in search performance represent large losses in efficiency .

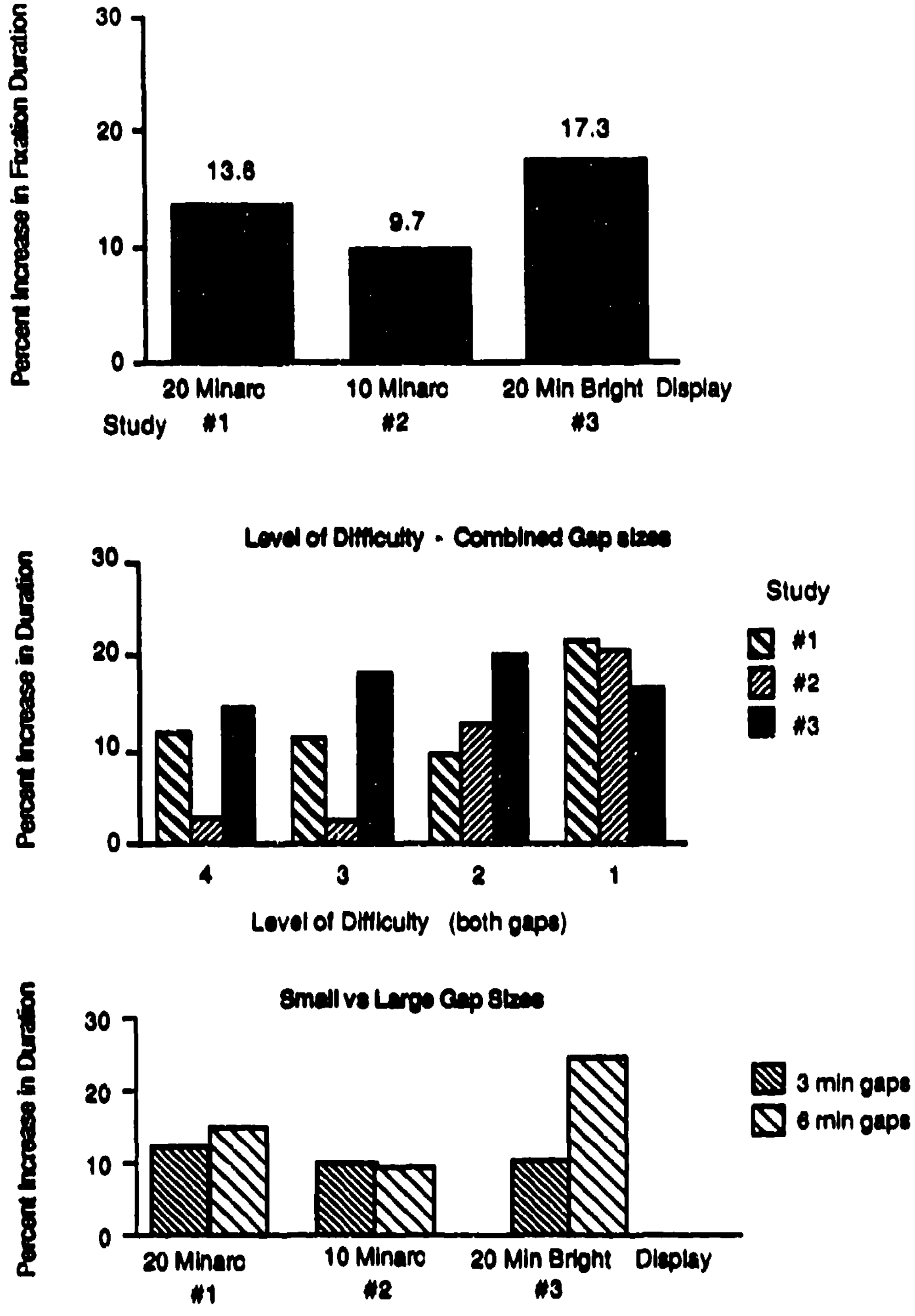


Figure 4. Summary of percentage increases in eye fixation duration averaged over the three studies and for the four levels of difficulty and gap sizes (3 min versus 6 min gap). Fixation duration increased under scotoma conditions in all three studies and was largest for the bright display, study #3. The largest percentage increase was for the less difficult display conditions, and also, for the largest gap size in study #3.

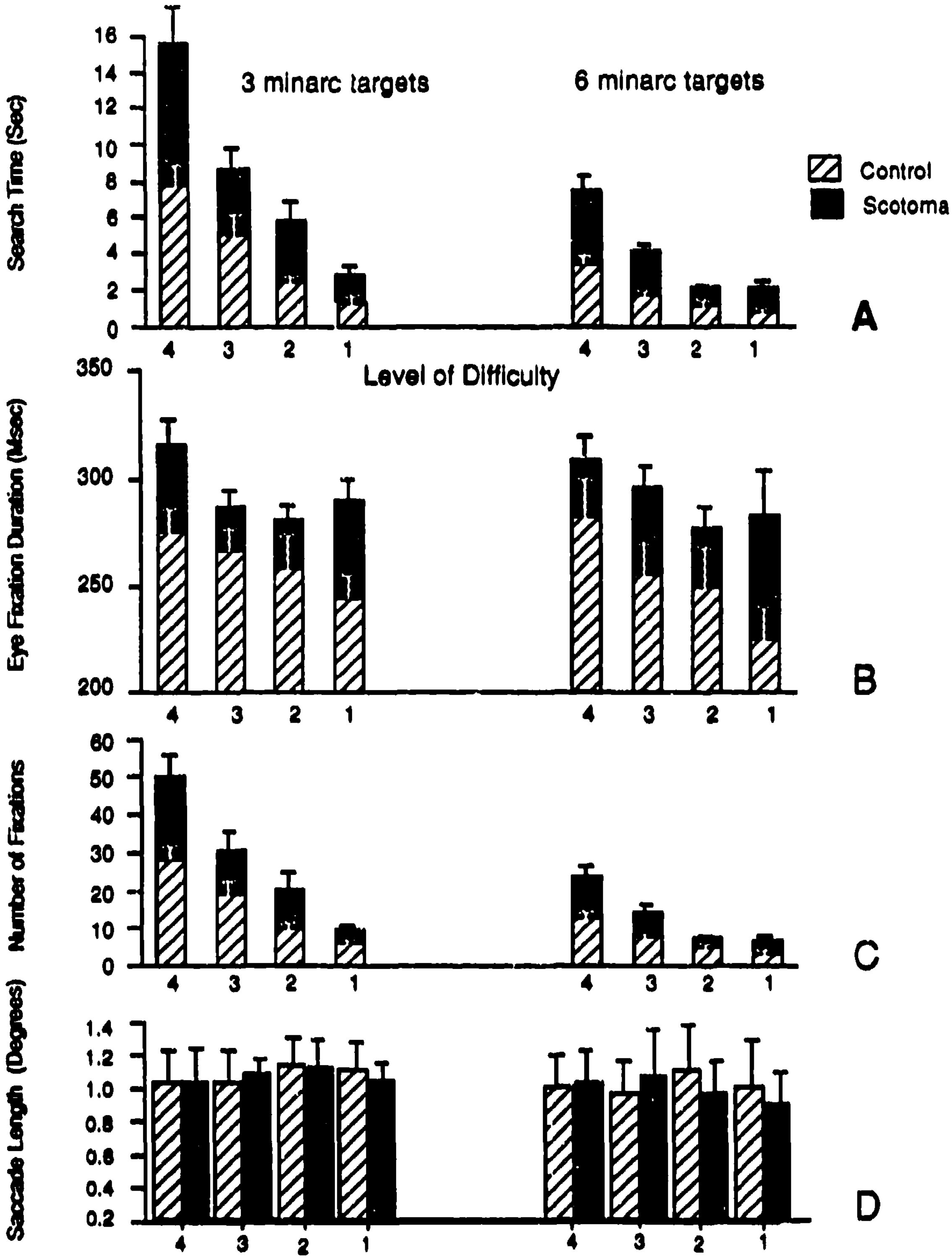


Figure 5. Search time, eye fixation duration, number of fixations and saccade length for control and 20 min scotoma conditions at four levels of display difficulty. Values for the 3 min target gaps are to the left and 6 min gaps are to the right. Standard errors are in brackets. N=12. Saccade length values are unstacked for clarity. The high correlation between search time and number of fixations is responsible for the close correspondence in their scotoma effects. Large scotoma effects are present at all levels of display difficulty for search time and eye fixation duration.

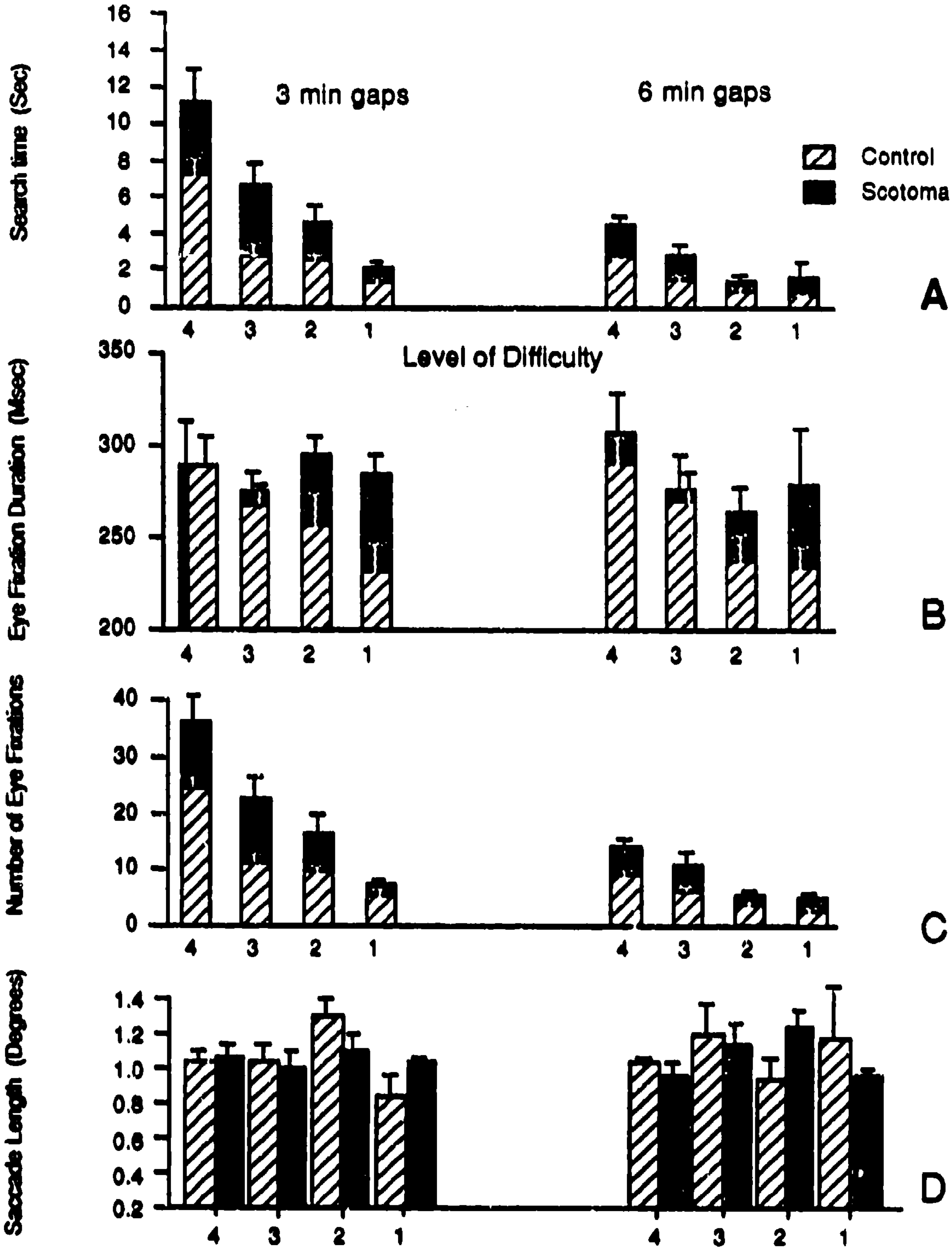


Figure 6. Search time, eye fixation duration, number of fixations and saccade length for control and 10 min scotoma conditions at four levels of display difficulty. Values for the 3 min target gaps are to the left and 6 min gaps to the right. Standard errors are in brackets. N=5. Saccade length values are unstacked for clarity. The high correlationbetween search time and number of fixations is responsible for the close correspondence in their scotoma effects. The magnitude of the impairment effects are smaller for search time than with the 20 min scotoma. The eye fixation duration increases are also smaller with this 10 min scotoma than the 20 min scotoma used in Study #1, Figure 5.

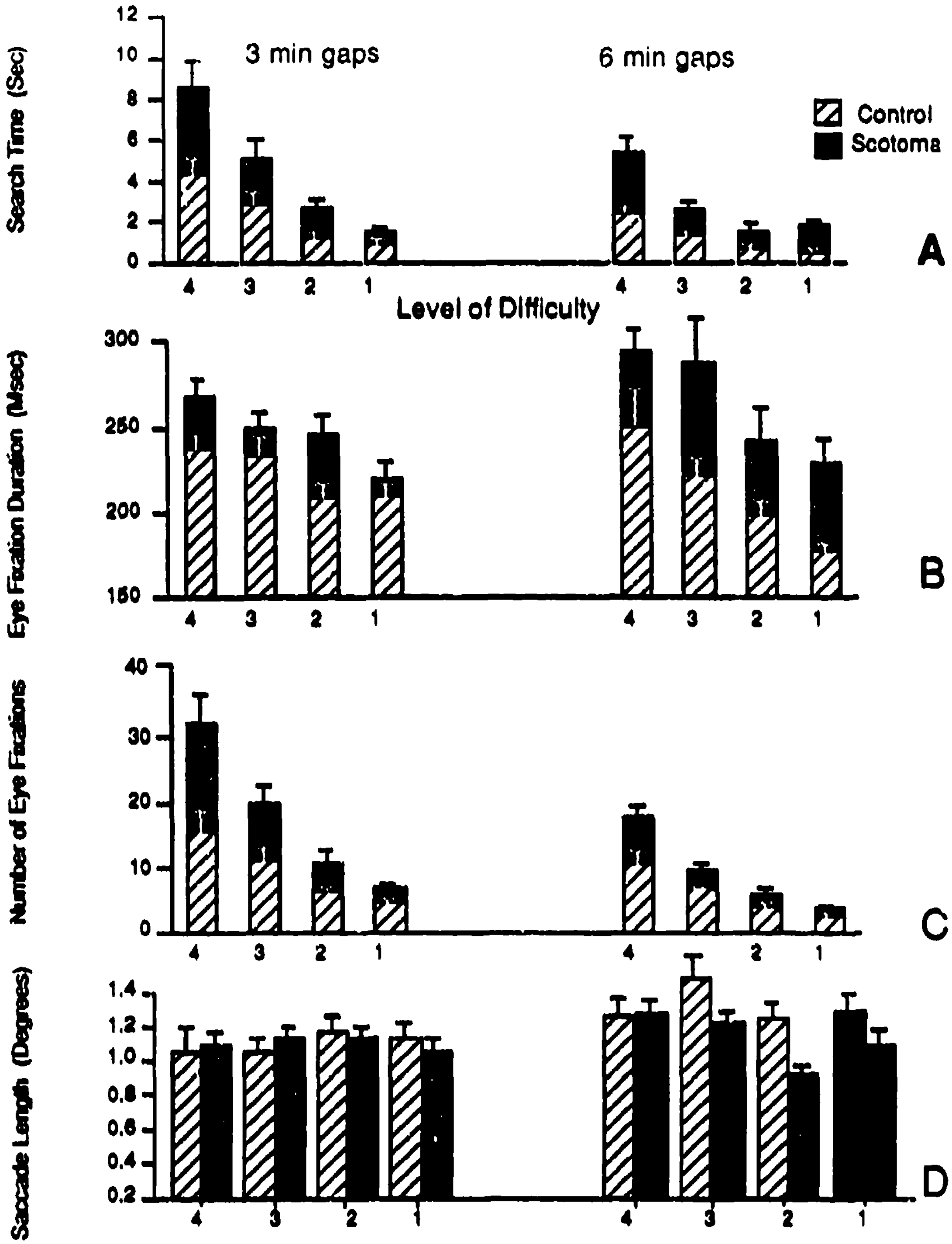


Figure 7. Search time, eye fixation duration, number of fixations and saccade length for control and 20 min scotoma conditions at four levels of display difficulty. Values for the 3 min target gaps are to the left and 6 min gaps to the right. Standard errors in brackets. N=11 Saccade length values are unstacked for clarity. The high correlation between search time and number of fixations is responsible for the close correspondence in their scotoma effects. The brighter display generally improved performance but strong effects from the simulated scotoma are still evident.

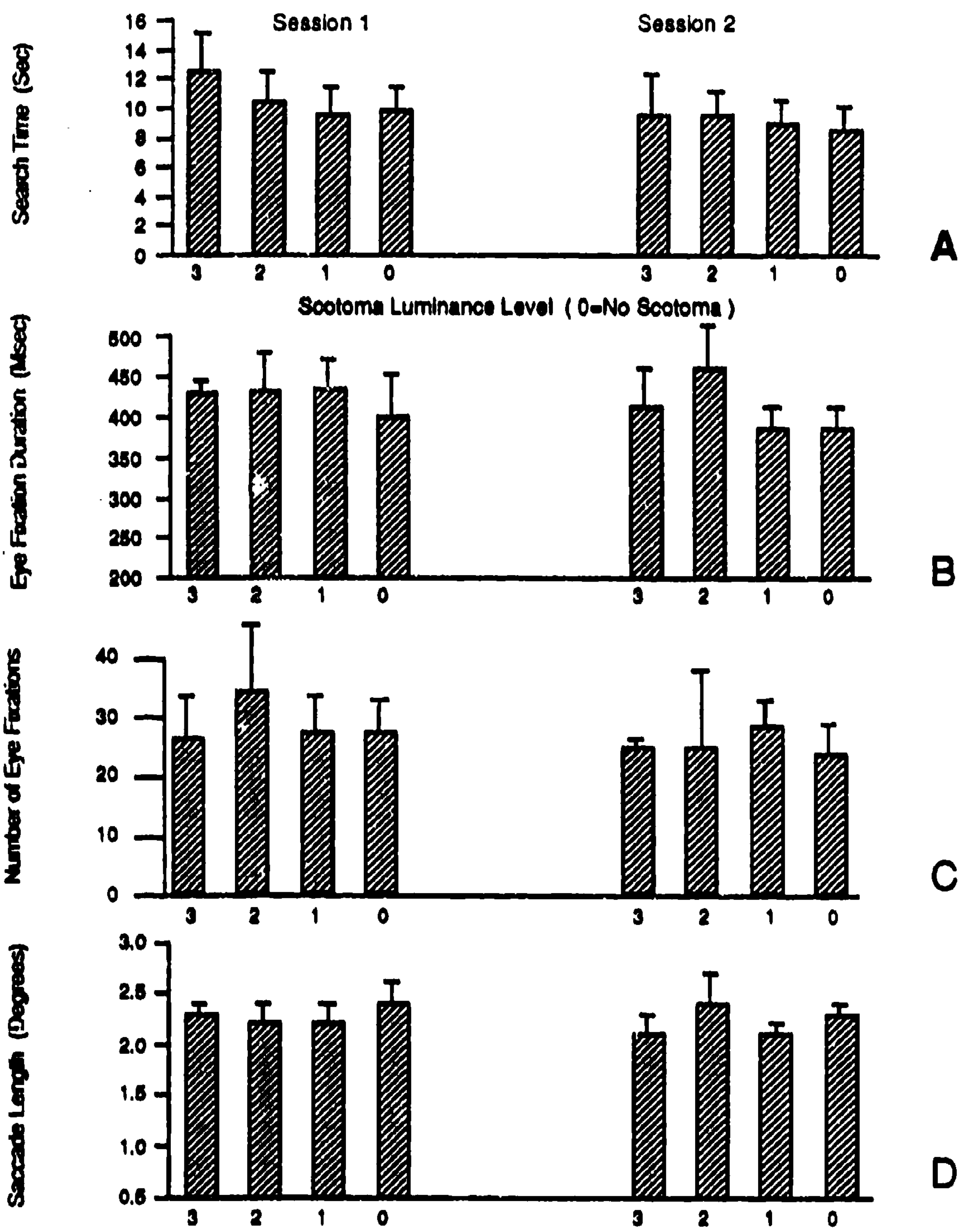


Figure 8. Search time, eye fixation duraton, number of fixations and saccade length for three levels of scotoma intensity and a no scotoma control (level 0) which were presented in blocks of trials. Some reduction in search time with intensity is seen in session 1 and a nominal reduction in session 2. The eye fixation durations are more irregular but the control condition is lower than the scotoma conditions. Standard error in brackets. N=5.

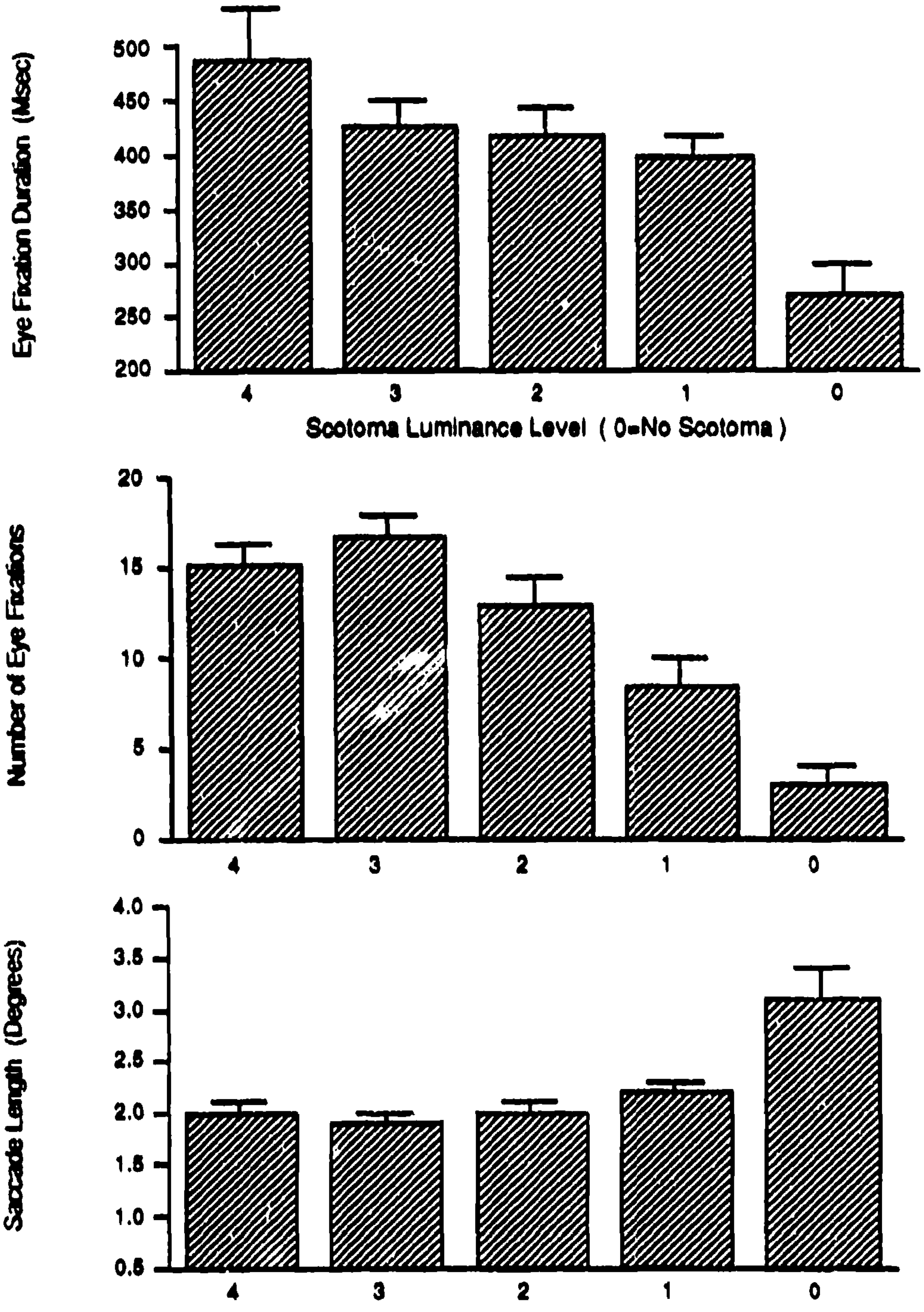


Figure 9. Eye fixation duration, number of fixations and saccade length for search with a 20 min scotoma which faded during each search trial. The target was witheld while the observer searched a level 4 difficulty display for the 3 min target gap which was turned on in level 1 or level 0. The fading period lasted only 25 sec, a relatively short lived scotoma afterimage. Some reduction in fixation duration is seen from the most intense level 4 to level 3 scotoma brightness. Standard errors in brackets. N=9. The data during level 1 and level 0 are artifactual because the target was presented during those epochs.

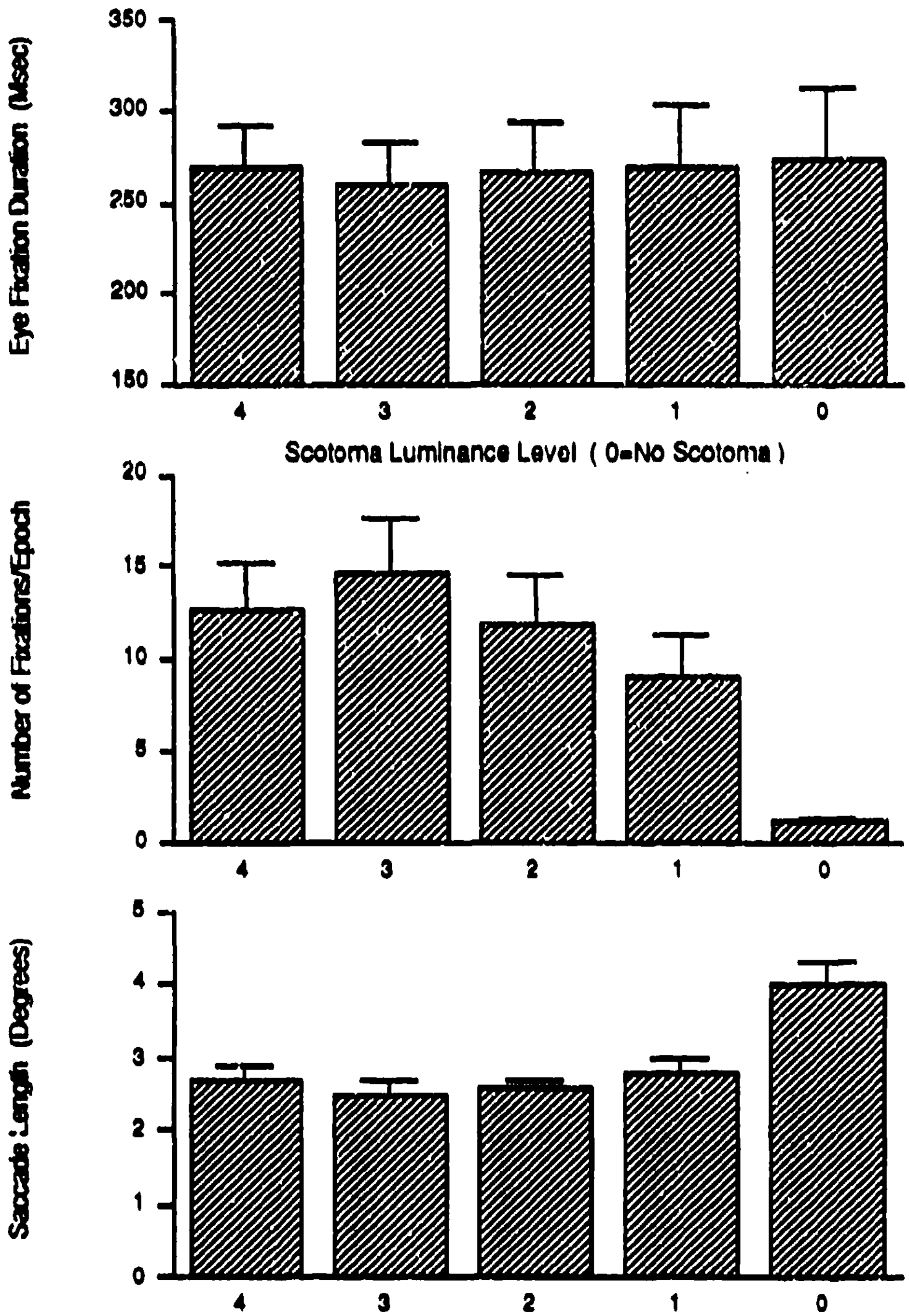


Figure 10. Eye fixation duration, number of fixations and saccade length for search with a 20 min scotoma which faded within 25 sec during each trial while observers performed sequential search of eight target locations. The target was withheld until level 1 or level 0. This procedure produced highly consistent eye fixation durations and only a small reduction is seen from level 4 to level3. No linear changes are evident with fading scotoma intensity. Standard errors are shown in brackets. N=4. Saccade length increases in level 1 and 0 are artifactual, as well as the low number of fixations.

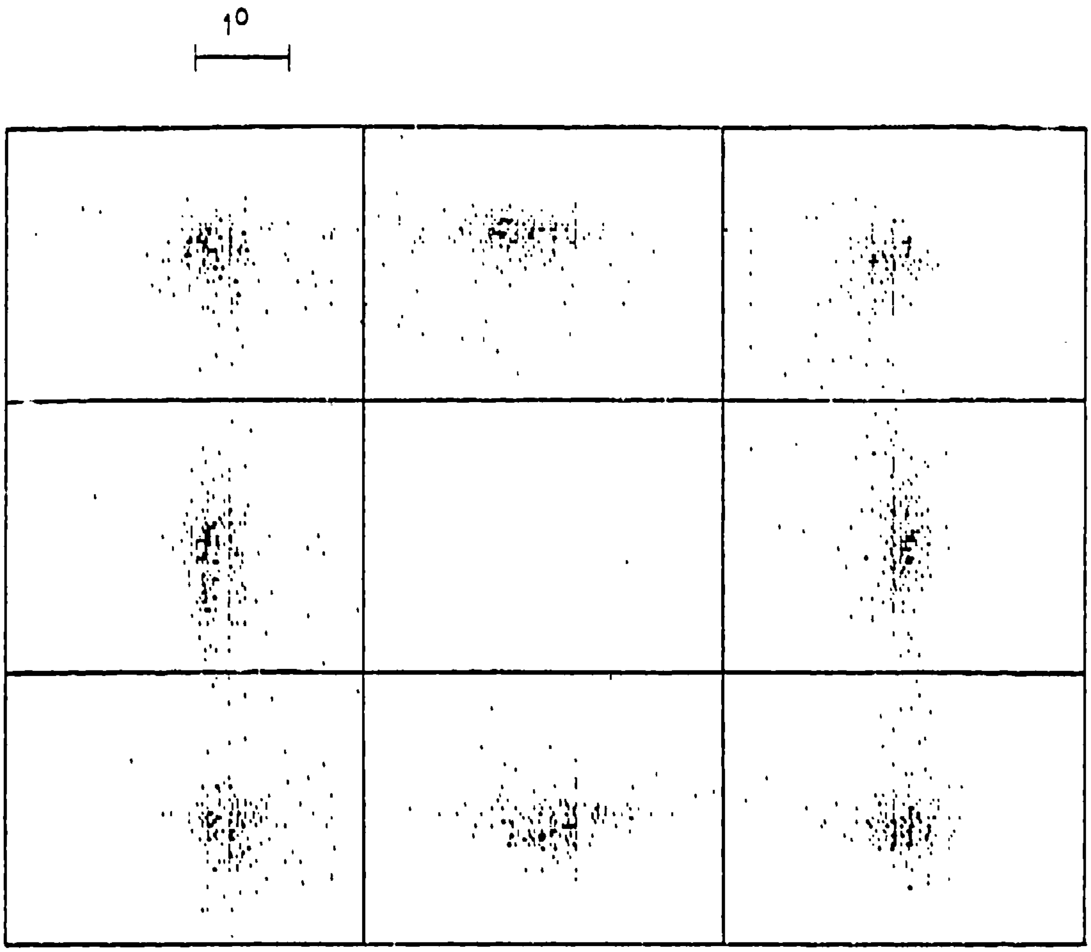
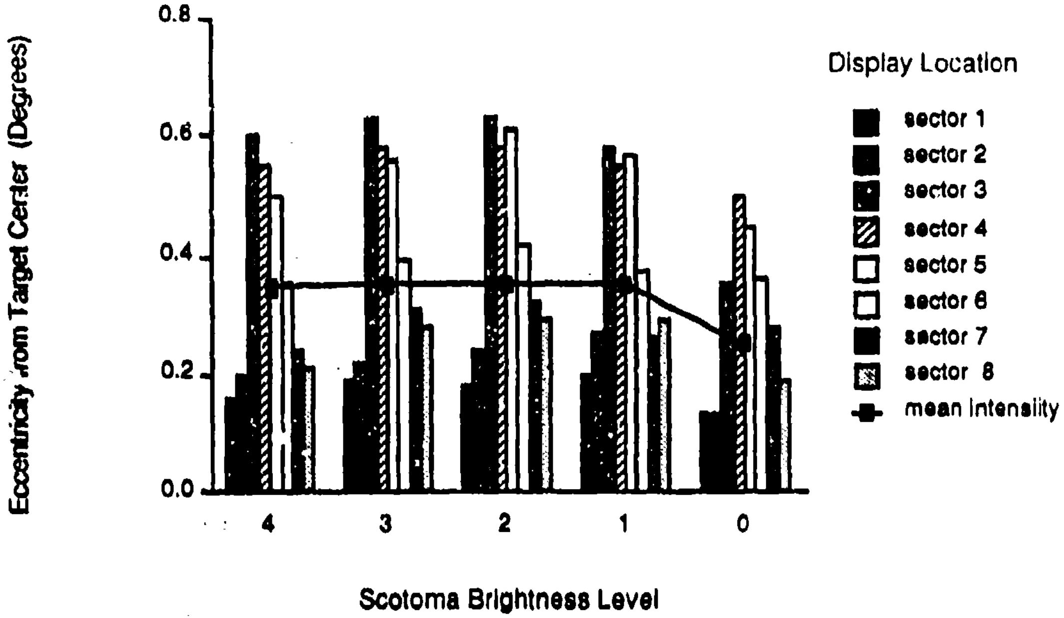


Figure 11. Fixation position scatter plot around eight target positions in the sequential search task. The pattern of fixations scattered around the target center is typical of the relative innaccuracy which was characteristic in this task. The spread of fixations in a vertical pattern on some target locations and in a horizontal pattern on other targets demonstrates the strong effect of target position in generating fixation errors. These errors compromised analysis of eccentric fixations due to the diminishing scotoma brightness.



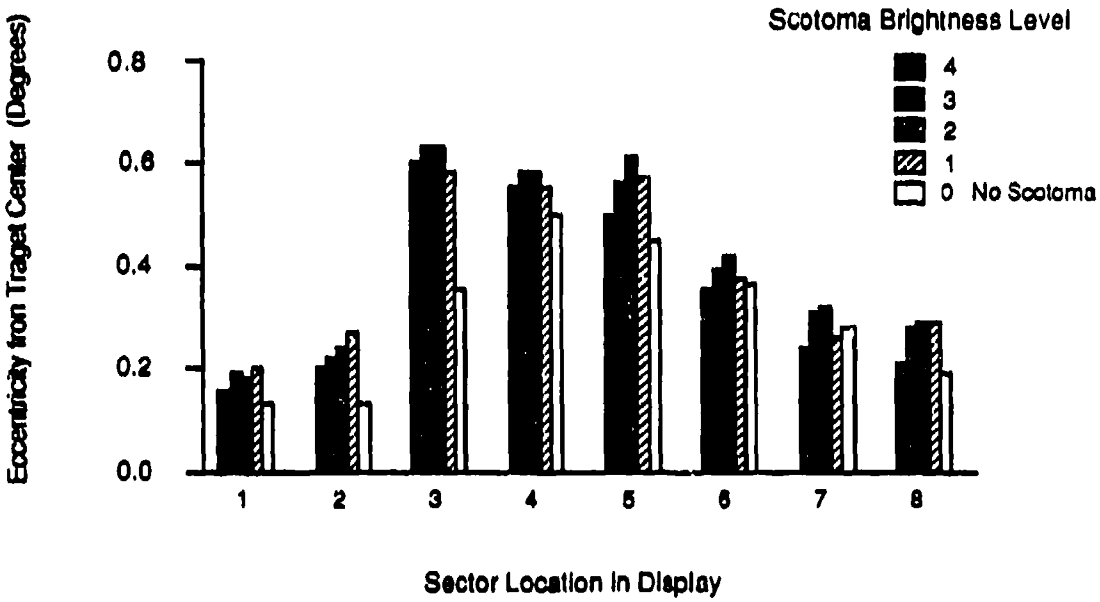


Figure 12. Eccentricity of eye fixation positions from target gaps during sequential search with a 20 min fading scotoma. A sector was defined by a radius of 1 degree around each of the eight search elements. 15% of total fixations fell outside any sector and were discarded as errors. Eccentricities are shown first for the four intensity levels with a breakdown for sector position. Below is shown the large effect of sector position within the search field. The hurried sequential search produced innaccurate eye fixations. No consistent effect of the scotoma fading is evident.

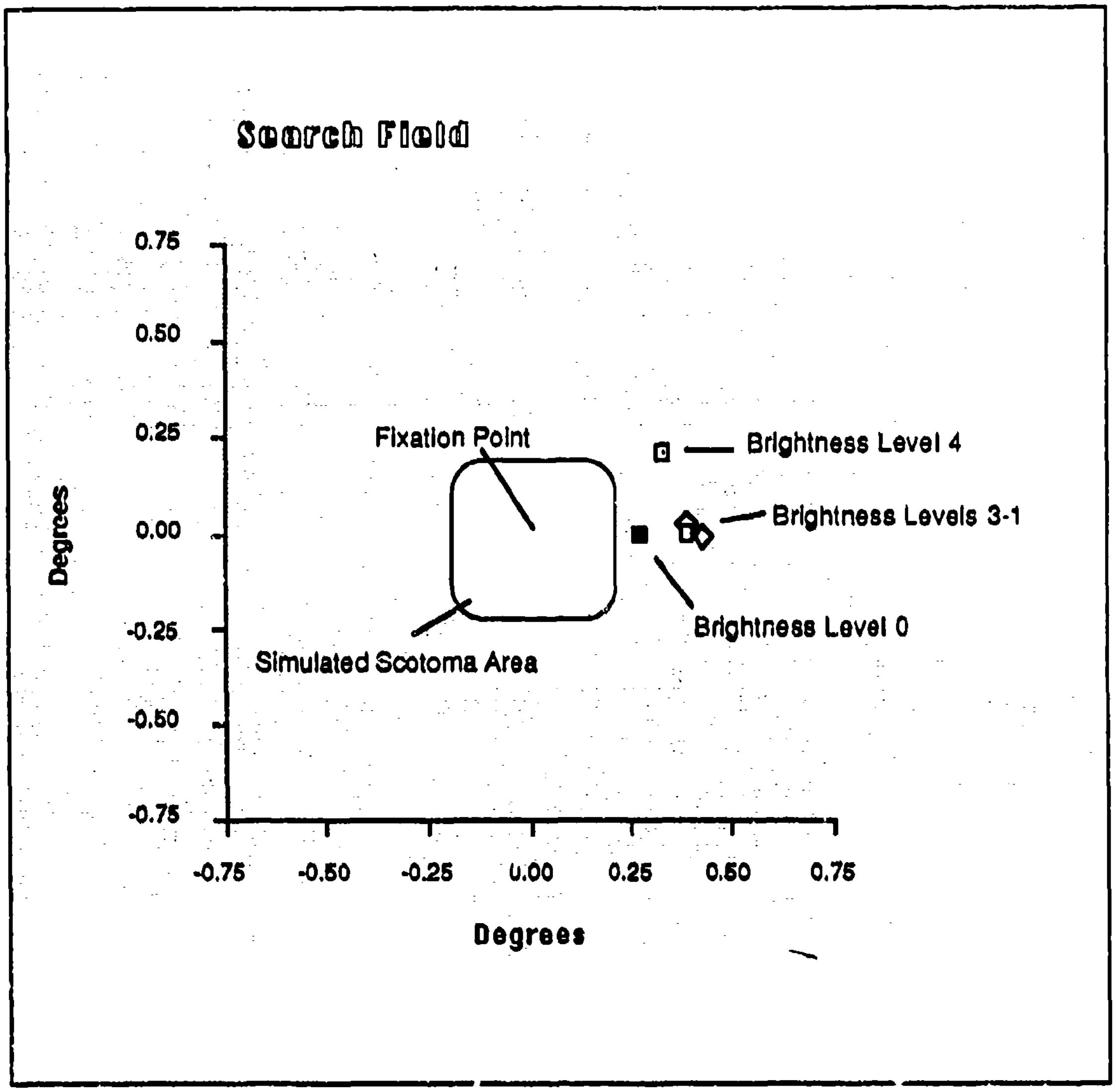


Figure 13. Composite of all eccentricities of eye fixation position from target gap. Results are from a preliminary study and subject to limited interpretation. The most eccentric eye fixations were made when the 20 min scotoma was most bright (Level 4). Lower luminance scotomata are clustered together, and, in the no scotoma control condition, the eye fixation position are closest to the true target gap center. The composite of the control eye fixation positions is eccentric relative to the true target center probably because the sequential search task generated some innaccuracies in the eye fixations. A total of 15,429 eye fixations are represented.

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