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Normal fixation of eccentric targets*

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Two-dimensional eye movements were recorded by a contact-lens optical lever while two experienced subjects attempted to maintain fixation at the center of a 1°.3-diam disk, at the center of two- and four-disk arrays separated by 10°.0 to 29°.5, or to maintain the same eye position after the disk was removed from view. Fixation stability was better with the foveal disk than when the target was presented in the near periphery. Fixation stability deteriorated slowly as target separation increased, but fixation stability with the most peripheral target was better than that with no target at all. This deterioration of fixation stability was associated with increases of the size of both saccades and intersaccadic drifts, but the frequency of saccades was not influenced systematically.

Index Heading: Vision.

Fixation stability remains much the same when the fixation target generates a visual error signal anywhere in the fovea.[1,2] The fluctuations of the line of sight increase markedly, however, when the visual error signal is removed and subjects are required to maintain eye position in complete darkness.[3] We know nothing about fixation stability or the eye-movement pattern when the visual error signal is generated in the peripheral retina. The present experiments begin to fill this gap.

METHOD

The contact-lens optical-lever technique was used to record two-dimensional eye movements on 35-mm infrared film moving at 1 cm/s in a modified Grass model C4H camera. The technique, described before, records small rotations of the eye, free from confusion with translations of the head or torsions of the eyeball.[1] The optical-lever length and projection film reader used for these experiments permitted eye position to be measured to about 10 s of arc.

Conditions

Subjects, in an otherwise dark room, were asked to fixate for 30 s. During the first 10 s, they fixated the center of a homogeneous 1°.3-diam disk of white light (74 mL), after which the disk (i) remained for 20 s more, or (ii) was replaced by four similar disks (a horizontal and a vertical pair) whose centers were separated by 10°.0, 21°.8, or 29°.5, or (iii) was replaced by a horizontal or vertical pair of disks separated 21°.8, or (iv) was replaced by complete darkness. Subjects attempted to maintain fixation at the position originally defined by the center of the 1°.3 disk before the stimulus display was changed. The disks were 0.57 m from the right eye and the center of the array was located 4°.3 to the left of each subject's primary position, so as not to block the view of the largest stimulus display by components of the recording system. The left eye was closed and covered. The single disk (fixated for 10 s at the beginning of each 30-s trial) was located at the center of the array that came into view when the centered disk was switched off. The experiment was run in blocks of seven trials. Each block consisted of a single record made with each of the six target arrays and a single record made when no target, whatsoever, was visible during the final 20-s period. The order of stimulus conditions was randomized within blocks.

Measures

Thirty-five records were made for each subject (five for each target condition) and measured as follows: Paired horizontal and vertical eye positions were measured at randomly sampled times within successive 0.5-s intervals in the last 8 s of the final 20-s portion of the trial, during which time the subject attempted to maintain his line of sight in the original orientation with the help of the same disk, or with one of the eccentric-disk target arrays, or in complete darkness. Only the last 8 s of the trial were measured in order to allow the eye to reach steady-state performance with each of the targets. All saccades during this portion of each trial were also measured so that the size of saccades and the size of intersaccadic drifts could be calculated.

Subjects

Two of us (AS and RS) participated in these experiments. Both had considerable prior experience fixating a variety of visible targets, and also in keeping the eye in place in complete darkness.

RESULTS

Two inverse measures of fixation stability are reported: the standard deviation of eye positions on the horizontal and vertical meridians, and an analogous two-dimensional measure that circumvents difficulties of interpretation encountered when only such arbitrarily selected meridians are analyzed. This two-dimensional measure is the area of the bivariate contour ellipse (BA) expressed in (minutes of arc)^2 of the solid angle subtended at the eye by an ellipse projected on a plane parallel to Listing's plane. The area of the bivariate contour ellipse as applied to the dispersion of the eye about its mean position can be visualized by considering the position of the image of the center of the target array on the retina. The bivariate contour ellipse as calculated in the present experiments would enclose that portion of the retinal surface where the image of the target center would be found 68.3% of the time (see Ref. 1 for a description of this measure and tests of the assumptions underlying its use). Fixation stability is summarized in Table I.

Both subjects showed better fixation stability with any of the visible targets than they showed in complete darkness. *BA* increased systematically as the four-disk arrays fell on more-peripheral portions of the retina. The four-disk array was not necessarily more effective than a pair of disks of the same angular separation, but whether the horizontal or vertical pair was more effective depend on the subject. Similar characteristics were shown by Rattle's[2] subjects when they attempted to fixate at the imagined center of a pair of small dots separated 230 min arc on either the horizontal or vertical meridian.

The effect of varying the eccentricity of the four-disk array on fixation stability is shown graphically in Fig. 1, where log bivariate area is plotted as a function of target eccentricity η.[4] For the single-disk target, η is the radius of the disk. For the multiple-disk arrays, η is the distance from the center of the 1°.3-diam disk to the center of the other disks. The logarithm of the bivariate area was used, to eliminate the influence of the arbitrary confidence limit selected for calculation of two-dimensional fixation stability in the present experiment on the shape of this function, which describes the effectiveness of targets at different retinal positions in guiding oculomotor control (see Ref. 1 for a justification of the log transform).

The relative fluctuation of the line of sight was less (0.5–0.8 log of ratios) when subjects fixated near the center of the 1°.3-diam disk (whose image is located entirely within the fovea) than when they attempted to maintain the line of sight by reference to four disks that were imaged on the near periphery. Three-times-greater eccentricity in the periphery had a smaller relative influence on fixation stability (0.3–0.5 log of ratios). Complete removal of visual input led to a further increase of the relative fluctuation of the line of sight (0.4–0.5 log of ratios). These results are shown in Fig. 1.

TABLE I. Inverse fixation stability of subjects AS and RS summarized as bivariate-contour-ellipse areas (*BA*) and standard deviations on the horizontal (*H*) and vertical (*V*) meridians during fixation of seven target arrays.

	AS			RS		
Target array	*H*	*V*	*BA*	*H*	*V*	*BA*
Centered 1°.3-diam disk	3.5	7.4	174	3.4	7.5	182
H & *V* disks, separated 10°.0	13.5	11.3	1087	8.0	13.8	788
H & *V* disks, separated 21°.8	11.2	14.8	1142	11.7	17.2	1332
H & *V* disks, separated 29°.5	16.1	19.5	2060	15.2	23.6	2406
H disks, separated 21°.8	34.4	19.6	3601	14.4	16.7	1676
V disks, separated 21°.8	9.8	12.1	851	12.6	23.7	2134
Complete darkness	30.5	26.1	5591	41.3	28.9	8262

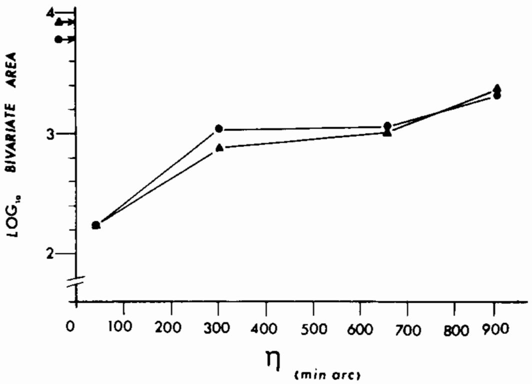

FIG. 1. Inverse fixation stability (log bivariate area) as a function of the eccentricity (η) of the target generating the visual error signal. Subject AS's stability is shown by the circles; RS's stability by the triangles. The arrows on the ordinate indicate each subject in complete darkness when no visual error signal was available.

Eye-Movement Pattern

The target array influenced the fixation eye-movement pattern, as can be seen in Table II. Saccade rates were influenced least and not systematically by the type of target (AS and RS range = 0.7 saccades/s) and were similar to saccade rates observed for these subjects during fixation of (i) small stationary points and disks of light,[1,5] (ii) a small point moving at constant velocity,[6] and (iii) an upper-case letter *T*, and also during normal reading.[7] The values obtained in the present experiment were also similar to saccade rates shown by 30 other contact-lens subjects in 14 experiments compiled by Ditchburn and Foley–Fisher.[8] In the Ditchburn and Foley–Fisher compilation, subjects fixated targets whose critical features were generally much smaller than 10 minutes of arc and the median of median saccade rate was 1.7 saccades/s with 50% of all subjects lying in the range of 1.4–3.3 saccades/s. Saccade rates in the present experiment also fell within this range under all conditions, suggesting that saccades occur 1 to 4 times per second regardless of the target.

The target array was more important to other characteristics of the fixation eye-movement pattern, however, as can be seen in the effect of the target on the size of saccades and the size of intersaccadic drifts (the change of eye position from the end of one saccade to the beginning of the next saccade). Saccade vector magnitudes shown by RS and AS, when they fixated near the center of the 1°.3-diam disk, were slightly

TABLE II. Mean saccade vector (*SM*) and mean intersaccadic-drift vector (*DM*) magnitudes in minutes of arc. Subjects AS and RS during fixation of seven target arrays. Saccade rate (saccades/s) (*SR*) and the number of saccades (*N*) that provided the basis for these measures are also shown. Standard deviations are given in parentheses.

			AS				RS	
Target array	*N*	*SR*	*SM*	*DM*	*N*	*SR*	*SM*	*DM*
Centered 1°.3-diam disk	85	2.1	8.9 (7.0)	6.4 (7.4)	99	2.5	7.7 (7.6)	4.8 (6.2)
H & *V* disks, separated 10°.0	58	1.4	9.7 (5.3)	8.5 (7.6)	95	2.3	14.4 (9.4)	8.7 (9.2)
H & *V* disks, separated 21°.8	78	1.9	16.2 (11.6)	9.9 (9.9)	98	2.4	18.6 (13.0)	16.6 (14.4)
H & *V* disks, separated 29°.5	73	1.8	17.5 (7.0)	9.5 (7.3)	91	2.2	24.2 (10.4)	13.2 (7.7)
H disks, separated 21°.8	86	2.1	19.9 (13.3)	10.9 (8.5)	101	2.5	21.2 (13.6)	11.2 (12.0)
V disks, separated 21°.8	76	1.9	15.8 (7.4)	8.2 (6.1)	101	2.5	19.7 (11.8)	10.8 (9.0)
Complete darkness	80	2.0	32.4 (19.2)	26.9 (18.7)	73	1.8	39.6 (17.2)	29.8 (18.7)

larger than the median of mean saccade vector magnitude (6.5 minutes of arc) reported by Ditchburn and Foley–Fisher[8] in experiments with much smaller targets. Both of our subjects made larger saccades when they tried to fixate near the center of four-disk arrays falling in the periphery. The effect of moving the target into the periphery, and of increasing eccentricity in the periphery, was more marked for subject RS, whose saccades almost doubled in size when the target moved to the nearest peripheral position. RS's saccade vector magnitude almost doubled again when the four-disk array was moved to the furthest peripheral position, and almost doubled once again between the most peripheral position and complete darkness. AS also showed a systematic increase of saccade vector magnitude with target eccentricity; in his case, however, the change from the foveal to nearest peripheral target had only a modest effect on saccade size. His saccades almost doubled in size across the region studied in the periphery, and, like RS, almost doubled once again between the most peripheral position and complete darkness. Saccade vector magnitudes, unlike fixation stability, were not affected when a pair of disks was substituted for the four-disk array at the same eccentricity. The difference of fixation stability observed when the target was changed from four disks to a pair is most likely to have resulted from reduced correctiveness of saccades in this stimulus condition, because saccades were not only about the same size with two as with four disks but they occurred as frequently.

Mean intersaccadic drift magnitude, like saccade vector magnitude, was larger with peripheral targets than with the foveal disk and larger still in complete darkness. Intersaccadic drifts in the dark were 2.5 to 6 times as large as intersaccadic drifts with visible targets. These large intersaccadic drifts that occur when subjects fixate in complete darkness have been shown to result from the loss of the corrective drift component when visual stimulation is not provided.[3]

In summary, (i) both saccades and intersaccadic drifts became larger when the target was moved from the fovea into and across the periphery. This change of the pattern of eye movements was accompanied by 0.8–1.3 log-ratio reductions of fixation stability. (ii) Saccades and intersaccadic drifts signalled by stimulation falling 40 minutes of arc from the line of sight were not much larger than saccades and intersaccadic drifts measured in numerous prior experiments in which the fixation targets were smaller than 5 minutes of arc. (iii) Saccade rate was not influenced markedly or systematically by any of the stimulus conditions, suggesting that saccades were not initiated by a retinal reflex, although their size and accuracy may have depended on the quality of the visual or proprioceptive signal that made the subject aware of the direction in which he was looking.[9]

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