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Analysis of Eye Movements during Monocular and Binocular Fixation*

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(Received December 1, 1959)

Recordings of the horizontal component of movements of the eyes were made during monocular and binocular fixation. The variation in the vergence of the eyes over time was found to be of the same order of magnitude as the variation in position of the individual eyes, even though the lateral positions of the two eyes are somewhat correlated. The drift and tremor of the two eyes are not correlated; the over-all correlation is due to the saccadic movements. Saccades in one eye seem to be always accompanied by simultaneous saccades in the other eye which are almost always in the same direction and about the same in size. The maintenance of binocular fixation does not seem to be dependent on a direct response to or sensing of vergence error. Rather, it appears to be dependent on the saccadic responses of the two eyes to their own fixation errors.

INTRODUCTION

THE development of high-resolution techniques of recording eye movements has led to considerable research on the nature of the eye movements which occur while a subject is fixating. Measurements of such movements have been studied in relation to visual acuity and other visual functions and to the mechanisms controlling the occurrence of eye movements. Most of this work has been done under conditions of monocular fixation. Measurements of the motions of the eyes during binocular fixation by Riggs and Ratliff showed that, while there was a considerable tendency for the eyes to maintain convergence during fixation, variations in vergence did occur.¹ Extensive quantitative measurements of changes in convergence were not made at that time. The present experiments had a dual purpose: to obtain a quantitative description of

the relative positions of the two eyes during continuous binocular fixation, and to get information relevant to the mechanisms responsible for the maintenance of binocular fixation. Measurements were made under conditions of monocular as well as binocular fixation in order to relate the results under binocular fixation to previous quantitative work.

METHOD

The principle of recording is illustrated in Fig. 1. The subject fixated on a bright point (F). He wore a contact lens corrected for the viewing distance used throughout these experiments (55 cm). A plane mirror was imbedded in the surface of the contact lens. Rays of light from a projector were reflected from this mirror to a vertical straightedge (E), where they formed an image of a uniformly illuminated bright rectangle (I). The rays getting past the straightedge fell on a photocell (P). The photocell drove the direct-coupled vertical deflection amplifier of a cathode ray oscilloscope. Eye movements caused the contact lens mirror to rotate, moving the rectangular image with respect to the straightedge. Any horizontal components of the eye movements caused the image to move perpendicular to the straightedge, consequently causing the amount of light on the photocell to change. These changes and, therefore, the horizontal components of the eye movements, were represented by deflections of the spot on the CRT. Two such systems were employed, one for each eye. Continuous photographic records of the movements of the spots on both oscilloscopes were made with a Grass oscilloscope camera. The images of the two CRT screens were superimposed by means of a beam splitter, so that they could be recorded simultaneously. One of the traces was dotted for identification by applying pulses to the "Z" axis of one of the scopes. The records were calibrated by measuring the spot

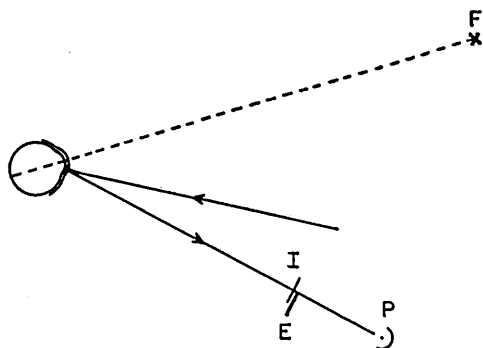


FIG. 1. Schematic diagram of the apparatus.

* This research was conducted in the Laboratories of the Psychology Department of Brown University, under a contract between Brown University and the Office of Naval Research, Department of the Navy.

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¹ L. A. Riggs and F. Ratliff, *Science* 114, 17 (1951).

deflection produced when the straightedges were moved with known displacements.

Recordings were made under two conditions of binocular fixation: near convergence (55 cm) and zero convergence (infinity); the fixation point was always at a distance of 55 cm. The data for each condition were obtained in four sessions of five minutes each, making a total of twenty minutes of fixation for each subject under each condition.

A sample record is given in Fig. 2. The upper trace represents the movements of the left eye, the lower, that of the right eye. The vertical lines above and below the records designate 5' angular rotations for the left and right eyes, respectively. The horizontal line designates a time interval of 0.1 sec. In addition to the three types of eye movements observed in monocular records—fine tremor, slow drifts, and saccades—variations in convergence are evident.

SUBJECTS

Two subjects were used. One was exophoric while the other had normal muscle balance. Both had normal fusion and stereoscopic acuity.

RESULTS

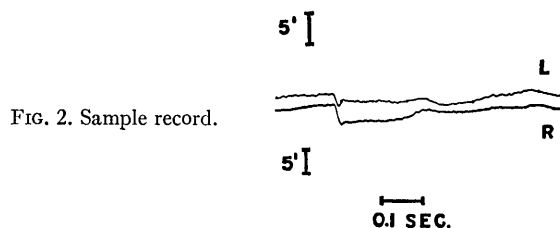
Analysis of Positions of Eyes

The records were first analyzed in terms of the variation of the positions of the two eyes during fixation. For this purpose the photographic records for each of the 5-min sessions were broken down into 1-min segments. Samples of the positions of the eyes were taken at arbitrary instants during these periods. Specifically, a measurement of the position of each eye was made once every two seconds of the record, making a total of 30 readings per min. Mean positions were computed and the data expressed in terms of deviations from the means. From these data the standard deviations of position of each eye for each minute were computed. The standard deviations of the differences in position were also computed. The "differences" standard deviation measures the variability of convergence. Median standard deviations in minutes

TABLE I. Median standard deviations of position of the eyes during binocular and monocular fixation (in min of arc). Twenty samples, 30 readings per sample. Sample durations 60 sec, 2 sec (last line).

Fixation condition	Subject	Separate eyes		Both eyes convergence
		Left	Right	
Binocular (near)	JK	1.46	1.98	1.87
	LAR	1.78	2.64	2.45
Binocular (far)	JK	2.32	2.06	2.04
	LAR	2.05	1.72	2.20
Monocular	JK	1.64	2.13	...
	LAR	1.77	2.04	...
Binocular (far)	LAR	[1.20]	[1.20]	[1.29]

[] sample duration = 2 sec



of arc for twenty minutes of fixation are presented in Table I. These results bear on the theory of stereoscopic acuity. Of particular significance here is the fact that the standard deviation of convergence is more than 2 min of arc while stereoscopic acuities of the order of 2 sec of arc have been reliably obtained.

Typical exposure times in stereoscopic acuity experiments are much shorter than 1 min. It may be that in these situations control of convergence is more precise than in the longer periods just discussed. In order to examine this question, twenty 2-sec intervals chosen at random from the 20 minutes of record obtained with LAR as subject under the binocular far-fixation condition were analyzed. Thirty readings of the positions of each eye were taken as before within each of these intervals. The median standard deviations in minutes of arc are given in the last line of Table I. It is evident that even for sample durations as short as 2 sec, variation of vergence is large compared to minimum angles of stereoscopic resolution. Even in the case of the 2-sec sample showing the smallest variation in convergence, the standard deviation was 0.51' of arc.

The data from the 2-sec samples were used to test the hypothesis that the drift movements in the two eyes are correlated. In order to do this, it was necessary to select sections of the record in which no saccades occurred. There were seven such samples, for which the N varied from 17–23. The correlations for the saccade-free sections of these samples were: -0.46 , -0.22 , -0.03 , 0.09 , 0.26 , and 0.63 . Considering all correlations together, there is no significant relationship. From these data we can conclude that except for the normal chance variation, the drift movements of the two eyes are uncorrelated. For the 1-min samples, the positions of the eyes are correlated (Table II). These data include the effects of the saccades. Thus it would seem that the main source of the correlation is the saccades.

Saccadic Movements

The previous discussion has emphasized the lack of perfect correspondence between the positions of the

TABLE II. Correlations of positions of eyes. Medians of 20 samples—30 readings/sample Pearson r 's

Subject	Fixation condition			
	Binocular (near)		Binocular (far)	
	JK	LAR	JK	LAR
r_{LR}	0.53	0.33	0.52	0.34

two eyes during binocular fixation. However, reasonably good binocular correspondence is maintained even during prolonged fixation. It would be of interest to determine the characteristics of the mechanism involved in maintaining this correspondence.

Two sorts of mechanisms might operate in this way. The first would sense any lack of correspondence, and then trigger a movement in each of the eyes such that their net result is better correspondence. For example, the mechanism might sense that the eyes are too divergent, and therefore trigger a movement in either one or both eyes, such that the eyes converge. The second type of mechanism might operate on each eye independently of the other. It has been shown that, during monocular fixation, the eye tends to drift in a manner not determined by eye position. The result of the drifts is to get the eyes "off-target"; the saccadic movements, which are related to eye position in an orderly way, tend to return it to its "on-target" position. If, during binocular fixation, the same mechanism operated in each of the eyes (two independent mechanisms), binocular correspondence could also be maintained. A number of modifications of these two types of mechanisms might operate as well. We have analyzed binocular eye movement records in an attempt to discriminate between some of these possible mechanisms.

RESULTS

The most striking characteristic of our eye movement records is the synchrony of saccades in the two eyes.

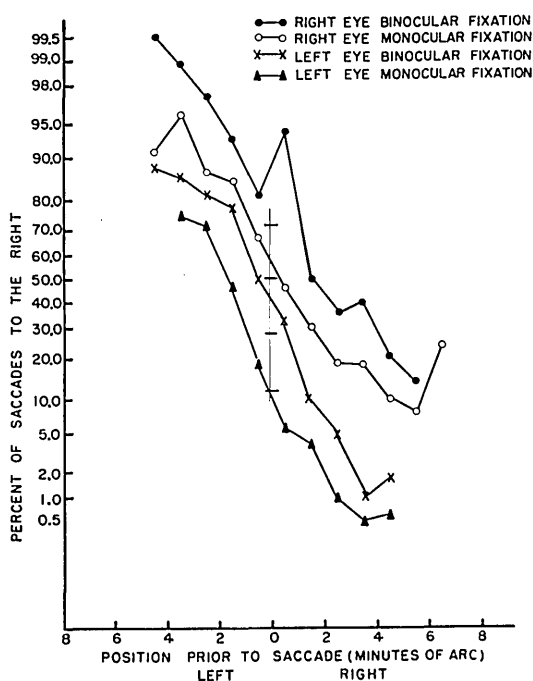


FIG. 3. Direction of saccades as a function of the position of the eyes before saccades. The ordinate is correct only for the case of right-eye monocular fixation. For the other conditions the ordinate is displaced up or down; the short horizontal lines indicate the 50% level for each curve.

TABLE III. Correspondence of direction of saccades in the two eyes for saccades greater than 1' in amplitude.

	Fixation condition			
	Binocular (near)		Binocular (far)	
Subject	JK	LAR	JK	LAR
Number of saccades in same direction	1016	966	722	1285
Total number of saccades	1023	1009	739	1299
Percentage of saccades in same direction	99.3	95.7	97.7	98.9

Examination of records obtained during 80 min of binocular fixation failed to reveal one unequivocal case of a saccade in one eye unaccompanied by a saccade in the other. When high-speed recordings were examined, the onsets of the saccade pairs were found to be simultaneous within measurable limits.²

This essentially perfect synchrony between pairs of saccades indicates clearly that convergence is not maintained by two completely independent systems, one for each eye. However, many different forms of interaction systems are possible. Therefore, a detailed analysis of the saccades was undertaken. For this purpose, the initial and final positions of the eyes were measured for each saccade. From this analysis it was clear not only that the saccades are synchronized in the two eyes, but that these synchronized pairs of saccades are almost always in the same direction. If saccades smaller than one minute of arc are eliminated,³ approximately 98% of the saccade pairs are in the same direction in the two eyes (Table III). Very seldom does a synchronous pair of saccades appear to be divergent or convergent. However, a pair of saccades in the same direction will result in a change in vergence if their amplitudes are different. For example, suppose that, before a pair of saccades, the eyes are too converged, and that the saccade pair is to the left in both eyes. If the left eye shows a greater amplitude of saccade, then the eyes will be less convergent after the saccades. In this case, it could be said that the saccade pair corrected the vergence error.

The relationship between the saccades in the two eyes can be expressed in terms of the correlation between their directed magnitudes. These correlations (Table IV) range from 0.76 to 0.91. These high correlations mean that the saccadic movements of the two eyes are not under independent control.

During monocular fixation, slow movements tend to move the eye away from its mean position and

² Because the eyes necessarily change position continuously rather than abruptly from zero to saccadic velocities, no advantage is gained in using very high film speeds. The limit of temporal resolution of the onset of saccades is about 0.01 sec.

³ Overshoot and oscillation often follow saccadic movements. It is also possible that what were considered small saccades might better have been classified as large tremor movements. For these reasons, it is probably meaningless to try to determine the direction of the small "saccades."

TABLE IV. Correlation of directed magnitudes of saccades.

Subject	Fixation condition			
	Binocular (near)		Binocular (far)	
	JK	LAR	JK	LAR
<i>r</i>	0.91	0.76	0.90	0.87

saccades tend to return the eye to that on-target position. Cornsweet performed a number of tests of the hypothesis that in the monocular case drifts and saccades are under visual control.⁴ No evidence was found for such control for the drifts. In the same series of experiments it was found that the probability of occurrence, magnitude, and direction of the saccades are related to the position of the eye preceding the saccade, and thus that the saccades are under visual control.

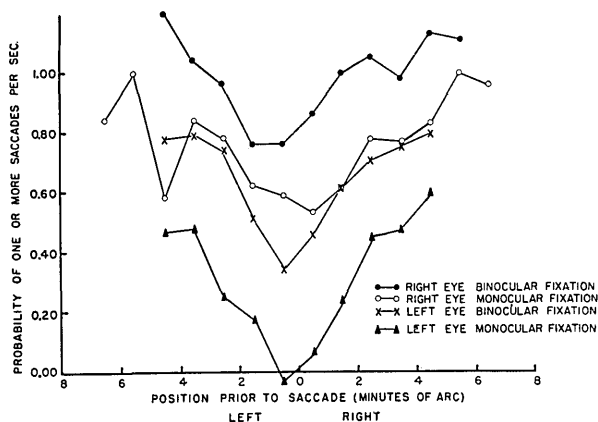


FIG. 4. Probability of occurrence of one or more saccades per sec as a function of position of the eyes before saccades. The ordinate is correct only for the case of the right-eye monocular fixation. The other curves are displaced by +0.20, -0.20, and -0.40 from top to bottom, respectively.

Similar tests for visual control of saccadic movements were performed on the present data. The results of this analysis are shown in Figs. 3 to 8. In order to simplify presentation, the graphs only summarize the results for one subject (JK) under monocular, and under "near" binocular fixation conditions. There were no consistent differences between the "near" and "far" binocular results for either subject. There were some differences between subjects which will be discussed. Since LAR is exophoric and since the main discrepancies between the two subjects were found under conditions of binocular fixation, it may be proper to consider JK's results as the more representative.

Figures 3, 4, and 5 show the relations between the position of the eyes before saccades and the direction of saccades (Fig. 3), the probability of occurrence of saccades (Fig. 4), and the absolute magnitude of

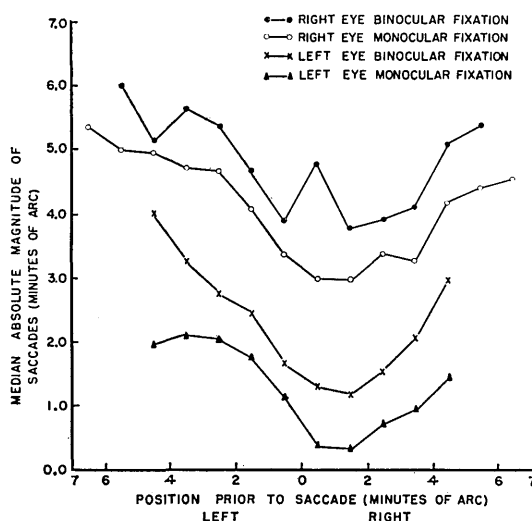


FIG. 5. Median absolute magnitude of saccades as a function of position of the eyes before saccades. The ordinate is correct only for the case of the left-eye binocular fixation. The other curves are displaced by +2.0, +1.0, and -1.0 from top to bottom, respectively.

saccades (Fig. 5) under conditions of monocular and binocular fixation. The results with monocular fixation serve to corroborate the findings reported by Cornsweet.² Figure 3 shows that when the eyes are off-target, the individual eyes tend to saccade toward the on-target position. Figure 4 shows that the probability of one or more saccades in any given second of time increases with increased deviation of the eye from the on-target position. Figures 5 shows that the absolute magnitude of the saccades increases with increased deviation of the eye from the on-target position. The results obtained with LAR under monocular conditions are in essential agreement with those presented here.

The curves for the individual eyes under the "near" binocular fixation conditions (Figs. 3, 4, and 5) are generally similar to those obtained under monocular fixation. Here there are some discrepancies between the two subjects. While for JK the slopes of the direction of saccades curves (Fig. 3) are the same for monocular and binocular fixation, those for LAR are somewhat steeper for monocular fixation. The absolute magnitude

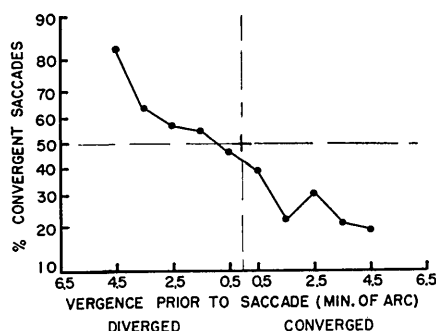


FIG. 6. Direction of the vergence component of the saccades as a function of the vergence before saccades.

⁴ T. N. Cornsweet, *J. Opt. Soc. Am.* 46, 987 (1956).

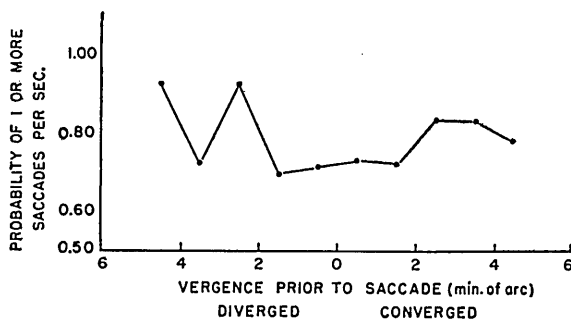


FIG. 7. Probability of occurrence of one or more saccades per sec as a function of the vergence of the eyes before saccades.

and probability of occurrence curves for LAR all show a dependence on eye position, but the function is not always U-shaped, the left wing of the curves being considerably more prominent than the right in some cases.

It might be expected that, as a result of eye dominance, the functions for one of the eyes might be better "tuned" (steeper) than those of the other, under binocular fixation. No evidence for this notion was found in the curves, although both subjects were right-eye dominant.

The dependence of the vergence component of the saccades on the vergence of the eyes immediately preceding the saccades is illustrated in Figs. 6, 7, and 8. Again the curves are for JK under the "near" binocular fixation condition. Figure 6 shows that the direction of the vergence component of the saccades is a function of the vergence before the saccades. This dependence was found for both subjects under both "near" and "far" binocular fixation conditions. The curve presented (and those not presented) shows much poorer tuning than the corresponding curves for the individual eyes in Fig. 3.

The dependence of the probability of occurrence of saccades on the vergence immediately prior to the saccade is illustrated for subject JK under the "near" binocular fixation in Fig. 7. This curve is essentially flat. The corresponding curve for JK under the "far" binocular fixation condition is also flat. The curves for

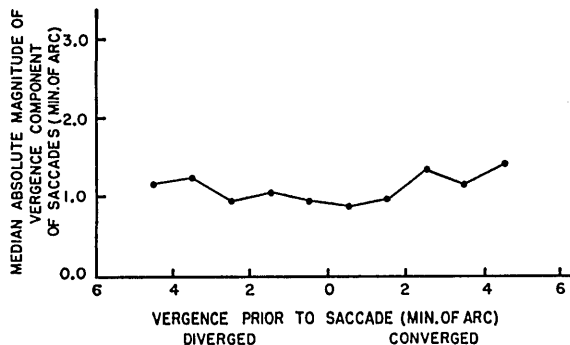


FIG. 8. Median absolute magnitude of vergence component of saccades as a function of the vergence of the eyes before saccades.

TABLE V. Correlation of directed magnitude of saccades and eye position prior to saccade.

Fixation condition	Subject	Left eye	Right eye	Vergence
Binocular (near)	JK	0.69	0.66	0.33
	LAR	0.51	0.41	0.12
Binocular (far)	JK	0.67	0.69	0.16
	LAR	0.53	0.51	0.16
Monocular	JK	0.70	0.66	...
	LAR	0.73	0.78	...

LAR under both "near" and "far" fixation conditions do show a dependence of probability of occurrence of saccades on vergence, the probability being greater when the eyes are more converged.

The dependence of the absolute magnitude of the saccades is illustrated in Fig. 8. The curve again is for JK under the "near" condition. Absolute magnitude shows little or no dependence on the vergence before the saccade. The other curves for both observers show a similar lack of dependence.

The dependence of the saccades on prior eye position was examined in another way. The correlation coefficients between directed magnitude of the saccades and eye position prior to the saccades were computed. These correlations are shown in Table V. Each of these correlations is statistically significant. The graphical analysis indicates the detailed relationship between certain properties of the saccades and eye position; the correlation coefficients provide an over-all numerical index. The two modes of analysis in general show the same main trends. For example, all of the correlations are positive which, in accordance with the sign convention used in the analysis, indicates that the saccades tend to return the eyes to the mean position.

The correlations of amplitude of saccade with eye position prior to saccade range from 0.41 to 0.78. The correlations for JK are remarkably constant, ranging from 0.66 to 0.70. They show no reduction under binocular fixation as compared to monocular fixation. There is no indication that the dominant eye differs from the other under binocular fixation.⁵

The correlations for vergence component, though all significantly larger than 0.00, are much smaller than those for the individual eyes. The correlation coefficient for JK under "near" fixation is larger than the other vergence component correlations.

The frequencies of occurrence of saccades under the various fixation conditions are summarized in Table VI. In seven of the eight comparisons more saccades were found to occur under binocular fixation than under monocular fixation. Six of the seven differences were

⁵ Some differences were found between the two subjects with regard to the correlation coefficients. The correlations for LAR are slightly higher than those for JK under monocular fixation conditions. Only the right-eye difference is statistically significant. The correlations for LAR's left and right eyes are lower for binocular fixation than under monocular fixation. They are also lower than those for JK. The right eye correlation is lower than that for the left under "near" binocular fixation for LAR.

TABLE VI. Saccade frequencies.

	JK		LAR	
	L	R	L	R
Binocular (near)	1758	1758	1568	1568
Monocular	1174	1625	1218	1067
Difference	584 ^a	133	350 ^a	501 ^a
Binocular (far)	1475	1475	1728	1728
Monocular	1174	1625	1218	1067
Difference	301 ^b	-150	510 ^a	661 ^a

^a 0.002 > *P*.^b 0.05 > *P* > 0.002.

statistically significant. The one difference in the other direction was not statistically significant.

The median absolute magnitudes of the saccades under the various fixation conditions for the two subjects are given in Table VII. In seven out of eight of the comparisons, the saccades were larger under monocular fixation. All of these differences were statistically significant including the one in the opposite direction.

DISCUSSION

Control of Fixation

It was pointed out earlier that monocular fixation is maintained by saccades, which correct for the slow random movements of the eye. The simple hypothesis that the two eyes operate independently to maintain their own fixation under binocular conditions has been shown to be false, for the saccades in the two eyes are correlated. It does seem possible, however, to account for the maintenance of binocular fixation in terms of a model in which the slow movements produce the errors in fixation and the saccades correct for the errors if the correlation of the saccades in the two eyes is taken into account.

Before indicating the nature of this model, the role of the other types of eye movements should be discussed. The fine tremor movements are quite small compared to the other movements and are, therefore, not important in this regard. The large slow movements or drifts have not been directly analyzed in the present

TABLE VII. Median absolute magnitudes of saccades (in min of arc).

Subject	JK		LAR	
	Left eye	Right eye	Left eye	Right eye
Binocular (near)	1.55	1.98	1.60	2.78
Binocular (far)	2.16	2.08	2.33	2.50
Monocular	1.79	2.66	2.51	3.96
Differences				
Monocular-binocular (near)	0.24 ^a	0.68 ^a	0.91 ^a	1.18 ^a
Monocular-binocular (far)	-0.37 ^a	0.58 ^a	0.18 ^b	1.46 ^a

^a 0.001 > *P*.^b 0.02 > *P* > 0.001.

work. Cornsweet has shown that the drifts are not related to eye position in either rate or direction under conditions of monocular fixation. On the other hand, Alpern and Ellen have reported smooth convergent movements of an occluded eye with changes in accommodation of the other eye.⁶ Westheimer and Mitchell found that the response to changes in stereoscopic stimuli included not only conjugate saccadic movements but also smooth convergent movements.⁷ Their experimental situations differ from ours in that the fixation objects were changed. Our data reveal that with constant fixation targets, the saccades of the two eyes are related to the position of the individual eyes at the time of occurrence of the saccade. This is true for binocular fixation as well as for monocular fixation. The saccades correct for the other forms of eye movements.

Our records show that the saccades always occur simultaneously in the two eyes, that they are almost always conjugate, and that their magnitudes are highly correlated. These facts imply that a central coupling mechanism must be included in any model proposed to account for the maintenance of binocular fixation. On the other hand Figs. 3, 4, and 5 show that the dependences of saccade occurrence, direction and magnitude upon eye position are not attenuated during binocular fixation. These facts can be incorporated into a model for the maintenance of binocular fixation which does not require that the eyes respond directly to vergence errors.

According to this model the monocular response functions (Figs. 3, 4, and 5) determine the occurrence, magnitude, and direction of the saccades for each eye during binocular fixation as well as during monocular fixation. In addition to this response of the separate eyes to their deviations from the on-target position, there is a central mechanism such that when a saccade is triggered in one eye as a response to its deviation from the on-target position, the other eye will show in general a smaller saccade in the same direction. Since the probability of occurrence of a saccade increases with the deviation of the eye from the on-target position, the eye with the greater deviation will more often trigger the saccade. This would result, on the average, in a reduction of vergence error without the vergence component of the saccades being directly determined by the vergence error before the saccade.

There is a relationship between vergence before the saccade and the direction of the vergence component of the saccades, i.e., the result of the saccades is more likely to be in the converging direction if the eyes are diverged prior to the saccade than if they are converged (Fig. 6). Since the eye with the greater error is presumed to "trigger" the saccade and make the larger saccade,

⁶ M. Alpern and P. Ellen, *Am. J. Ophthalmol.* **42**, 289 (1956).⁷ G. Westheimer and A. M. Mitchell, *Arch. Ophthalmol.* **55**, 848 (1956).

the vergence component should be in the right direction. It might be expected that when the eyes saccade the magnitude of the saccades in each eye would be appropriate to the error for that eye at that instant if maintenance of fixation was dependent on a mechanism which sensed *vergence* errors. This would result in a relation between the vergence error and the magnitude of the vergence component of the saccades. According to Fig. 8, this is not the case. Apparently, as revealed by the high correlations between the saccades in the two eyes (Table IV), the coupling of the saccades in the two eyes is quite strong. According to the model proposed, the occurrence of the saccades should not be related to vergence error. Little or no relation was found (Fig. 7). The small over-all relation found in the correlation between the directed magnitudes of the vergence component of the saccades and the vergence error would seem to reflect merely, as

mentioned before, that the direction of this component was usually appropriate.

Since, according to the model proposed, both eyes would be triggering the saccades in response to their own errors of fixation, and since the drifts in the two eyes seem to be independent, we would expect more saccades in the case of binocular fixation. Table VI reveals that in general this is the case. Both of the subjects used have normal binocular vision. If one eye were to dominate in binocular vision, we might expect no increase in saccade frequency and a flattening of the curves for the nondominant eye for binocular fixation in Figs. 3, 4, and 5. According to the suggested mechanism, the eye not triggering the saccade is expected to exhibit a generally smaller saccade. This should result in a decrease in the median saccade amplitude during binocular fixation. Table VII reveals that this is, in general, the case.

Attenuation of Infrared Radiation by Fogs*

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(Received July 22, 1959)

Optical transmission has been measured in fogs for wavelengths from 1–11 μ . The results, together with the data of Arnulf, Bricard, Curé, and Véret, are analyzed under the assumption that particle sizes in natural aerosols follow the distribution law proposed by Junge: $n(r) = Cr^{-p}$, where $n(r)dr$ is the number of particles per cm^3 with radii between r and $r+dr$, and C and p are some constants. The dependence of transmission on wavelength in fogs is of several forms, yet the theory accounts satisfactorily for each of them. Particle size measurements, when made, were in accord with the distribution law, and the values of p so obtained agree with the values inferred from optical transmission measurements.

I. INTRODUCTION

ATMOSPHERIC transmission measurements in the range 1–11 μ were made under a variety of weather conditions of low visibility—rain, snow, sleet, freezing rain, and fog—which occurred in Chicago during the winter of 1958–1959. Although fogs are infrequent in this area, over seventy sets of transmission data were obtained in the few foggy days experienced, and in every case there was a progressive increase of transparency with wavelength for those wavelengths in the well-known “windows” of the infrared spectrum.

Transmission in the “windows” during the other weather conditions mentioned above did not change with wavelength. This is, of course, to be expected when the wavelength is so very much smaller than the obstructing particles.

The physical theory describing optical scattering in

an aggregate of particles or droplets has long since been verified, and the usual approach, when a natural aerosol such as a fog is studied, has been that of counting up droplets for all the sizes present by some physical technique, and then calculating the net optical transmission predicted by theory for the totality of sizes; the result subsequently is compared with transmission data. Besides tedium, this approach has the additional disadvantage that little or no insight is gained through transmission measurements concerning general characteristics of the particle-size distribution.

An alternative method is due to Junge.¹ Several years ago, he proposed on the basis of considerable evidence that size distributions in natural, suspended aerosols (e.g., fog and haze) are described by a rather simple expression, or law. From this it is possible to calculate analytically, rather than numerically, the optical transmission characteristics and, as a result, one may observe

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† Now at General Atomic, San Diego, California.

¹ C. Junge, *J. Meteorol.* **12**, 21 (1955); *Ber. Deut. Wetterdienstes*, **38**, 264 (1952).