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Effect of Target Size, Luminance, and Color on Monocular Fixation*

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A contact-lens technique was used to record eye movements made by two subjects attempting to maintain fixation at the center of concentric round targets of several sizes (1.9′–87.2′ diam) and luminances (2.8, 7.8, and 21.5 mL). Fixation of red, blue, and white 1.9′-diam targets was also examined. Analysis-of-variance designs were employed to remove variability arising from sources other than these stimulus variables. Statistically reliable differences in mean fixation position were found with targets of different size, luminance, and color. The largest difference observed was less than 4′ and under most conditions was less than 2′. The bivariate dispersion of the eye about its mean position varied in a complex manner with the size and luminance of the target object. No statistically reliable effects of stimulus variables were found on drifts. Saccade frequency was considerably reduced with the largest targets. Results are discussed in terms of a "fixed error-signal system" for the control of eye position.

1. INTRODUCTION

PRECISE position control of the fixating eye is known to be under visual control. When no fixation object is visible, the eye rapidly drifts away from the fixation position established when visual guidance was possible.[1–3] Inasmuch as corrective movements of the eye require the presence of a visible fixation stimulus, it seems likely that control of eye position would vary with properties of the fixation stimulus. Two studies have shown limited influences of specific stimulus variables on fixation performance. Gaarder found that the direction of saccades exhibited while fixing on a complex pattern, asymmetric with respect to the fixation point, is influenced by the orientation of the pattern.[4] Fender found differences in the mean fixation position when the subject was presented with either a small red, blue, yellow, or white target.[5]

To date, there has not been a detailed study of the effects of these or other stimulus variables on monocular fixation. The lack of interest may stem from the failure to observe such effects in the first studies that employed the contact-lens technique.[6,7] These early studies were concerned with relatively gross features of fixation and it is only possible to conclude that large effects are not observed with the type of targets that were used.

Three experiments were performed to examine the influence of target size, luminance, and color on four dependent variables which were chosen (1) to be representative of over-all fixation performance or (2) to give a somewhat detailed picture of fixation movements. The four dependent variables were: mean fixation position, variability about this mean position, the size of drifts, and the frequency of saccades. The specific measures are described in Sec. 2.4. The reasons underlying the choice of the particular stimulus variables are discussed in Sec. 4.2 when a fixation-error-signal system guiding the direction and extent of corrective eye movements is proposed.

2. METHOD

2.1. Apparatus

Recording

Eye movements were recorded by a contact-lens technique incorporating features which permit simultaneous and independent recording of rotations about horizontal and vertical axes in Listing's plane, uncontaminated by torsions of the eye or translations of the head. The recording system, which was similar to one previously described by Nachmias,[2] is shown in Fig. 1.

A projection system images a small portion of a lamp filament on a plane mirror (CLM) attached by means of a stalk to a scleral contact lens worn on the right eye of the subject. An image of a wedge-shaped aperture (WA) is formed by lenses (L3 and 4) on a horizontal slit directly in front of a continuously moving photosensitive surface (camera). The wedge aperture is oriented so that movements of the eye about its vertical axis (horizontal rotations) result in proportional changes in the lateral position of the vertical edge of the aperture on the film, while movements about a horizontal axis (vertical rotations) result in proportional changes in the width of the photographic trace as different parts of the wedge fall on the slit (see insert, Fig. 1). Recordings were made on Eastman Kodak Tri-X film moving at 22.2 in./min in a modified Dumont Oscillograph-Record Camera (model No. 321). An automobile headlight bulb (GE 1183) operated at 4.25 A was used in the recording system (S1). A circular polarizer (P) (Polaroid Corp. HNCP 35) was placed in front of the lens (L4) in order to reduce the light reflected back to the eye from the camera. The resolution

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[1] T. N. Cornsweet, J. Opt. Soc. Am. **46**, 987 (1956).

[2] J. Nachmias, J. Opt. Soc. Am. **49**, 901 (1959).

[3] J. Nachmias, J. Opt. Soc. Am. **51**, 761 (1961).

[4] K. Gaarder, Science **132**, 471 (1960).

[5] D. H. Fender, Brit. J. Ophthalmol. **39**, 294 (1955).

[6] F. Ratliff and L. A. Riggs, J. Exptl. Psychol. **40**, 687 (1950).

[7] R. W. Ditchburn and B. L. Ginsborg, J. Physiol. **119**, 1 (1953).

of this system with the projection measuring device employed was about 10″.

The right eyes of the two subjects were fitted with molded scleral contact lenses. A round, first-surface mirror (5-mm diam and 0.5-mm thick) was attached by means of a hollow aluminum tube and molded foot to the temporal side of the corneal bulge of the lens. The mirror was cemented to an aluminum ball-and-socket joint machined at the end of the tube. The joint was filled with soft wax which permitted adjustments of the mirror when warm but effectively resisted displacement once chilled. The contact lenses themselves weighed 550 and 750 mg; the attachments 160 and 150 mg. A dental-impression-compound biting board served to steady the head and an eye patch was used to cover and close the left eye.

Fixation

Collimated light from an automobile headlight bulb (S2) (GE 1183) operated at 5.4 A was diffused by a piece of opal glass (O) mounted directly behind a disk (TA) containing a number of round apertures of various sizes. The distance of the apertures to the eye by way of a path containing two mirrors (M3 and 4) was 1.8 m and the five targets used in the experiments subtended 1.9′, 12.5′, 27.9′, 49.8′, and 87.2′. The aperture disk was mounted on a modified auto-tuning motor (Collins type 596A1) that allowed rapid and reproducible changes in the size of the fixation targets. The maximum distance between the centers of the five targets was less than 1′ and each target's position was reproducible to better than 10″. A similar disk (NDA) holding eight Kodak Wratten neutral density filters, covering a 16 dB (40:1 luminance) range in approximately 2 dB (1.6:1 luminance-ratio) steps, was placed between the source and the collimating lens. A third auto-tuning motor (CA) was used to place color filters in the collimated beam just behind the opal diffuser. The various apertures and filter combinations could be preselected: A given fixation target was obscured by a shutter (SH) and replaced within 3 sec by a target differing in size, luminance, or color.

The neutral density filters were calibrated *in situ* with a photomultiplier photometer (Photovolt 520M with tube C); absolute luminance calibration, which was performed at the beginning and end of the experiments, consisted of photometry of a large, uniformly transilluminated field with a Macbeth illuminometer and subsequent matching of a 50′ portion of the large field with a juxtaposed target of the same size.

2.2. Subjects

Two subjects, MH, a graduate student at the University of Pennsylvania and RS, the author, served in the experiments. Both subjects were emmetropic and had acuities of 20:20 with the contact lenses in place.

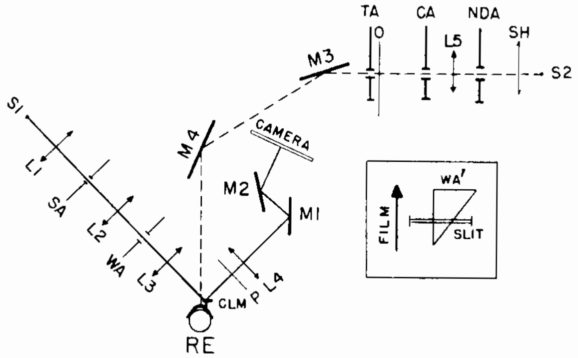

FIG. 1. Schematic diagram of the fixation (dashed line) and recording (solid lines) apparatus. S1 and 2 recording and fixation sources; L1–5 lenses; SA and WA apertures; TA automatic device for changing target apertures; CA and NDA automatic devices for changing color and neutral density filters; M1–4 first-surface mirrors; CLM small first-surface mirror attached to a contact lens worn on the right eye RE; P circular polarizer; O opal diffuser; SH shutter. The insert shows the image of WA on a horizontal slit in front of the film. The arrow indicates the direction of film motion.

Both subjects had served previously in eye-movement-recording experiments and were experienced in wearing contact lenses and maintaining fixation for prolonged periods. RS had also served in a variety of psychophysical experiments and had a great deal more practice in fixation than did subject MH, whose prior experience was limited to her performance in 15 eye-movement-recording sessions for a total of 350 thirty-sec fixation trials. Both subjects were acquainted with the purpose of the research, but neither had practiced fixation at the center of large targets nor examined the recordings during the course of the research.

2.3. Sampling

Records were obtained while subjects attempted to maintain fixation for 30-sec periods. Only the final 20 sec of each 30-sec trial were examined, in order to reduce variability arising from changes in adaptation that accompany changes in fixation targets. Ten random samples of the horizontal and vertical position of the eye and of the horizontal and vertical 0.2-sec drifts (differences in horizontal and vertical position at the beginning and end of a 0.2-sec interval during which no saccade occurs) were obtained for each trial. Each position sample was randomly selected within successive 2-sec intervals. The 0.2-sec drifts were estimated, so far as possible, with the random-time sample of position as the starting point for the drift measurement. Drift measurements were made either 0.2 sec before or after each random-position sample. When drift could be measured at both times (no saccade occurred 0.2 sec before or after the position sample), the choice was decided randomly. In those relatively infrequent cases where saccades occurred in both intervals, the film was advanced every 0.1 sec until a saccade-free 0.2-sec interval appeared. The number of saccades occurring during the final 20 sec was also counted.

2.4. Measures[8]

Saccade frequency (SF) and trial-mean position were simply the number of saccades counted on each trial and the trial mean of the 10 vertical and horizontal coordinates of eye position expressed in min arc. The trial-mean magnitude of the drift vectors (DM) was used to summarize the ten 0.2-sec drifts of the eye.

In order to describe the variability of the eye about its mean position on a given trial, a single over-all measure was used that circumvents difficulties in interpretation encountered when only arbitrarily selected meridians are analyzed.[9] If the measured positions of the eye are assumed to have a bivariate normal distribution, the dispersion of these measures can be represented by an ellipse whose area is analogous to the standard deviation of a univariate distribution. The area of such an ellipse is calculated as follows:

$$A=2k\pi\sigma_{\mathrm{H}}\sigma_{\mathrm{V}}(1-\rho^2)^{\frac{1}{2}}$$

where A is the area of a bivariate normal ellipse, σ_{H} and σ_{V} are the marginal standard deviations along two meridia, and ρ is the product-moment correlation of these two position components. The value selected for k establishes the confidence limit for the ellipse, the probability of a given observation falling within it being given by

$$P=1-e^{-k},$$

where e is the base of the natural logarithm. In the present experiments a value of $k=1$ was used; the probability is, therefore, 63.2%. This area measure as applied to the dispersion of the eye about its mean position can be visualized by considering the position of the image of a small fixation target (or the centers of the larger targets) on the retina. The bivariate contour ellipse as calculated in the present experiments would enclose that portion of the retinal surface where the target image would be found 63.2% of the time. Actually, the area measure is expressed in (min arc)^2 of the solid angle subtended at the eye by an ellipse projected on a plane surface parallel to Listing's plane. Logarithms of the trial-position areas ($\log A_{\mathrm{p}}$) were used in the analyses of variance and for the various graphs in order to eliminate the influence of the arbitrary confidence limit selected upon the shapes of the various functions. Analyses performed to test the bivariate normal assumption are described in Sec. 3.3. The measurements were processed by a Control Data 160A computer which also performed a number of statistical analyses.

2.5. Design and Procedure

Experiment 1—Design

A recording session consisted of 25 thirty-sec trials in five blocks of five trials each. Each block consisted of a different order of all five target sizes. A single luminance level was employed at each session, the order of luminances balanced within replications. The three luminance levels were 2.8, 7.8, and 21.5 mL and the diameters of the five targets were 1.9′, 12.5′, 27.9′, 49.8′, and 87.2′. The lowest luminance level was selected so as to be 4 dB above that required for the smallest target to remain visible while the subject maintained fixation for 30 sec.

There were 12 recording sessions constituting a fully balanced 5×3×5-factorial analysis-of-variance design.[10] In order to keep the amount of film measurement within manageable limits, the film from only six recording sessions (the first and last replications) was sampled and analyzed. The results of Experiment 1 are based, therefore, on 150 thirty-sec fixation trials for each subject; 75 early and 75 after 150 further practice trials with the various size and luminance combinations.

Experiment 1—Procedure

The subject dark adapted for 7 min after insertion of the contact lens. The recording system was aligned during this period and there was a practice trial with the 1.9′-diam target at the luminance of the day just prior to the 25 experimental recordings. The small target was visible throughout dark adaptation.

Subjects were instructed to maintain fixation at the center of the various targets. The stimulus objects appeared on a background which was dark with the exception of a dull glow in the periphery produced by stray light from the recording system. Each trial was begun at the discretion of the subject when the new stimulus object appeared to be homogeneous and free from after-images from the prior trial. On the average, the 25 trials were completed within 25 min; the subject remained in place on the biting board throughout. There was only one recording session on a given day. A single practice session (25 trials, five with each target at 7.8 mL) preceded the start of the first experiment. Once the experiments were begun, it was not necessary to discard any sessions or trials for technical reasons.

Experiment 2—Design

A recording session consisted of 18 thirty-sec trials. Either the 1.9′, 27.9′, or 87.2′-diam target was used at

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[8] Approximately 6% of the records were measured twice. The second measurements were made throughout the several months of film reading without access to prior data. The variance attributable to measurement error is: SF, 0.074 saccades; mean horizontal position, 0.049′; mean vertical position, 0.012′; DM, 0.087′, and $\log A_{\mathrm{p}}$, 0.001 (min arc)^2.

[9] To illustrate, the standard deviation of the horizontal component of rotation might not be affected by changes in luminance while along some other meridian large effects do, in fact, occur. Since such directional nonuniformities along various meridians within and between individuals have been shown, a measure of dispersion which includes all directions of rotation was used.[2,3] An alternative approach would be to find the meridian along which maximum and minimum treatment effects do occur for each subject.

[10] W. Cochran and G. Cox, *Experimental Designs* (John Wiley & Sons, Inc., New York, 1957).

each session which consisted of six trials at each of the three luminance levels employed in Experiment 1. There were six recording sessions in all, constituting a 3×3-factorial analysis-of-variance design.[10] In the first three sessions, the luminance levels were presented in an ascending order; in the last three the order of luminance was reversed. The 1.9′, 27.9′, and 87.2′-diam targets were presented in the first three sessions; in the last three, the order of sizes was reversed.

Experiment 2—Procedure

The subject was dark adapted for 5 min and adapted to the appropriate luminance level for 1.5 min before each group of six trials. No light from either the fixation or recording apparatus was visible during the initial or subsequent two periods of dark adaptation. A practice trial preceded the six recordings at each luminance level. The recording system was aligned during the period of light adaptation and the practice trial which preceded the six trials at the initial luminance level. On the average, the 18 trials were completed in 35 min. Five of the six trials at each luminance level were randomly selected for measurement. The results are based, therefore, on 90 trials for each subject; 30 with each luminance level, each having 10 with each of the three target sizes. In other respects the procedures were the same as Experiment 1.

Experiment 3—Design

The effects of color were studied at a single recording session consisting of 24 trials (8 blocks of 3 trials, one with each color). The smallest aperture (1.9′ diam) was the only target size employed in this experiment. Light passing through it appeared either red, blue, or white after transmission by a Kodak Wratten No. 70, 49B, or 25 dB neutral density filter. The order of colored stimuli followed a fully balanced latin square.[10]

Experiment 3—Procedure

At a preliminary session neutral density filters were selected so that the luminance of each of the three colored targets would be 8 dB (63%) above the level required for the targets to remain visible throughout 30-sec fixation periods. The colored targets appeared to be approximately equal in brightness in the dark under these conditions.

3. RESULTS

The results of each of the 3 experiments are considered only with respect to within-session stimulus variables: target size in Experiment 1, luminance in Experiment 2, and color in Experiment 3. The effects of luminance, particularly, can be evaluated only in Experiment 2 which was specifically designed to examine this factor. In Experiment 1 there are large differences in the amount of light entering the eye when a new target is presented at each trial, and time limits imposed by wearing a scleral contact lens severely interfere with the control of retinal adaptation. The results of the luminance experiment (Experiment 2), however are needed to interpret the influence of target size in Experiment 1. The fact that similar effects of target size can be shown to occur both within (Experiment 1) and between (Experiment 2) recording sessions offers assurance that the results do not depend on "carry over" effects.[11]

The results which are described were found to be either (1) statistically reliable for both subjects or (2) statistically reliable for one and similar for both.[12]

3.1. Over-all Performance

Small, statistically reliable differences in mean fixation position were found for both subjects when they fixated targets of various sizes, and for subject RS when targets of different luminances and colors were employed (see Tables I and II). The largest difference in mean position, however, was smaller than 4′ (the difference between a red, as compared to a white target found for subject RS in Experiment 3). With most other fixation objects, the observed differences were smaller than 2′.

The bivariate dispersion of the eye about its mean position was found to vary with the size of the target

TABLE I. Means of the relative horizontal (H) and vertical (V) trial mean fixation positions in minutes of arc. The negative signs indicate that the mean position of the eye was to the right on the horizontal component or above on the vertical component relative to the smallest, least luminous, and white target in Experiments 1, 2, and 3, respectively. The targets were concentric to less than 1′

Experiment 1 (30 trials/target size)						
Subject	min-arc-diam	1.9	12.5	27.9	49.8	87.2
MH	Vertical	0.0	−1.9	−2.4	−3.7	−2.3
RS		0.0	−0.4	−0.4	2.9	2.2
MH	Horizontal	0.0	0.4	0.2	0.0	0.6
RS		0.0	0.3	0.2	0.4	−2.2
Experiment 2 (30 trials/luminance)						
Subject	log mL	0.45		0.89		1.33
MH	Vertical	0.0		0.6		0.0
RS		0.0		2.7		−1.7
MH	Horizontal	0.0		−1.9		−0.6
RS		0.0		−1.1		0.2
Experiment 3 (8 trials/color)						
Subject	color	white		red		blue
MH	Vertical	0.0		2.2		−1.0
RS		0.0		−1.2		2.1
MH	Horizontal	0.0		0.7		−2.0
RS		0.0		−3.9		0.4

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[11] These effects could be of two kinds: a somewhat mysterious effect of after-images of small targets which aids in the fixation of larger ones; or practice effects, relatively stable fixation of large targets requiring periodic trials with smaller ones.

[12] See R. M. Steinman, Ph.D. dissertation (University Microfilms, Ann Arbor, Michigan, 1964) for the complete analyses of variance and tabled data.

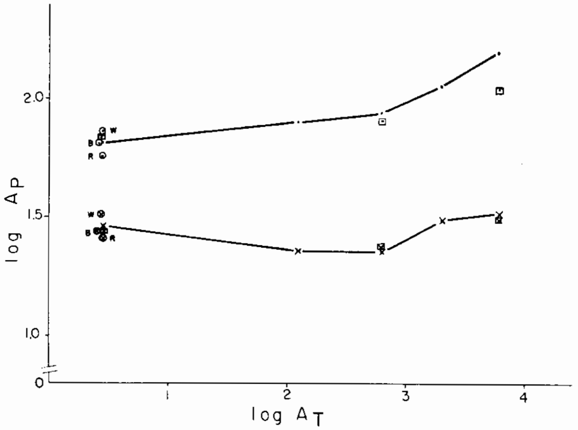

FIG. 2. Mean bivariate dispersion ($\log A_p$) as a function of the logarithm of the area of the fixation target averaged over three luminance levels. The line connects the five data points from Experiment 1 where target size was the within-session variable. Squares enclose points from Experiment 2 where only three target sizes were employed, each at different recording sessions. Circles enclose points from Experiment 3 where red (R), blue (B), and white (W) 1.9′-diam targets were presented 8 dB above a 100% visibility threshold. The crosses are for subject RS; the filled circles, subject MH.

(see Fig. 2 and Table III). The dispersion of subject MH increased monotonically with target size: Her increase was particularly marked with the largest two targets (49.8′- 87.2′-diam). MH also exhibited a great deal less stability with all fixation objects than subject RS, who maintained his eye near its mean position most effectively with 12.5′ and 27.2′-diam targets. The bivariate dispersion of his eye was not much greater with the smallest target than with the largest target ($\Delta \log A_p = 0.06$). No reliable differences in fixation stability were observed for either subject between the red, blue, and white targets in Experiment 3. Both subjects, however, showed least dispersion with the red target and most with the white target. The largest difference (relative to over-all fixation stability observed) was between the red and white targets for subject RS [$\log A_p$ (white)$-\log A_p$ (red)$=0.08$]. Increasing luminance was found to reduce the variability of eye position (see Fig. 3).

TABLE II. Partial summary of the analyses of variance of horizontal (H) and vertical (V) trial mean position.

			Subject MH		Subject RS	
	Source	*df*	*MS*	*F*	*MS*	*F*
Experiment 1						
V	Size	4	64.18	3.28[a]	73.38	8.65[c]
	error	32	19.56		8.48	
H	Size	4	2.08	0.14	36.47	8.12[c]
	error	32	15.23		4.49	
Experiment 2						
V	Luminance	2	3.74	0.92	148.76	19.86[c]
	error	72	4.05		7.49	
H	Luminance	2	26.35	2.14	12.99	4.16[b]
	error	72	12.31		3.12	
Experiment 3						
V	Color	2	21.16	2.92	22.30	3.14
	error	14	7.24		7.11	
H	Color	2	15.40	1.34	44.98	9.63[c]
	error	14	11.51		4.67	

[a] $p < 0.05$.
[b] $p < 0.01$.
[c] $p < 0.001$.

TABLE III. Partial summary of the analyses of variance of bivariate dispersion ($\log A_p$).

		Subject MH		Subject RS	
Source	*df*	*MS*	*F*	*MS*	*F*
Experiment 1					
Size	4	0.656	12.38[c]	0.168	3.50[a]
error	32	0.053		0.048	
Experiment 2					
Luminance	2	0.060	1.36	0.224	5.09[b]
error	72	0.044		0.044	
Experiment 3					
Color	2	0.020	1.05	0.009	0.22
error	14	0.019		0.040	

[a] $p < 0.05$.
[b] $p < 0.01$.
[c] $p < 0.001$.

3.2. Fixation Movements

Neither subject exhibited statistically reliable effects of target size, luminance, or color on drift magnitude in the experiments specifically designed to test the influence of these variables. Saccade frequency, on the other hand, was sensitive to these variables. Both subjects made fewer saccades with the largest target (see Fig. 4 and Table IV). This finding was most

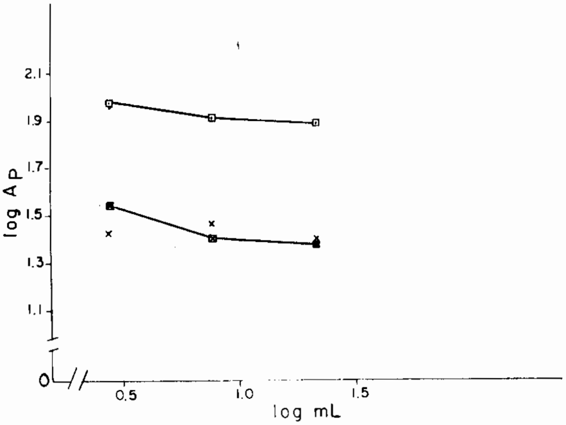

FIG. 3. Mean bivariate dispersion ($\log A_p$) as a function of th luminance of the fixation target (log mL), averaged over thre target sizes (1.9′, 27.9′, and 87.2′ diam). The line connects th data points from Experiment 2 where luminance was the within session variable. Points from Experiment 1 for the same siz targets are also plotted. Experimental luminances were 2.8, 7.8 and 21.5 mL.

TABLE IV. Partial summary of the analyses of variance of saccade frequency (SF).

		Subject MH		Subject RS	
Source	*df*	*MS*	*F*	*MS*	*F*
Experiment 1					
Size	4	107.8	13.47[b]	1631.0	31.81[b]
error	32	8.0		51.3	
Experiment 2					
Luminance	2	24.0	1.76	48.0	0.89
error	72	13.6		53.7	
Experiment 3					
Color	2	8.0	0.44	212.0	4.71[a]
error	14	18.4		45.0	

[a] $p<0.05$.
[b] $p<0.001$.

marked for subject RS who exhibited about half as many saccades with the 87.2′-diam target as with any of the smaller targets. MH, whose over-all saccade rate was much lower than RS (1.3 saccades/sec and 2.0 saccades/sec, respectively), also showed fewest saccades with the largest target.

3.3. Test of the Bivariate-Normal Assumption

The assumption that the measures of horizontal and vertical position of the eye have a bivariate normal distribution was tested with the data from 642 trials (292 for MH and 350 for RS), each providing 10 samples of paired horizontal and vertical position measures. The pairs of observations from each trial were normalized and the goodness of fit to the bivariate normal distribution was determined by means of two χ^2 tests employing 20 and 100 intervals (concentric circles which divide a plane with $P=1$ into either 20 or 100 intervals).

The normalized measures of bivariate position depart significantly ($P<0.001$) from those expected in a bivariate normal distribution for *each* subject in *both* tests. The departures from normality are, however, quite small as is shown in Fig. 5 where the percentage of observed magnitudes of normalized position vectors is plotted as a function of the value of $2k$ (in effect, 24 "slices" through the bivariate normal "hill" or "mound": each "slice" increasing the probability by 0.04). The percentages expected from a bivariate normal distribution (see Sec. 2.4) are also shown (solid line).

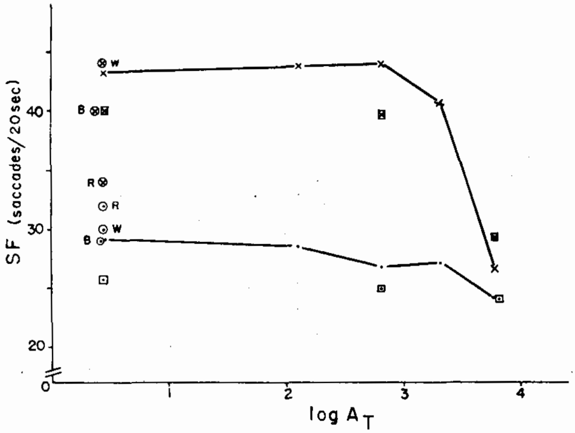

FIG. 4. Mean saccade frequency (SF) as a function of the logarithm of the area of the fixation target ($\log A_T$) averaged over three luminance levels. The significance of the symbols is the same as in Fig. 2.

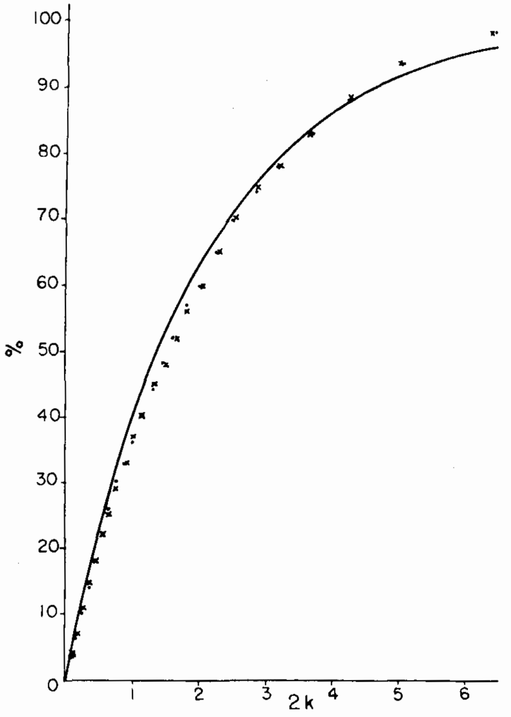

FIG. 5. Cumulative percentage (%) of normalized position vectors of different vector magnitudes ($2k$). Bivariate normal, solid curve. See Sec. 3.3 for an explanation of this graph.

Ellipses defined with $k=1$, the value chosen for calculation in the present experiments, would enclose 63.2% of the observations if the distribution were bivariate normal, whereas in the data obtained from each subject, they enclose about 60% of the observations. The normalized empirical distributions for each subject were also tested and found to have point symmetry.

The fact that both subjects show very similar distributions of eye position despite large individual differences in the effects of stimulus variables suggests that these small departures from normality reflect general, if obscure, features of eye movements. By and large, the area of a bivariate normal ellipse seems to be a good approximation when used to measure the variability of the fixating eye about its mean position.

4. DISCUSSION

4.1. Comparison with Prior Experiments

A few prior contact-lens studies were examined to determine whether observed performance was representative of that usually reported.

The saccade-frequency measure is most readily compared. Saccade rates ranged from 0.7 saccades/sec to 2.3 saccades/sec in four prior studies where subjects fixated small targets (smaller than 5′).[1,2,7,13] Rates for the most similar target condition (1.9′-diam target in Experiment 1) were 2.1 saccades/sec and 1.5 saccades/sec for subject RS and MH, respectively.

Mean 0.2-sec-drift-vector magnitude is more difficult to compare: Nachmias[2] reports *median* 0.2-sec-drift-vector magnitudes of 2.0′ and 1.5′ for his two subjects. Median drift-vector magnitudes were estimated from frequency distributions plotted for the individual drift samples measured in Experiments 1 and 2. The *median* 0.2-sec-drift-vector magnitudes were 1.8′ and 1.3′ for subjects MH and RS, respectively.

A measure of bivariate dispersion of the eye about its mean position has been reported only once before. Nachmias[2] plotted bivariate dispersion for fixation of a small target by one of his subjects which, when converted to $\log A_p$, is 1.77. This value is similar to that (1.81) obtained for subject MH with the smallest target in Experiment 1. Such bivariate dispersion measures can be compared with standard deviations along an average single meridian by assuming $\sigma_H=\sigma_V$ and $\rho=0$ for the bivariate contour ellipse whose probability is 68%. In this case, the standard deviation on a single meridian for the fixation of a small target for subject RS would be approximately 2.2′, for subject MH 4.9′, and for Nachmias' subject 4.7′.

To the extent that direct comparison is possible, the quantitative results of the present experiments agree fairly well with prior investigations except that RS shows more stable fixation than is usually reported.

4.2. Theoretical Implications

No theory is available that can relate in detail fixation performance to the visual-position information provided by the retinal images of stationary fixation objects of different sizes, luminances, or colors. A simple, fixed error-signal system, suggested by Cornsweet,[1] can be evaluated and extended in light of the present observations.

Cornsweet proposed that saccadic correction is triggered and its direction and extent determined by displacement of the retinal image of a small target from some "optimal locus" assumed to be at the center of the fovea. This "optimal locus" is considered to be the origin of the error-signal system that guides corrective eye movements. If such an "optimal locus" were not confined to a very few minutes of arc on a given retina, such a simple, fixed error-signal system would have to be discounted. To illustrate, if the "optimal locus" were not fixed in position on a given retina, the "local sign" from a particular signal element would be required to signal a movement, for example, to the left on one trial and to the right on another, depending upon where the signal element was located relative to the "preferred" fixation position on the particular trial.[14] Such an untidy state of affairs could, in fact, exist but it would require that the system signaling the relative position of the retinal image of a target object be complex in the sense that it would depend on and vary with conditions established at each attempted fixation. If, on the other hand, there is a small invariant "optimal locus" on a given retina which is employed whenever a subject establishes fixation, a simple fixed signal grid can be considered.

It is clear from prior studies that there is a circumscribed preferred fixation locus on a given fixation trial: The standard deviation of a fixating eye is on the order of 5 minutes of arc and "fixation errors" (differences between the trial-mean fixation position and the position of the eye at the end of each saccade) are smaller than 3 minutes of arc. It had not been established, however, that there is only *one* such position, a single "optimal locus" fixed on a given retina. Prior investigators did not examine differences of the mean positions of the eye on various fixation trials. Instead, mean eye positions from relatively few fixation trials were arbitrarily superimposed and attention was confined to detailed examination of a large number of saccadic and drift movements.[1–3]

The present experiments permit a direct examination of the simplifying assumption that the "optimal locus" is both *small* and *invariant* in position on a given retina. The observed differences between mean fixation positions with the various kinds of targets employed were quite small. The largest difference was less than 4′ and in most cases was less than 2′. Such differences in mean fixation position correspond to a displacment of the center of a target image by *at most* 12 cones at the center of the retina and fewer if the "optimal locus" is not, in fact, within the densely packed foveal "bouquet."[15] To a first approximation, the assumption of a single invariant "optimal locus" is supported by the results of the present experiments.

The *size* of the "optimal locus" observed on a large number of independent fixation trials with a variety of target objects can be estimated from the average of the horizontal and vertical mean-position-error variances. The square roots of the observed averaged error variances (analogous to the standard error of trial-mean position on a representative meridian) were 3.5′ and 2.4′ for subjects MH and RS, respectively. If we wish to estimate the average diameter of the "optimal locus" with 87% confidence (3σ), the observed "loci" were smaller

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[13] J. Krauskopf, T. N. Cornsweet, and L. A. Riggs, J. Opt. Soc. Am. **50**, 572 (1960).

[14] "*Local sign*" refers only to a signal which can be used to guide the direction and size of corrective eye movements. Such "*motor* local signs" may be related to other "local signs" which lead to the perceived direction or movement of an object in space relative to the observer. See J. Bruel and G. Albee, Psychol. Rev. **62**, 391 (1955) for a discussion of the possible relationship of eye position and eye movements to the perception of direction and movement.

[15] S. L. Polyak, *The Retina* (The University of Chicago Press, Chicago, 1941).

than 10.5′ and 7.2′ for the two subjects averaged over the three experiments. Such an area is considerably smaller than the reported diameter of the central "bouquet" (20′). Whether the fixation locus lies in the central bouquet cannot be determined simply by recording eye movements.

These estimates of the size of the "optimal locus" must be considered as upper bounds. The true "optimal locus" must be smaller. A few obvious sources of variance were removed but a larger number of replications and more efficient experimental designs would yield smaller values.

The present results make it *plausible* to maintain that the direction and size of corrective movements (initiated by unspecified processes) are signaled by the stimulation of retinal elements whose distance and direction "local signs" are fixed relative to an "optimal locus" which serves as the origin of a fixed error-signal coordinate system. The "optimal locus" is (1) both small and invariant and (2) "local signs" of symmetrically placed signal elements are equal in magnitude and opposite in sign. If these assumptions are true, the mean position of the eye should be invariant with target size, luminance, and color. The variability of the eye about this position might be greater (1) as the edges of larger targets fall on more peripheral parts of the retina where the signal elements are more widely spaced or (2) with targets at lower luminance levels whose edges are less likely to provide effective stimulation to the signal elements (the functional density of signal elements might be greater with more luminous targets).

In this simple fixed error-signal system, the control of eye position can be summarized as follows:

1. *Small targets*. When a corrective movement occurs, its direction and size are the result of the "local sign" of the particular signal element that is stimulated by the retinal image of the fixation object. If the image is in the "optimal locus," the error signal will be zero, and movements that occur are "noncorrective." If the image is elsewhere, the "local sign" of the element stimulated will guide a movement that will tend to re-establish the position of the retinal image of the target object at the "optimal locus."

2. *Large targets*. When a corrective movement occurs, its error signal is the resultant of the direction and distance "local signs" of all the signal elements stimulated by the edges of the target. If the "optimal locus" is at the true center of a symmetrical target, the resulting error signal is zero: At all other positions or with asymmetrical targets, the signal is such as to reduce the differences among the various error signals. Relatively large targets completely in the periphery are functionally the same as small targets, inasmuch as all stimulated elements signal a movement in the same direction.

In conclusion, there seems to be no doubt that the size, luminance, and color of the fixation object influence the maintenance of monocular fixation. The effects are complex, subject to large individual differences, and in many instances small even though the stimuli (at least with respect to size and color) were varied over a relatively large range of values. Saccade frequency, bivariate dispersion, and mean position have been more sensitive to experimental manipulation than drift magnitude. In most instances the separation of these stimulus effects required the use of analysis-of-variance designs which permit the removal of variance from extraneous sources. Such designs imposed a number of statistical restrictions (particularly independence) that led to the use of summary measures drawn from a relatively large number of 30-sec fixation trials as the unit of analysis. Observations made under these restrictions, which differ rather markedly from those usually employed in eye-movement research, are in good agreement with data previously obtained.

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