A PHOTOGRAPHIC INVESTIGATION OF 
LATERAL FUSIONAL MOVEMENTS OF THE EYES

Dissertation

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I. INTRODUCTION

As the eyes are directed hither and yon in space, the images formed in the two eyes are made to fall on corresponding areas of the two retinas by means of disjunctive movements of the eyes, with the result that the sensory impressions arriving at the visual cortex can be integrated to form a "single" mental image.

For the present study it is convenient to divide the fusion process into two components: namely, sensory and motor. The sensory process is concerned primarily with the integration of the images received at the cortex from the two eyes into a single image, while the motor process is concerned with positioning of the eyes so that the sensory process can operate satisfactorily. It is the motor process with which the present investigation is concerned.

The types of innervation which affect the relative directions of the two eyes are psychic (associated with the awareness of distance), accommodative and fusional. Of primary interest is the fusional innervation, which, so to speak, takes up the slack left by the other two types of innervation.

Fusional movements of the eyes include changes in the relative elevations of the lines of sight of the two eyes to bring both lines of sight to a common plane of regard, but the present investigation is concerned with the convergence and divergence fusional movements which occur when both lines of sight are kept in a common plane of regard. Photographic records were made of the motor response of the eyes to several different types of fusional stimuli. By analyzing
these records it was possible to study the nature and the time characteristics of the fusional response, lateral fluctuations of the lines of sight during steady fixation, the effect of perceived distance on the fusional response and the contribution of convergence as a cue to distance.

A. Development and Anatomy.

According to Duke-Elder (1949, pp. 3815-3820) convergence movements develop later in life than other types of eye movements. They do not appear to be present at birth, but are well developed at the end of the first 6 months of life. At the end of the first year corrective fusion reflexes have developed, although they do not appear to become fully established until after the age of 5 years.

While fusional reflexes are generally thought of as operating at a subconscious level, there are changes in convergence associated with changes in attention which have to be considered in connection with fusional movements. If, for example, one holds a pencil in front of his eyes while fixating a point on the wall beyond the pencil, he is aware of two images of the pencil. If he now directs his attention to the pencil by simply "looking at it", the two eyes automatically converge on the pencil. Another way in which the role of attention becomes manifest is through its steadying affect upon binocular fixation.

These affects may be mediated through accommodative and psychic convergence, without involving any direct relation between "attention" and the fusional movements.

The anatomical origin of motor impulses subserving fusional move-
ments is not known, but from the small amount of evidence available it appears definite that impulses for fusional movements have to be mediated through the occipital lobes (Cogan, 1948, pp. 92-94). Pathological evidence indicates that the pathways from the cortex are by way of the anterior brachia and the superior colliculi rather than through the pons as is the case for conjugate lateral movements (Cogan, 1948, p. 88; Duke-Elder, 1938, p. 288; Reese and Yaskin, 1941).

While it is generally accepted that a median unpaired group of cells, located in the oculomotor nucleus and known as Ferlia's nucleus, is the motor center for convergence movements, there is some doubt as to the existence of a center subserving divergence. Duke-Elder (1938, p. 288) regards divergence as a relaxation of convergence, as also do Scobee and Green (1946). There is, however, some evidence for the existence of a separate divergence center (Bruce, 1935; Cogan, 1948, p. 91; Adler, 1950, p. 358).

B. Eye Movements During Steady Fixation.

It is now well known that the eyes are continuously in a state of movement even during "steady" fixation. (Adler & Fliegelman, 1934; Ratliff & Riggs, 1950; and Riggs & Ratliff, 1951) The smallest of tremors occurring during steady fixation are reportedly of the order of 15-20 seconds of arc, and are smaller than the sensitivity of the apparatus used for the present investigation. The largest of these movements, however, are 5 minutes of arc or over, and since the combined effect of all may be as great as 10 minutes of arc, in some cases totaling 20-30 minutes (Ratliff & Riggs, 1950), horizontal components should and do register on the records. In contrast to the smaller movements
Riggs and Ratliff (1951) reported that the relatively large drifts and jerky motions were generally rather closely synchronized, and that they appeared to be coordinated in the achievement of convergence and lateral fixation on the target point.

C. **Convergence as a Cue to Distance.**

One of the most important assets attributable to the highly developed visual apparatus of man is the ability to perceive distance accurately. This was likely a very helpful factor to man in conquering his primitive enemies, and in this modern world of speed and machinery has lost none of its significance. The effective performance of many everyday tasks is made easier through utilization of the many cues which enable the individual to localize objects in space.

While it has been demonstrated satisfactorily that changes in perceived distance produce changes in accommodation and convergence (Fry, 1940; Neumueller, 1942; Hofstetter, 1942, 1950 and 1951; Ittelson and Ames, 1950), there has been considerable controversy centered around the contribution of accommodation and convergence to perceived distance.

Woodworth (1938, pp. 665-680) reviews the experiments of Wundt (1862), Hillebrand (1894), Dixon (1895), Bourdon (1902), Peter (1915), Bappert (1923) and others who attempted by direct experiment to discover the contribution of convergence and/or accommodation to perceived distance. The experiments of Wheatstone (1852), Judd (1897), Carr (1935) and others who made use of a stereoscope in attacking the problem also are described. The results of all of the experiments were inconclusive and controversial.

Although a sensory nerve supply to the extra-ocular muscles frequently is assumed to exist (Duke-Elder, 1938, pp. 172 and 578; Cogan,
1948, p. 4), investigators have been unable to demonstrate the existence of a proprioceptive system in the extra-ocular muscles (Cogan, 1948, pp. 4-5; Adler, 1950, pp. 333-339), and the mechanism whereby convergence could serve as a cue to distance is not obvious. On the other hand, if one voluntarily over-accommodates or over-converges for an object, the object appears to diminish in size and to move away. This observation would seem to indicate that either accommodation, convergence or both do provide some basis for judgment of distance. While one cannot rule out convergence and accommodation as cues to distance, they appear to contribute little under ordinary circumstances and, at best, errors in distance judgments are large when other factors are excluded.

D. Previous Photographic Investigations.

Numerous different objective methods, all falling into the general category of direct observations, mechanical recordings, photographic recordings or electrical recordings, have been used in studying the movements of the eyes. Subjective methods making use of after-images and the blind spot also have been utilized. Many variations of each method have been used, according to facilities available at the time and the nature of the problem to be studied. A rather comprehensive review of all of these methods was made by Carmichael and Dearborn (1947, pp. 146-205), and a rather complete history of photographic methods may be found in Taylor (1937, pp. 47-105). Other reviews and detailed descriptions of specific methods are to be found elsewhere in the literature.

5.
Orschansky (1859) appears to be the first to develop a photographic method of recording of eye movements, but did not publish any results. Dodge & Cline (1901) were the first to develop a photographic method which did not require attachments to the eyes of the subjects. Using a falling plate camera "to photograph the movement of a sharply defined reflection from the eccentric surface of the cornea", Dodge (1903) studied the eye movements in the horizontal plane and classified them into five general types. Type V consisted of convergence and divergence movements, which were uniquely differentiated from other types of movements by their slowness. Whereas it took only 40 milliseconds to complete a fixational movement of 10 degrees, it took 400 milliseconds to complete 10 degrees of convergence.

Judd (1907) used a regular motion picture camera to study convergence and divergence movements as the subject looked back and forth between two points. The slowness of convergence and divergence movements as compared to other eye movements was noted, and his records showed that convergence often was preceded by a conjugate movement of the eyes. According to Judd, the two eyes did not always move to points of convergence or divergence at the same rate nor always in similar paths. He attributed this lack of similarity to external muscular causes and not to internal nervous adjustments.

Allen (1949) photographically recorded accommodative convergence responses as his subjects responded to various levels of accommodative stimuli. He found accommodative convergence movements which reached a maximum velocity of 175 centrads per second, and velocities of 100 centrads per second were not uncommon.
In an investigation of lateral fusional movements (Stewart, 1950), photographic records were made of the response of the eyes to "jump ductions" stimuli. The subject fixated a small round spot subtending approximately 20 minutes of arc at the eye, and by means of a shutter system the small spot was replaced by two larger spots each subtending 1.0 degree. These larger spots were polarized so that one was seen by each eye, and their separation on the screen could be varied to provide various amounts of fusional stimuli.

Figure 1 shows a series of typical convergence records obtained from these experiments as the stimuli were "jumped" from zero to various amounts Base-in and Base-out. One scale division along the ordinate is equal to a change in convergence of approximately one prism diopter, and one scale division along the abscissa is equal to one second of time. The origin of the coordinate system represents the time at which the fusion stimuli were presented and the amount of convergence in play at that time, and the numbers on the response curves indicate the magnitude of the stimulus in prism diopters.

It was found that during "steady" fixation of the 20 minute and 1 degree spots, the convergence of the eyes was almost constantly changing and that the reaction time for lateral fusional movements appeared to be less than reaction time reported for other types of eye movements. It also was found, when small changes in fusional stimuli suddenly were presented to the eyes, that there often was an apparent moving together of the targets which was not accompanied by an immediate or well defined movement of the eyes. This was more frequently the case for divergence than for convergence. When fusion stimuli
Figure 1.

Jump Ductions

DSS

B.I.

5 B.O.

1 B.I.

1 B.O.

B.O.

3

4

6
requiring larger movements of the eyes were presented in the Base-out direction, there was a tendency for the maximum convergence to be reached rapidly and to be followed by a drift back toward the phoria position. In the Base-in direction, there was a tendency for the maximum divergence to be approached gradually, although there usually was a rapid movement at the beginning.
II. APPARATUS

The general plan of the apparatus is illustrated schematically in Figure 2. Subjects were seated 150 cm. from a cylindrical screen whose axis of rotation X passed vertically through the center of an imaginary line connecting the centers of rotation of the two eyes. The screen measured 8 ft. horizontally and 4 ft. vertically.

A projector P was located above and behind the subject's head, and the projector beam passed through a doubling device M located directly above the subject's head on the axis of the cylindrical screen. The subject viewed the screen through filters placed in front of the eyes at F.

A light source R was placed above and in front of each eye so that its beam passed over the filter to the eye, from which it was reflected under the lower edge of the filter and into the camera C.

A. Projection System.

A plan view of the projection system is shown in Figure 3. The doubling device mentioned above consisted of the mirror system $M_1$, $M_2$, $M_3$ and $M_4$. One pair of mirrors divided the beam and reflected the two halves to the second pair of mirrors which controlled the position of the doubled image on the screen.

In order to describe the projection system, let us trace two beams from a point 0 in the object plane of the projector to the screen. After passing through the objective lens of the projector, the beams were incident upon red and green Corning filters (H. R. Signal Red Color Spec. No. 2-60 and Sextant Green Color Spec. No. 4-64). These
Figure 2.

**Side View Showing General Arrangement Of Apparatus**
Plan View Of Projection System

Figure 3.
filters were selected because for practical purposes there was no overlap in their spectral transmissions. Immediately beyond the filters and approximately on the axis of the cylindrical screen, two vertical plane mirrors $M_1$ and $M_2$ were mounted at $45^\circ$ to the projector beam and at right angles to each other. Here one beam was reflected to the left and the other to the right to mirrors $M_3$ and $M_4$, respectively; from here they were reflected to the screen. $O_R$ and $O_G$ on the screen represent the doubled images, one red and the other green, of the single point $O$ in the object plane of the projector.

Now, $M_3$ and $M_4$ each were mounted to rotate around vertical axes and were geared together so that when set in motion $O_R$ and $O_G$ were displaced horizontally, in equal amounts but opposite directions across the screen.

By placing in front of the subject's eyes filters which were identical to those mounted in front of the projector, each eye was able to see only one of the images on the screen. Monocular fields through the filters extended nasalward approximately $30^\circ$, temporalward beyond the screen and vertically to the edges of the screen.

B. Photographic System.

A Reid streak retinoscope with the mirror assembly removed was mounted above and in front of each eye, as indicated in Figure 4. Light from these sources was reflected from the corneas and into the tubes of a modified Ophthalmograph. The Ophthalmograph contained a mirror which could be dropped into the light path, reflecting it to a ground glass screen where it could be focused for the plane of the film. The line filaments of the retinoscopes were adjusted to form vertical
Figure 4.

Side View of Photographic System
images on the cornea and in the film plane. Further elongation was obtained by cylindrical lenses incorporated into the camera lens system. As illustrated by the inset at the lower right of Figure 4, a narrow horizontal slit placed immediately in front of the film allowed only a small strip of the image to reach the film. With this arrangement, only the horizontal components of the subject's eye movements were recorded on the film.

Two problems were involved in analyzing the changes in convergence from the two lines on the film which depicted the movements of the eyes. Since changes in distance between the two lines represented changes in convergence, the first problem was to find a suitable means of measuring these distances. The second consideration was that of being certain of measuring between two points exactly corresponding in time. By using a slit in front of the film plane the second problem was eliminated, and one could be assured of measuring between points corresponding in time simply by measuring across the film from one line to the other in a direction perpendicular to the edge of the film.

A sprocket driven by a modified phonograph turntable assembly moved the film past the slit at the rate of 1.57 cm. (approximately 0.60 inches) per second.

In order to mark the film, a small source was placed inside the camera housing. An electric current to it was so regulated that when it was flowing just enough illumination would fall upon the film to fog it slightly. In order to produce faster heating of the filament, enough current to make the filament glow slightly was supplied con-
tinuously. Delay of this source in producing a mark on the film was estimated to be less than .005 second.

C. Film Analyzer.

Considerable effort has been spent in the design and construction of suitable apparatus for analyzing the photographic records. In a previous study (Stewart, 1950) an apparatus was built which did a fairly satisfactory job, but which required two persons to operate. The basic principle of the older method was used in designing an improved apparatus which could be operated by a single experimenter.

A rapid method of transcribing changes in convergence by measurement of changes in separation between the two lines on the film record was devised, and a schematic representation of the main features of the apparatus may be seen in Figure 5.

The film was pulled through the object plane of a projector by a sprocket drive which was geared to the motion of a recording board. As the beam left the projector it was split, and the two beams were cross polarized. Upon arriving at the viewing screen another pair of crossed polaroids allowed only the right half of one image and the left half of the other image to be seen when observed from the other side of the viewing screen. As can be seen by following the two light paths from the projector to the screen, the prism system reversed right for left in one beam. When the two images were aligned vertically by adjustment of the plane mirror, they appeared on the screen as in Figure 6-A, where \( L_1 \) and \( L_2 \) are the two images of the left eye record and \( R_1 \) and \( R_2 \) are the two images of the right eye record. The dividing line down the center of the screen is the junction of the
Figure 5.

lever moved by motion of inclined plane attached to recording pen

plane mirror

film

bulb

projector

gearad to motion of recording board

beam splitter

polaroids

frosted glass

viewing screen

right angle prism

penta prism
crossed polaroids, and was oriented to correspond to the slit in the
film plane of the camera; that is to say, it was perpendicular to the
image of the edge of the film. When the film was moved through the
projector, the two images appeared to flow into each other at the di­
ving line as indicated by the arrows in Figure 6.

If the optical system were adjusted so that the two images were
vertically coincident at the center of the viewing screen, as shown in
Figure 6-A, then $L_1$ and $L_2$ would flow into each other as also would $R_1$
and $R_2$. If, however, the plane mirror were adjusted so that the two
images were vertically separated as shown in Figure 6-B, then $R_1$
and $L_2$ would flow into each other only so long as the distance between the
two lines on the film remained unchanged. If changes in convergence
occurred, they were indicated on the film record by changes in separa­
tion of the two lines. Now, when $R_1$ and $L_2$ began to separate at the
center of the screen they could be brought back into alignment by rota­
ting the plane mirror located above the beam splitter in Figure 5. In
order to rotate the mirror it was necessary to move the recording pen
assembly, to which was attached an inclined plane. Movement of the
inclined plane raised or lowered the lever, thus rotating the mirror.

It can be shown that the displacement of the pen necessary to
realign the images after they separated on the screen is directly pro­
portional to the separation of the images and, therefore, also pro­
portional to the corresponding change in distance between the two lines
on the film. The displacement of the pen thus could be calibrated in
terms of angular rotation of the eyes.

To obtain a convergence record, one simply kept $R_1$ and $L_2$ coinci­
Figure 6.

Viewing Screen Of Film Analyzer

19.
dent at the dividing line at the center of the screen by operating a lever which moved the recording pen assembly back and forth perpendicular to the direction of movement of the recording table.

Traces of the record of an individual eye, for example the left eye, were obtained by keeping $I_1$ or $I_2$ flowing into a fixed point on the dividing line.

The gear ratio between the recording table and the film drive determined the magnification along the time scale, and the slope of the inclined plane determined the magnification of the eye movements.

D. **Size Changing Apparatus**.

In most of the experiments about to be described, the target consisted of a diamond shaped quadrilateral, whose size could be varied by means of the apparatus shown in Figure 7. Two knife edges $E_1$ and $E_2$ were attached to plates $P_1$ and $P_2$. These plates were linked to the eccentric pins on gears $G_2$ and $G_3$, which rotated in opposite directions and drove the plates back and forth in the object plane of the projector with one moving back when the other moved forth. As the plates slid back and forth the diamond shaped aperture alternately expanded and contracted. The amount of this expansion could be controlled by adjusting the eccentricity of the pins on $G_2$ and $G_3$ and the lengths of the links. The projection system formed red and green images of this diamond shaped aperture on the screen. In the experiments using size changes, the limits of the horizontal diameter of the targets on the screen were adjusted to 70 mm. and 210 mm., giving size changes on the screen in the ratio of 1:3. The velocity of the size change varied as a sine function, with zero velocity at the limits and maximum 20.
Mechanism For Producing Size Changes
velocity at the size of 140 mm.

A slot in the lever which extended from the gear system of the rotating mirrors rode on an eccentric pin on G₁. As G₁ rotated, the images moved back and forth on the screen, moving in opposite directions as they passed each other at the center of the screen. The velocity of separation of the targets also was a sine function, and, when the three gears, G₁, G₂, and G₃ were synchronized with each other and connected to the output shaft of an electromagnetic clutch C, the velocity of separation of the targets reached zero and maximum values at the same times as the velocity of the size changes.

The input shaft of C was driven by an electric motor M. Speed of rotation of the gears could be set at any desired value by means of a mechanical speed control device, R.

The sequence of events comprising one cycle of operation may be followed by referring to Figure 8 and can best be seen by holding the figure so that the arrows are pointing toward the top. Although the horizontal and vertical dimensions of the diamond were approximately equal, the vertical diameter has been reduced relative to the horizontal diameter in preparing Figure 8. One scale division along the horizontal axis is equivalent to a horizontal distance along the screen which subtends one degree at the eye, and the horizontal diameters are drawn to scale according to the angle subtended.

At A the two targets are superimposed and subtend approximately 5.3 degrees. Velocity of both the size changes and convergence changes is at a maximum. Moving on the time scale from A to B, the
targets continue to decrease in size and separate. In this example
the red target moves to the right and the green to the left.

B represents one of the limits of size and convergence, at which
the velocity of each is zero. From B to C the targets increase in
size as they move toward superposition.

As the targets cross at C the velocity of size and convergence
again reaches a maximum, and from C to D they continue to increase in
size as they separate (in opposite direction to their separation at
B).

D is the other limit of size and convergence, at which the veloc­
ity of each is zero. From D to E the size decreases as the targets
move together again. At E the same conditions exist as at A, and the
cycle repeats itself if the apparatus continues to operate.

Whenever size changes were used, the size cycle was repeated ex­
actly as illustrated above. By exchanging the filters right eye for
left, the separation of the targets could be divergence at B and con­
vergence at D, or convergence at B and divergence at D. The amplitude
of the convergence changes could be controlled by adjusting the eccen­
tricity of the pin on $G_1$ in Figure 7.

In order to simulate an object moving in space, the pin on $G_1$ was
adjusted so that the targets were superimposed when they were 140 mm.
in diameter and separated a distance equal to 1/2 the pupillary dis­
tance of the observer when at either limit. The filters and mirrors
were then so arranged that convergence was required as the targets in­
creased in size and divergence was required as the targets decreased
in size.

When set up in this fashion, the size changes and stimulus to convergence were equivalent to a 140 mm. target moving back and forth from 1.0 M. to 3.0 M. in front of the observer's eyes. This stimulus pattern is represented to scale in Figure 8 if the left eye views the green target and the right eye views the red target. The broken line represents the path of the center of the green target across the screen and the dotted line represents the path of the red target across the screen. As indicated on the time scale, the cycle was completed in 4.8 seconds.

Modifications of the apparatus for other experiments are described in Part III and Part IV.
III. PROCEDURE

The subject was seated on an adjustable stool and the head rest and biting board aligned for the camera and light sources. The filters were then positioned in front of the eyes so as to cover the screen without interfering with the photographic system. After approximate adjustment of the camera system, final adjustment and focus were made with a 6.5 X hand magnifier.

The screen was dimly illuminated in order to prevent shadows from falling upon it. The targets appeared to the observer to be in a dark field and when fixating the targets he was scarcely aware of the existence of the screen. When the apparatus was set into operation, as described in the preceding section, none of the subjects failed to perceive the correct depth effect, nor to be fairly accurate in their estimation of the distances involved. After watching the targets for several minutes and reporting and verifying their experiences, the subjects were asked to try to remember the magnitude of the depth effect in this, the "control" run, so that they might compare the depth effects obtained in the subsequent runs to that obtained in the "control" run.

Hereinafter the pattern of convergence changes in the control run will be referred to as "regular" convergence and a pattern of twice this amplitude as "double" convergence. "Opposite" convergence is equal in magnitude but of opposite direction to that of the control; that is, the targets were diverged as their size increased and converged when their size decreased. "Double opposite" is twice
the amplitude of "opposite."

In separate runs the pattern of size changes described above was combined with one of several different patterns of convergence changes, as listed below.

(1) Regular Convergence (Control).
(2) Double Convergence.
(3) Opposite Convergence.
(4) Double Opposite Convergence.
(5) Zero Convergence.
(6) Occlude Regular Convergence (Same as (1) except that one eye was occluded).
(7) Occlude Zero (Same as (5) except that one eye was occluded).

For the remainder of the runs indicated below the size of the targets was held constant at the 140 mm. size.

(8) Regular Convergence with no Size Change.
(9) Double Convergence with no Size Change.
(10) Regular Convergence with no Size Change, but with Ground Added.
(11) Double Convergence with no Size Change, but with Ground Added.

The ground added in (10) and (11) consisted of shadows of the apparatus cast on the screen from a bright light located behind the observer and a meter stick placed near the targets.

During all of the runs, the subjects were instructed to maintain fixation within the area of the target, preferably near the center,
and to note size and distance changes. In addition they were asked to report any doubling that occurred during the run and to make any further comments regarding their experiences. These subjective reports were recorded at the end of each run.

During each run a photographic record was made of the horizontal components of the movements of each eye.

Modifications of the apparatus and procedures followed for other experiments are described in Part IV.
IV. RESULTS

In the graphs included in this report, a movement of the right eye (R) or the left eye (L) to the left is represented by a shift toward the top of the graph, and a movement to the right is represented by a shift toward the bottom of the graph. An increased convergence is represented by an upward displacement of the convergence record (c) and divergence by a downward displacement.

A. Time Scale.

In order to establish the time scale, it was necessary to determine the velocity of the film past the slit in the camera. This was done by interrupting the light beam entering the camera with an episclotister operated by a synchronous motor. The resulting film record thus consisted of a series of dashes of known separation in time. By counting the number of dashes in a given length of film, the film speed was found to be approximately 0.60 inches per second. Knowing this, the time scale for a given setting of the analyzer could be found by running through a known distance on the film and measuring the corresponding distance on the graph. Expansion and contraction of the film after developing likely resulted in some variation in the time scale from day to day. It is not believed that this error was serious, and the data indicate that it was not.

Unless otherwise specified the horizontal scale divisions of the eye movement graphs presented are approximately equal to one second of time.

B. Eye Movement Scale.

29.
Because of the lag found to exist between actual convergence and stimulus to convergence (Stewart, 1950), it was decided to use fixations between known distances on the screen to establish a scale representing changes in the position of the eyes. For this purpose, the subject fixated first one and then the other of two crosshairs located 2 degrees apart on the screen. When the subject felt that he was maintaining good fixation, he pressed a switch which allowed the current to flow through the film-marking light inside the camera. This point is represented in the data by a vertical line and the word "on". The two sections of film for the two crosshairs were then run through the analyzer on the same graph, and the distance between the two records represents an eye movement of 2 degrees.

Samples of these calibration runs are shown in Figures 9 and 10. In Figure 9 the left eye was occluded. $R_L$ represents the right eye fixation of the left crosshair and $R_R$ represents the right eye fixation of a crosshair two degrees to the right of the first. The line in between each pair of records is the time scale. Figure 10 is the same as Figure 9 except that in Figure 10 the right eye was occluded and the left eye was fixating the two crosshairs.

Figures 11 and 12 show movements of the left eye $L$, the right eye $R$ and the convergence record $C$ as the subject binocularly changed fixation from one crosshair to the other. In Figures such as 11 and 12 the absolute distance between the individual records for the right and left was determined arbitrarily by the experimenter when the film was run through the analyzer. It can be seen in Figures 11 and 12...
Figure 9.

Calibration Data - 2° Fixation
Figure 10.

R G B

L L
on

off

L R
on

off

L L
on

off

L R
on

off

Calibration Data 2° Fixation
32.
Figure 12.

2° Fixation - Right To Left
that changes in convergence do not result from changing fixation be-
tween the two points on the screen.

The eye movement scale was established by obtaining an average
value of the average distance between a series of records such as
the four shown in Figures 9 and 10. Although the fluctuations due to
unsteadiness in fixation are large relative to the distance between
the two lines, it is believed that the scale which was established
in this fashion was fairly accurate. It was in good agreement with
values obtained from similar records of fixations between crosshairs
separated by 3.8 degrees and 7.6 degrees.

The vertical scale divisions of the graphs contained in this
report represent one degree eye movements or one degree convergence
changes, as the case may be.

Blinks are indicated by blank spaces in the records which may or
may not be filled in by dots.

C. **Eye Movements During Steady Fixation.**

In Figures 13 and 14 are the traces of records as the subjects
binocularly fixated the center of a crosshair oriented obliquely to
form an X. Figure 13 may be taken to represent a typical "good" re-
cord. The wiggles, drifts and jerks of the traces for the right and
left eyes were found throughout the records studied in this investiga-
tion, and none of these movements appeared to be associated with any
particular type of fixation object. Presumably, these small movements
all have been described at one time or another by Dodge (1903), Judd
(1907), and in greater detail by Adler & Fliegelman (1934), Lord &
35.
Figure 13.

Binocular Fixation Of Crosshair
Figure 14.

Binocular Fixation Of Crosshair

L B Z

on

off

37
Wright (1948), Ratliff & Riggs (1950) and Riggs & Ratliff (1951).

The convergence records during binocular fixation of the cross-hair indicate that considerable fluctuation in convergence commonly occurs without the subject's awareness of diplopia. While the author found this same sort of thing with round spots subtending 20 minutes and 1 degree at the eye (Stewart 1950), it was assumed that this would not occur to any appreciable extent with a crosshair. For short intervals the eyes may maintain a relatively fixed degree of convergence, but during a fixation lasting several seconds the fusion mechanism does not appear to hold convergence fixed within an interval of less than approximately \(\frac{1}{4}\) degree. It was not uncommon to find fluctuations of one degree as, for example, in Figure 14.

In Figure 14 the convergence increased as the subject concentrated on fixing the crosshair and relaxed after the end of the run, possibly indicating the influence of attention on the convergence innervation. It is to be noted that, although the subject was instructed to report any diplopia which occurred, none was reported.

Figure 14 also illustrates three types of convergence changes which were found to occur throughout the investigation: (1) From a to b the eyes seemed to drift in a rather uncoordinated fashion. This type of movement commonly occurred in either convergence or divergence. (2) From b to c, c to d and d to e the convergence movements were coordinated and appear purposive in nature. (3) At a, c, d, e and f sudden changes in convergence associated with jerks or fixational movements produced peaks on the convergence graph. Although these rapid changes in convergence appear always to result from the position 38.
of the right eye this does not occur consistently in this fashion in other records of this subject nor in other subjects investigated.

At c the peak produced in the convergence graph was the result of a jerk occurring only in the right eye; at d both eyes moved quickly to the right and back to the left but the right eye travelled farther to the left, producing the peak; at e both eyes moved quickly to the right and back, the left eye stopping short of its original position and the right eye passing beyond.

In Figure 15 the left eye was occluded and the crosshair fixated with the right eye. The same types of movements occurred as in the case of binocular fixations, with the possible exception described in (2) above.

The similarity between the convergence records for monocular and binocular fixations of the crosshair may be seen in Figure 16. These convergence records were taken from a series of "good" fixations. The upper pair is for binocular fixation and the two lower pairs for monocular fixation, as indicated.

D. Perceived Distance and Convergence.

It was hoped that the design selected for the apparatus would permit the author to obtain records of fusional movements under somewhat realistic conditions, and adding the size changing mechanism to the fusion stimulus appeared to produce the desired effect. The red and green targets fused readily into an intermediate yellow, and only rarely did one color dominate over the other. If this occurred it was usually at the break point where the borders were beginning or had begun to overlap. It is believed that any rivalry which occurred re-
Monocular Fixation Of Crosshair
(Left Eye Occluded)
Figure 16.

R G B

BOTH EYES

RIGHT EYE FIX

LEFT EYE FIX

Convergence Records During Fixation Of Crosshair

\[41\]
sulted from the borders and not from the colors.

From the beginning of the experiments it was obvious that the size change was the dominant factor in determining the perceived distance of the target. Regardless of variations produced in the convergence cycle, a good depth effect was produced so long as the size changing mechanism was operating.

In making comparisons of subjective experiences, the observer had to rely upon his memory impression of the control run. In order to test his memory, the control run occasionally was presented without notifying the observer that it was the control run. Usually he reported a depth effect equal to that of the "control", rarely it was less than that seen in the control run, but never greater.

Four different observers participated in the experiments described in this section. Although complete objective and subjective records were obtained for each, data for only two observers are included in this report. It is believed that the records selected are representative of the data obtained for all of the observers.

Superimposed upon the graphs is a sine curve representing the stimulus pattern. The author attempted to locate the vertical position of the stimulus curve relative to the response so that it would be in agreement with the subjective report of the observer.

The clinical findings of RGB and LBZ indicated that for these experiments both may be considered to be emmetropic. Each had a small exophoria at distance and 5-6 prism diopters of exophoria at 40 cm.

As mentioned previously, L and R are traces of the individual eye records and the absolute distance between L and R in these figures was 42.
arbitrarily determined so that they would not cross each other. The two sine curves superimposed upon them represent the movement of the centers of the targets back and forth across the screen. For regular convergence they are the same curves as in Figure 8. The distance between the two sine curves is determined by the separation of L and R and by the vertical distance between C and the curve representing the convergence stimulus. The actual paths of the centers of the targets would be parallel to, but not necessarily coincident with, the curves representing them.

Figures 17 and 18 are sample records of the response of the eyes during the regular convergence (control) run. In Figure 17 the observer appears to have maintained fixation near the centers of the targets, and the convergence lagged behind the stimulus by approximately 30 minutes at each limit. The changes in convergence appear to be largely the result of movements made by the right eye.

In Figure 18 the subject seems to have attempted to maintain fixation on the right edge of the target. Fixational movements and changes in convergence were so executed that they tended to permit the left eye to follow the right border of its target at the expense of the right eye, although less movement would have been required to keep the right eye on its target.

In Figures 19 and 20 the amplitude of the convergence pattern was doubled. LBZ reported partial doubling when the target appeared to be receding, but obtained fusion at the limit. The diplopia did not seem to affect the apparent fore and aft movement, which was possibly a little greater than for the control run. He appears to
Figure 18.

Regular Convergence
LBZ

Double Regular Convergence

Figure 19.
Figure 20. Double Regular Convergence
have fixated near the center, and the large fixational movement may have been to the left edge of one of the targets. The divergence and convergence movements were symmetrical and well coordinated.

RGB reported a depth effect comparable to that of the control run, although he could not maintain fusion at the far (divergence) limit. Figure 20 was the first cycle of this run and, from the convergence amplitude of subsequent cycles, it can be deduced that fusion must have been temporarily lost after the blink. As before, he appears to have attempted to fixate the right border; after the blink, however, he appears to have given up the border in favor of a position nearer the center.

For the runs illustrated in Figures 21, 22, 23 and 24 the convergence cycle was reversed with respect to the size changes; that is, convergence was required as the targets became smaller and appeared to recede and divergence was required as the targets increased in size and appeared to move nearer.

LBZ (Figure 21) reported that he "couldn't see anything different from the control run." The numerous fixational movements are suggestive of an alternation from one eye to the other, and do not seem to be concerned with maintaining fixation on any particular part of the target. Although he may have been alternating between the two left borders at the beginning, this could not continue beyond two seconds after the beginning of the record.

Although RGB reported a constant slight overlap which reversed at each limit, the depth effect was good and was estimated to be about three-fifths as great as that for the control run. Both eyes appear
Figure 21.

Opposite Regular Convergence
Double Opposite Convergence
Figure 2.

RGB

Double Opposite Convergence
to have followed the movement of the targets during the first part of the run, but from about 1.3 to 2.0 seconds only the right eye did so and from 2.0 on perhaps only the left eye. The eye movements did not seem to follow the borders.

For the Double Opposite Convergence runs shown in Figures 23 and 24 the convergence and divergence movements occurred rather symmetrically and well coordinated, although LBZ's left eye appears to have followed its target better than did the right eye.

LBZ experienced a partial diplopia as the targets became smaller, but obtained fusion at the limit. To him the depth effect from this run was the same as for the Double Regular Convergence run; that is, it was equal to or slightly greater than that for the control run.

RGB obtained single vision only "through about one foot of the total range," with greater doubling during the first half of the cycle. He said that the depth effect was not affected by the doubling although the apparent movement was not as great as that of the control run.

In spite of the increased amount of doubling reported during the Opposite and Double Opposite runs, the disparity of the targets produced fusional movements with amplitudes as large as those recorded for Regular and Double Regular runs. The most conspicuous difference between the two types of convergence records is the increased time lag between stimulus and response when the conflicting stimuli were viewed. This increased time lag must account for the increased number of reports of diplopia.

For the runs corresponding to Figures 25, 26, 27 and 28 the target size was held fixed at 14.0 mm. LBZ reported a small amount of
Figure 25.
Figure 26.

Regular Convergence  No Size Change
Figure 27.

LBZ

Double Convergence  No Size Change
Double Convergence
No Size Change

Figure 28.
fore and aft movement which increased when the amplitude of the convergence pattern was doubled, but RGB was not aware of any fore and aft movement whatsoever. Both observers reported occasional slight diplopia for the Double Convergence runs.

When a background was added for the runs in Figures 29, 30, 31 and 32, the target appeared to move in front of the plane of the screen and decrease in size during convergence and appeared to move behind the plane of the screen and increase in size during divergence. RGB reported some diplopia but LBZ did not. In these runs the depth effect resulted from binocular parallax and the size changes experienced were a function of the perceived distance of the target which subtended a fixed angle. The eye movements resulting from the disparate targets do not appear to have been significantly different from those which occurred during any of the previous runs.

Figure 33 is a sample of the records obtained from the Zero Convergence run. Although convergence drifted back and forth, the direction of the drifts did not appear to be related to the size changes of the target. RGB once reported the depth effect for Zero Convergence as equal to that for the control run and another time it was slightly less. A record for LBZ is not shown, but he reported a depth effect equal to that of the control.

In all of these runs the eyes responded to the convergence stimulus and if awareness of distance produced convergence movements it cannot be detected in the records presented thus far.

Figures 34 and 35 show that, when one of RGB's eyes was occluded,
Regular Convergence - No Size Change - Ground Added
Figure 30.

Regular Convergence  No Size Change  Ground Added

RGB
Figure 31.

LBZ

Double Convergence
No Size Change
Ground Added
Figure 32.

Regular Convergence  No Size Change  Ground Added
Figure 33.

Zero Convergence
Figure 34.

Occlude Zero Convergence
Figure 35.

Occlude Regular Convergence
awareness of distance was capable of eliciting a rather consistent convergence pattern corresponding to the apparent movement produced by the size changes. This response occurred whether the target was oscillating, as for Figure 35, or stationary, as for Figure 34.

When one of LBZ's eyes was occluded, drifts in the convergence records were found, but they did not follow a consistent pattern as for RGB. This is shown by Figures 36 and 37 in which the right eye was occluded. In these records the changes in convergence do not appear to be related to the size changes.

During the monocular runs the depth effect for both subjects was equal to that of the control run.

E. Psychic Convergence.

One of the purposes of the monocular experiments described in the previous section and illustrated in Figures 34, 35, 36 and 37 was to study the effect of the observer's awareness to distance upon the convergence response. Some records showed rather consistent responses in the direction to be expected from the depth effect experienced by the observer. Other records, however, showed little if any definite response pattern of this type. It was felt that some further study in this direction might prove more helpful in determining the nature of this type of convergence response.

A so-called rotating "T" was projected on the screen with a Clason projector, and the T rotated so that the two sets of lines were at 45° and 135°. The observer's right eye was occluded and in front of the left eye were placed lenses, the effective power of which at the spectacle plane was approximately -1.00 D. sph. C - .75 66.
Figure 37.

Occlude Regular Convergence
The size of the image on the screen was decreased to the limit of the projector. Under these conditions all subjects reported that the lines at 135° were clear and those at 45° blurred. If the size of the image on the screen was then increased to its limit, producing an image the size of which was approximately four times that of the smaller image, the observer reported that the image appeared to come nearer. As this happened, the lines at 45° became more distinct, such that the two sets of lines were equally clear, or that those at 45° were clear and those at 135° were blurred. The image was decreased to the limit and the original set of lines became clear at the expense of the other set.

It was assumed that, so long as the lines alternately cleared and blurred, changes in accommodation were occurring as a result of the changes in apparent distance of the target. The analysis of the photographic records during these runs consistently demonstrated changes in convergence occurring concurrently with the changes in accommodation.

Convergence records from a series of such runs are found in Figure 38. For convenience, the time scale has been reduced and the beginning of the records separated vertically. Beginning at the top, these four records were the first, third, fourth and fifth of a continuous series of six runs. The letter a indicates the approximate point on the record at which the size increase began and b the approximate point at which the limit was reached. The letter c indicates approximately the beginning of the size decrease and d approximately 69.
the point at which the limit in that direction was reached.

In Figures 39, 40 and 41 the time scale is spread out and traces of the right and left eye movements are shown. The letters a and b have the same meaning as in Figure 38.

In Figure 41 the time interval between c and d was approximately 3 seconds, and the divergence response did not begin until 2 seconds after d.

Because the accommodative changes were not determined quantitatively, no quantitative attempt was made to relate the convergence changes to the accommodative-convergence relationship. It is assumed, however, that the changes in convergence resulted from this relationship, since they occurred concurrently with accommodative changes.

F. Jump Ductions.

In the following experiments the fusion stimuli were "jumped" by means of a solenoid which displaced one of the levers controlling the positions of mirrors \( M_3 \) and \( M_4 \) in Figure 3. For most of the runs the diamond shaped target was used, and its size was set at a horizontal dimension of 140 mm. For the other runs a rectangular target, measuring approximately 25 cm. vertically and 15 cm. horizontally, was used. The rectangle enclosed a black cross which was formed by a 6 mm. wide vertical line and a 1.5 mm. wide horizontal line.

Figure 42 shows a series of convergence records which were made as the diamond was jumped back and forth from superposition to 1.2°.
of divergence. Zero on the abscissa represents the point in time at which the targets were jumped, and the numbers indicate the sequence in which the runs were made. For records 1, 3, 5 and 7 the targets were jumped from superposition to the diverged position and for 2, 4, 6 and 8 they were jumped from the diverged position back to superposition.

If one follows the continuous record from beginning to end, one finds that the eyes tended to assume a somewhat diverged position when the stimuli were at the zero position. Consequently, little or no movement was necessary to "fuse" the targets when they first were jumped. After the jump, however, the eyes usually drifted out more. Run number 1 in Figure 42 shows this to a slight extent. When the targets were jumped back to zero, run 2, the eyes responded somewhat sluggishly, taking 1 second and two discrete responses to complete a movement approximately equal to the change in stimulus. They then began a drift back out and the next jump, run 3, simply allows a continuation of the drift. In run 4 the eyes responded with a more rapid movement, but again made two discrete responses and consumed 1 second of time in converging for the targets. Here, convergence was maintained fairly well, although the response in run 5 consisted of another drift which on the original record continues out to a position equal to the beginning of run 4. In run 6, the eyes responded the full amount with a single convergence movement and maintained their new position until the blink, after which they only partially recovered. The convergence movement at the beginning of run 6 covered about
1.2° from trough to peak in approximately 290 second, an average velocity of 4.14 degrees per second. Using the slope, however, one finds a maximum velocity of 5-6 degrees per second. In run 7 the response was similar to the other divergence runs, drifting back and forth so that smaller movement was required for run 8 than for run 7. The maximum velocity of the convergence movement in run 8 was about 7 degrees per second.

Figure 43 shows a series of runs similar to those in Figure 42, but the targets were jumped between zero and 2.3 degrees of divergence. The results are similar in many respects to Figure 42; however, the divergence response becomes more definite even though the eyes do not appear always to respond to the full 2.3 degrees. Maximum velocity of the convergence movements was about the same as before, and that of the divergence movement in run 5 was about 4.5 degrees per second.

In Figure 44 the targets were jumped from zero to 4.6 degrees of divergence. The eyes responded through a total range of approximately 3.25 degrees, and the subject was unable to fuse the targets in the diverged position. The maximum velocity of the convergence movements was 10-11 degrees per second and the average velocity from trough to peak was about 6 degrees per second. The slope of the large divergence movement in run 3 indicates a maximum velocity of 3.25 degrees per second.

Reaction time for convergence movements was just under 200 milliseconds. For divergence the beginning of the movement frequently is difficult to locate, but in these records reaction time appears to be slightly less than that for convergence movements.
Figure 42.

Jump Ductions - 1.2°
Figure 1: Jump Ductions - 2.3°
Figure L4.1.

Jump Ductions - 4.6°
Figures 45 and 46 were made from runs 1 and 2 of Figure 44. These are included to demonstrate the relationship between the fixational movements and the large peaks in the convergence records. This sudden increase in convergence occurred rather consistently in all of the data obtained for LBZ, and frequently, although not as consistently, for all of the other subjects. The peak rarely, if ever, was produced in the direction of divergence. While these movements appeared at times to be in the interest of maintaining fusion, as certainly is so in Figure 46, they appeared at other times to be a definite hindrance, as in Figure 45 where the subject was unable to obtain fusion. This type of convergence, whatever it may be, is unique in that (1) its velocity is high for convergence movements of comparable magnitude, (2) it occurs only in one direction, (3) in the records studied it seldom produced changes in convergence exceeding 20 minutes of rotation and (4) it does not appear to be a direct response to fusion stimuli, since it occurred in the absence of a stimulus to fusion as for example in Figures 33, 34 and 35. The magnitude of the response does not seem to be very well correlated with the size of the fixational movement with which it is associated, although fixational movements of greater extent than 2 degrees were seldom to be found in these data. There is a marked similarity between convergence peaks associated with fixational movements and peaks associated with the "flicks" found on the fixation records. Whether or not they have the same neurological basis is not known.

As well as could be determined, the velocity of the fast component of the convergence peak was at least 9 or 10 degrees per 80.
Jump Duction - 4.6° Divergence to Zero
second, possibly much faster. The velocity of the divergence component of the peaks varied from zero up to about three degrees per second.

Figure 47 shows the continuous convergence record as the rectangular targets were jumped back and forth from 3.15 degrees of convergence to 3.10 degrees of divergence. The time interval between jumps was decreased until the subject no longer was able to follow the targets. This record clearly shows trends previously found for this type of stimulus (Stewart, 1950). The divergence jump was followed by a rapid movement, after which divergence tapered off into a gradual drift of the eyes outward. Following the convergence jump, the eyes moved rapidly to a convergence maximum, after which they gradually drifted back in the direction of the phoria position.

Jerks in the convergence record occurred in association with fixational movements in a similar fashion as for LBZ; however, they occurred less consistently and to a lesser degree than for LBZ, seldom turning up at all in the converged position of the eyes. Regarding this, it may be significant that fixational movements were not as large as those in Figures 45 and 46, and they were smaller when the eyes were converged than when the eyes were diverged. It is possible that the same innervation was constantly present, but that it did not always make its presence known by producing discrete peaks. For instance, if their frequency were increased or their amplitude decreased they would tend to disappear from the convergence records. Because of the association of the peaks with fixations and
Figure 49. DSS

Jump Ductions
3.15° Convergence to
3.10° Divergence

Page 84.
flicks, however, this possibility is not likely.

Beginning with 14 the subject no longer could follow the jumps, although there was a partial response at 14, 15 and perhaps at 16. From there on, either the targets furnished no stimulus whatsoever to fusion and the eyes drifted out, or else the subject responded only to the divergence stimulus.

In Figures 48 and 49 the time and convergence scales have been spread out and the large convergence and divergence movements in Figure 47 grouped together so that they can be studied more carefully. Each run is identified by the same number in both figures.

Using the slopes of the large movements, the average maximum velocity of the four convergence movements was 7.25 degrees per second, and of the four divergence movements it was 6.30 degrees per second. The difference in velocities may simply reflect the size of the movements, since the convergence movements were larger than the divergence movements. However, the general appearance of the convergence graphs gives one the impression that the velocity of divergence movements is slightly less than that for convergence movements.

Reaction times appeared to be approximately 190 milliseconds for convergence and rather indeterminate for divergence. Runs 5 and 7 indicate rather definitely, however, that divergence movements have a shorter reaction time than convergence movements.

The occurrence of fast conjugate movements, most of which were less than a degree, is indicated on the graph by a small vertical line across the record. The peaks which are not accompanied by con-
Figure 18. DSS Jump Ductions
3.15° Convergence to
3.10° Divergence

Time Scale (Sec)
DSS Jump Ductions
3.10° Divergence to
3.15° Convergence
jugate movements resulted from flicks. Of special interest is the manner in which the peaks associated with the conjugate movements and flicks tend to slow divergence movements and to accelerate convergence movements, giving the impression that the large movements are composed of a series of smaller movements. Whether this is so or whether one is merely superimposed upon the other is not evident from these data. It seems more likely, however, that the peaks are simply superimposed upon the larger movements.

G. Removal of Stimulus to Fusion.

The results shown in Figure 50 were obtained with the targets in a converged position. As the subject continued to look at the targets, the one seen by the left eye was suddenly eliminated, leaving no stimulus to fusion.

In Figure 50 three sample convergence records have been superimposed at the point at which the fusion stimulus was removed. For each amount of convergence it took approximately two seconds of time to reach what is assumed to be the phoria position. Using the average slope of the divergence movement, the eyes diverged at the rate of about 1.75 degrees per second from the 3.4° position, 4.0 degrees per second from the 5.8° position, and 6.0 degrees per second from the 7.6° position.

An attempt was made to perform the same experiment with divergence rather than convergence in play, but when the targets were diverged to the limit of fusion the drift in the direction of the phoria was only about one degree. Clinically, the distance phoria of DSS was 1 prism diopter of exophoria. The straight-forward position
Figure 50.

Drift to Phoria Position after Removal of Stimulus to Fusion

3.4°

5.8°

7.6°
of the eyes would be equivalent to approximately 2.5 degrees of divergence on the screen, and since DSS was myopic with a far point of about 40 cm., with accommodation relaxed the phoria position on the screen would be near 3.0 degrees of divergence. One would not therefore expect a drift from divergence stimuli of less than 3.0 degrees. In order to reach a divergence of 5.6 degrees, which was near the limit for DSS, it was necessary to move the targets out slowly. Once fusion was broken, reversion to fusion was impossible without repeating the procedure. The drift after the stimulus to fusion was removed was one degree or less, which would indicate that in the process of reaching 5.6 degrees of divergence some additional convergence was relaxed. Another factor to be considered in the results obtained is the amount of lag allowable because of fixation disparity.

The drift from a 3.0 degree divergence stimulus is shown in Figure 51-A and the return to fusion in Figure 51-B. The record for 5.6 degrees of divergence is shown in Figure 52. As stated, the drift after removal of the fusion stimulus was about the same in each case. Fusion could not be reestablished, and the eyes made no further divergence when the stimulus was returned. The fixations to the right after the left eye was occluded and the fixations to the left after removal of the occluder may indicate that the eyes were symmetrically diverged at the beginning of the run. This is inferred because, if the eyes were not completely diverged for the targets, a fixation to the right would be expected when the left eye was occluded in Figure 52. When the occluder was removed the eyes made
Figure 51

A. Drift to Phoria from 3.0° Divergence

B. Return to Fusion from Phoria to 3.0° Divergence
Figure 52. DSS Drift from 5.6° Divergence to Phoria

Occluded Left Eye

Removed Occluder
a larger excursion to the left in order to fixate the left eye's target. If the eyes had now turned back to the right a degree or so they would have been in their original position at the beginning of Figure 52, but neither eye would be pointing directly at its target.

H. Divergence Limit.

When the eyes are diverged to their limit, accommodation is fully relaxed and accommodative convergence no longer can be used in the interest of single vision. If the targets are diverged slightly beyond the limit of single vision, one would assume divergence movements resulting from an effort to obtain fusion to be purely fusional in nature.

In Figure 53 the targets were gradually diverged and left stationary at a position such that the observer could maintain fusion only part of the time. When they were double, he pressed a micro-switch which operated the film-marking light; when single vision was obtained he released the switch. Records a and b show convergence graphs during and after transition from double to single vision; c and d show convergence changes during and after transition from single to double vision.

From an inspection of these and other similar records it does not seem possible that changes in convergence can account for the transition from single to double or double to single vision. The possibility exists, however, that the targets appeared single when fixating near the center and double when fixating near the borders. But, while the film record for Figure 53 contained numerous fixa-
Figure 53.

Convergence Records of the Eyes at Limit of Divergence
tions of $1/2$ to 2 degrees in magnitude and covering a total range of 3 or 4 degrees, there did not appear to be any consistent relationship between the direction of gaze and the reports of single and double. Another subject attempted to fixate the edge of the target; yet, one was equally unable to account for his reports of double and single vision on the basis of the convergence records.

The peaks on the convergence graphs were associated with fixational movements exactly in the manner illustrated earlier in Figures 45 and 46. In Figure 53 the divergence component of the peaks could be regarded as fusional movements. It should be remembered, however, that just the opposite appeared to be the case in Figure 46. The velocities and other characteristics of the convergence peaks appear comparable to those found elsewhere in this investigation.
V. DISCUSSION

A. Movements of the Eyes During Steady Fixation.

For short periods of time it appears possible to hold the eyes in relatively fixed positions while attempting to maintain steady fixation on a small object such as a crosshair. As discussed previously, however, small tremors and jerks are constantly present. According to a recent study by Ratliff and Riggs (1950), during the steadiest of fixations total movement due to the combined effects of these small motions over a period of three or four seconds was usually less than 10 minutes of arc. The validity of this statement is generally born out in the data collected in the present investigation, but fixations of such precision would seem to be the exception rather than the rule. Fixation within this degree of precision was maintained only in the most favorable circumstances and generally for periods of time of the order of one second or less. During fixations lasting several seconds excursions of the eyes in excess of 10 minutes of arc usually are to be found. The data indicate that the range of 20—30 minutes of angular rotation found by Ratliff & Riggs "in some cases" perhaps is the normal case, and the range of 10 minutes of arc the more or less optimum in precision. Needless to say, one is completely unaware of the occurrence of these movements; so far as he is concerned, his eyes are completely stationary.

The largest of these small excursions resulted from at least two distinct types of movement:

(1) Rapid Flicks. These movements presumably are the ones des-
scribed by Lord & Wright (1948) as rapid "flicks" of .02 to .03 second duration, which were 3 to 14 minutes of arc in magnitude, and which occurred at an average frequency of 1.5 to 2 movements per second.

At the end of a flick the eye sometimes assumed a new direction a few minutes of arc from its original position.

Records obtained in the present investigation are in general agreement with this. The flick sometimes consisted of a back and forth movement returning to, overshooting, or undershooting its original position. Other flicks displaced the eye in only one direction.

Both types of flicks were usually somewhat coordinated between the two eyes, although they also occurred independently in one eye as, for example, at C in Figure 14. Frequently the two eyes were displaced unequal amounts at the end of the flick, resulting in small changes in convergence. It may be significant that the changes in convergence resulting from this type of movement always produced increased convergence, rarely if ever producing a divergence of the eyes.

The neurological origin of these movements is not known but, because of their simultaneous occurrence in the two eyes, impulses would have to originate at least as far up as the oculomotor center in the midbrain. Nor is the functional significance of these movements apparent. Although the changes in convergence at times tended to aid in maintaining fusion, they occurred in the absence of fusional stimuli and at times when they tended to hinder rather than aid the fusion mechanism.

These and other small movements have received considerable
attention as to their relationship to visual acuity (Alder & Fliegelman, 1934; and others). Since this problem is beyond the scope of the present study, this mention of it will suffice.

If the flicks have a functional relationship to maintaining fixation, it is not apparent from the records obtained. At times they appeared to correct for drifts found on the records, but attaching this functional significance to them does not seem justifiable in view of the fact that the eye often returned to the same position at the end of the jerk. Also, a flick displacing the eye in one direction was sometimes followed by another flick displacing it in the opposite direction. On the other hand, the possibility exists that the flicks resulted from an attempt to bracket the fixation point. If it is impossible to maintain perfect fixation, this would offer the best means of keeping the image always as near to the center of the fovea as is possible.

(2) Drifts. For lack of a more descriptive general term, the second type of eye movement is referred to as a drift. These movements were considerably slower, and they occurred either in a coordinated fashion in the same or opposite direction for the two eyes or somewhat independently in one eye or the other. It was upon these movements that the smallest tremors were superimposed, and presumably these are the same motions described from monocular records as "slow drifts" by Ratliff & Riggs (1950).

Lord & Wright (1948) attributed most of the movement occurring between flicks to movements of the head. While this is a possibility
which cannot be excluded from the present study, it is assumed that use of a biting board and head rest plus cooperation of the subjects reduced the effect of head movements to a minimum. Sample records of head movements published by Ratliff & Riggs (1950) showed displacements on the film equivalent to 4-5 minutes of arc or less. If this is a fair sample, head movements would not account for a very great part of the results found consistently throughout the data.

Whether a relationship exists between the drifts and the jerks is not obvious, although they frequently occurred in such a fashion that one type might be a corrective response for the other.

If, as has been suggested by Verhoeff (1935), Walls (1948) and Fry and Bartley (1950), one never sees simultaneously with both eyes but normally alternates from one to the other, the shift from one eye to the other may possibly be reflected somewhere in the pattern of eye movements found in these fixation records. For example, the frequency of the jerky movements frequently was comparable to binocular rivalry rates. This interesting possibility is contra-indicated, however, by the fact that the movements occurred in the absence of a fusional stimulus.

During single binocular vision there exists, because of Panum's areas, a certain range in any direction through which the eyes can deviate from perfect convergence on an object without awareness of diplopia. During single binocular vision the difference between the convergence stimulus and the actual convergence of the eyes is called fixation disparity. Ogle and others (Ogle, 1950; Ogle & Prangen, 1950; Ogle, Mussey & Prangen, 1949) have studied fixation disparity.
in some detail. They made numerous subjective measurements using a target consisting of Snellen letters arranged around a blacked out square. The total field subtended 20 degrees and the square 1.5 degrees at the eye. Further details of the apparatus and procedures are fully described elsewhere (Ogle, 1950; Ogle, Mussey & Prangen, 1949). In general, their measurements showed that the farther the eyes were forced to deviate from the phoria position in order to maintain fusion the greater the amount of fixation disparity measured. For small amounts of convergence beyond the phoria position fixation disparity was found to exist to the extent of several minutes of arc. Diplopia usually resulted when fixation disparity reached a value of 10-15 minutes, although for at least one subject it went beyond 25 minutes.

In contrast to Ogle's measurements, data obtained by the author in this and in a previous (Stewart, 1950) investigation indicated that fixation disparities of considerably greater magnitude can and do occur. Although the targets used by the author were different from the ones used by Ogle, the phenomenon was present in records obtained with each of several different targets. On the other hand, the measurements of Ogle may represent the minimum amount of fixation disparity that could occur under the circumstances, while the author's data tend to indicate the maximum degree of fixation disparity possible under different circumstances. For instance, there is no reason to believe that the larger values of fixation disparity, found by Ogle when his subjects were forced to use large amounts of
convergence or divergence to maintain fusion, could not occur with lesser amounts of convergence or divergence in play. In other words, one is likely to use larger amounts of fixation disparity when the demand on the fusion mechanism is great, but this does not preclude its use under less demanding circumstances. The assumption that such is the case appears to be supported by the data presented in this report.

Using the crosshair for binocular fixation, it was found on the "best" records, made during a high degree of concentration on the part of the subject, that the convergence in play fluctuated through a range of 15 minutes or more. Other records taken during binocular fixation of the crosshair showed fluctuations well over a full degree, without any awareness of a diplopia. While records such as that shown in Figure 14 might be used to illustrate an effect of attention on the fusion mechanism, why was not the observer aware of a diplopia at some time during the run? Without a diplopia, why did not a change in the perceived distance or direction of the crosshair occur? The answers to these questions are not to be found in the data, and further experimentation is needed to determine whether the variations of fixation disparity registered in the photographic experiments are or are not present during subjective measurements of fixation disparity such as have been made by Ogle.

B. Convergence as a Cue to Distance.

The depth effect produced by the size changes did not appear to be influenced by variations in the convergence stimulus pattern used
for the monocular, opposite or zero convergence runs. Since the pattern of the convergence response always corresponded to the convergence stimulus, it seems safe to conclude that if convergence per se provides a cue for perceived distance, this cue is ignored and supplanted by the stronger size change cue.

C. Effect of Perceived Distance Upon Fusional Movements.

It has been demonstrated that awareness of distance can produce measurable changes both in accommodation and in convergence (Ittelson and Ames, 1950). Although it is possible to demonstrate a type of convergence response to awareness of distance which is not accompanied by an accommodative change (Hofstetter, 1951), it is best to consider the simultaneous responses found by Ittelson and Ames as a single response. Hofstetter (1950) showed that the ratio of convergence to accommodation in this response was in accord with the accommodative convergence to accommodation (ACA) ratio.

In the present investigation it was demonstrated that changes in accommodation occurred concurrently with changes in convergence as a response to awareness of distance produced by increasing and decreasing the size of a target. If a convergence response was produced by size changes in other experiments of this investigation, it is assumed that this was of this same type. The lack of consistency in records obtained during the monocular runs made in the present investigation probably shows that the initiation of the response is dependent upon the subject's paying attention to distance cues.
It is obvious that in everyday life the convergence response resulting from awareness of distance can make a noteworthy contribution to the efficient operation of the fusion mechanism. But whether this type of accommodative convergence response is different from the accommodative convergence resulting from, say, a concave lens placed before one eye might well be questioned. Of course, the external stimulus is somewhat different in the two cases, but that does not necessarily mean that the neurological processes and pathways generating nerve impulses for convergence need be different in the two cases. On the contrary, it would seem that the flow of impulses serving the accommodative convergence response would be independent of the manner in which accommodation is stimulated.

In Figure 54 for LBZ and Figure 55 for RGB the dashed and dotted lines represent the convergence stimulus values for the convergence cycle when set for the double regular convergence and the double opposite runs, respectively; the solid lines represent the response of the eyes as obtained from the convergence records of the same runs. Divisions along the abscissae are seconds of time, and divisions along the ordinates are degrees of convergence. Since the absolute values for the convergence response were not known, the author took considerable freedom in determining the vertical relations between these curves.

During the double regular convergence run from which the lower curve in Figure 54 was made, LBZ experienced a partial diplopia when the target was moving away from him. He said, however, that
Figure 5h.

Relation of Convergence Stimulus to Response
Figure 55.

Relation of Convergence Stimulus to Response

105.
fusion was obtained at the limit and held during movement toward him. The apparent movement of the target was equal to that of the control run. During the double opposite convergence run from which the upper curve was made, he again experienced a partial diplopia when the target was moving away from him, but said that fusion was obtained at the limit and held during the movement toward him. Apparent movement was equal to that of the control.

During the double regular convergence illustrated in Figure 55, RGB reported a diplopia only at the far limit of the apparent movement, and the depth effect was equal to or greater than that of the control. For the double opposite convergence run he reported marked diplopia at both ends of the apparent movement, and the movement was estimated to be two-thirds as great as that for the control.

Typical of most of the records obtained in these experiments is the large lag between the upper and lower limits of the stimulus and response curves. In view of the play allowable in convergence during fixation of the crosshair, however, one perhaps should not be too surprised at this.

It can generally be said that, in spite of the conflicting stimuli presented during this experiment, the motor portion of the fusion mechanism performed very well. For example, the total magnitude of the response to the conflicting stimuli usually was equal to that for the regular stimulus; sometimes the response was of greater magnitude, as in Figure 54, and sometimes it was
less as in Figure 55. Nevertheless, the observers reported doubling more frequently with the conflicting stimuli, indicating that perceived distance does have some sort of influence on the adequate functioning of the total fusion process.

It is recalled that the convergence records of the monocular runs for RGB showed a consistent pattern induced by the apparent fore and aft movement of the target, and it seems reasonable to believe that this response also occurred in other runs during which size changes were taking place. If present, it could account for the extreme difficulty which RGB encountered in attempting to maintain fusion during the opposite convergence runs. Whether the response to awareness of distance occurred or whether it was inhibited poses an interesting question.

The convergence records of the monocular runs for LBZ did not show the consistent tendency present in RGB's, and he had considerably less difficulty than RGB in maintaining fusion during the opposite convergence runs. Since the response to awareness of distance occurred for LBZ during the experiment using the "T", its absence during other experiments must mean that he was able to inhibit the response. How this was accomplished is not clear, but one possibility is that at times he simply did not pay attention to the distance cue. This is to make a distinction between his being aware that the target was moving in a qualitative sort of manner as contrasted to his paying attention to the two specific positions between which it was moving.
If the near response was present during the runs shown in Figures 54 and 55, then the curves could represent an additive result of superimposing the near response upon the fusional response. For the opposite convergence runs this would produce a reduced amplitude of convergence, as for RGB in Figure 55. It is more likely, however, that the amplitude of the convergence response depended entirely upon the disparity produced by the targets. If the near response occurred there would have been more disparity to be overcome by fusional movements during the opposite runs than for the regular runs. LBZ compensated for the adverse effects of the near response, but RGB did not.

It should be noted that doubling can result from an insufficient amplitude or by too great a time lag between stimulus and response. The sluggishness of fusional movements as compared with other eye movements is well known, and one of the functions of accommodative convergence appears to be that of speeding up the fusion process. Since the amplitude of the convergence graphs for the opposite convergence runs was usually as great as for the regular convergence runs, the increased amounts of diplopia encountered during the opposite convergence runs probably resulted from a temporal failure of the relatively slow fusional convergence to keep up with the targets.

Generally speaking, the fusional motor process appears to function independently of awareness to distance; that is to say, disparity in and of itself, rather than the stereo effect result-
ing from the disparity, appears to furnish the stimulus for fusional movements, and perceived distance has no direct effect upon fusional movements.

D. The Nature of Fusional Movements.

Reaction time for fusional movements obtained in the jump duction experiments was less than 200 milliseconds, which is approximately the same as reaction time for accommodative convergence and for fixational movements.

In the same experiments, the velocity of fusional movements appeared to be proportional to the size of the movement. The maximum velocity of fusional movements up to 5 or 6 degrees was 10 degrees per second, or less, and was reached after a relatively long period of acceleration; this is to say that fusional movements are considerably slower and the period of acceleration is longer than for fixational movements of comparable size.

Since the muscles producing convergence movements are capable of contracting at a much faster rate to produce fixational movements, the slowness of contraction for convergence movements is due to the innervation reaching the muscles and not to the muscles themselves.

Although the small sharp convergence peaks associated with fixational movements and "flicks" could be passed over as innervation artifacts, some consideration should be given to their characteristics and possible neurological origin. The velocity of
these small convergence increases appears high enough to be com-
parable to velocities of larger accommodative convergence movements
reported by Allen (1949); however, small, slow accommodative
changes produced by the awareness to distance experiments resulted
in a slow change in convergence, and no increase in frequency of
these peaks appears in those records. Since small changes in accom-
modation occurring during steady fixation are likely to be com-
parably slow, it is unlikely that the peaks are associated with
accommodation and, therefore, are not accommodative convergence.

The reason for the association of the peaks with a fixational
type of movement is not evident, but the fact that they also occur
with flicks, which do not appear necessarily to be fixational or
which occur in only one eye, would lead one to believe that they
are not simply artifacts of fixational movements. If this were so,
one would expect them also to occur rather frequently in the diver-
gence direction.

Considered from the standpoint of a one-component convergence
mechanism, the peaks might be regarded as the result of some sort
of innervation which opposes the elastic forces tending to diverge
the eyes.

E. Accommodative Convergence and the Maintenance of Fusion.

Accommodative convergence normally functions as a process
which reduces the demand on the fusional mechanism when one looks
from one distance to another. In addition to this, however, accom-
modative convergence may be used as a more direct aid for main-
taining single vision. For example, one uses accommodative convergence in going from "blur" to "break" during the measurement of ductions. Also, persons with high phorias at near will sometimes use accommodative convergence to such a degree as to produce considerable blurring in order to prevent the occurrence of a diplopia.

The transition from one type of movement to the other represents a point of considerable interest, and one can raise the question as to the specific nature of the stimulus which can cause accommodation to blur the image in the eyes in the interest of single vision.

F. Instability of Accommodative Convergence During Binocular Fixation.

It can be observed when measuring a phoria, that accommodation and, therefore, accommodative convergence are probably in a constant state of fluctuation, and there is little reason to believe that they are any more fixed and stable during binocular fixation. What, then, is the functional significance of small changes in accommodative convergence during steady fixation? At least three possibilities exist:

(1) The changes in accommodative convergence may simply occur spontaneously as a result of inability of the accommodative mechanism to maintain a steady state. In this event, the disparities resulting from these spontaneous fluctuations should produce a compensatory, or corrective, fusional response.

(2) The accommodative changes may play a purposive or syner-
gic role in cooperation with the more sluggish fusional response. In other words, whenever the so-called fusional innervation becomes too weak or too slow, it is aided by accommodative convergence. Since this sort of relationship is known to exist, as for example, when ductions are measured, there is no reason to believe that accommodative convergence does not continuously serve in this capacity.

(3) Another possibility is that small spontaneous fluctuations in accommodative convergence which are normally present do not produce enough disparity to require a motor compensation, and their effect is dampened out by the process of sensory integration at the cortex.
VI. SUMMARY AND CONCLUSIONS

In this investigation, lateral fusional movements of the eyes have been studied from photographic records obtained as different types of stimuli were presented to the eyes.

Convergence records made during binocular fixation of a crosshair indicated that for only short intervals of time was the convergence held relatively fixed. On the best fixation records, obtained during a high degree of concentration on the part of the observer, it appeared that convergence could not be held fixed within a range of less than approximately 0.25 degrees for fixations lasting several seconds.

With a diamond shaped target which alternately could be contracted and expanded, it was possible to create an illusion of apparent movement of the target between distances of one and three meters in front of the observer. By synchronizing a convergence stimulus with the size changes, the author was able to study the effects of perceived distances upon the fusional response.

In the data obtained in experiments using this apparatus, fusional convergence appeared to respond efficiently to the disparity produced by convergence stimuli, independently of a conflicting perception of distance. It was concluded that perceived distance had no direct effect upon the fusional movements recorded. Furthermore, it appeared that, if convergence per se provides a cue for perceived distance, it was ignored and supplanted by the strong-
or size change cue.

Changes in convergence induced by an illusion of nearness or farness were demonstrated to occur concurrently with changes in accommodation.

Experiments in which the convergence stimulus was "jumped" suddenly from one value to another, showed different characteristics when the targets were jumped to a position requiring convergence than when they were jumped to a position requiring divergence. In each case, the response contained a similar acceleration, but convergence decelerated more rapidly than divergence. After reaching a maximum convergence value, the eyes gradually drifted in a divergent direction, whereas the fast divergence movement tapered off and gradually drifted out toward its maximum value.

Reaction time appeared to be less than 200 milliseconds for this type of movement, and convergence movements appeared to attain a slightly higher velocity than divergence movements. For jumps of up to 5 or 6 degrees the maximum velocity for convergence was 10 degrees per second, or less. Acceleration and deceleration also were more gradual than for fixational movements of comparable size.

If the fusion targets were placed in a convergent position and one of them suddenly eliminated, thereby removing the stimulus to fusion, a divergence movement occurred. The greater the amount of convergence in play at the beginning, the greater the velocity of the divergence movement. When, however, the targets were
placed in a divergent position, and one of them suddenly eliminated, a drift of only a degree or so in a more converged direction occurred from the position near maximum divergence of the eyes.

In the final experiment presented in this report, the targets were diverged until the subject could maintain single vision only part of the time. With the targets in this position, when the observer experienced a diplopia he pressed a microswitch which registered this point on the film record; when single vision was obtained he released the switch registering this point on the record. Neither the transition from double vision to single vision or the transition from single vision to double vision were accompanied by corresponding changes in convergence. Whether the subject attempted to fixate the center of the diamond or the border, it did not appear possible that changes in convergence could account for the reports of single and double vision.

Throughout the data small peaks, associated with fixational movements and small "flicks", were found on the convergence records. These peaks were formed by a relatively fast increase in convergence which usually was followed by a slow divergence movement. As well as could be determined, the velocity of the convergence component appeared to be 10 degrees or more per second, and the divergence component seldom exceeded 3 degrees per second. The peaks occurred rarely, if ever, with a fast divergence component followed by a slow convergence component; that is to say, the peaks always pointed in the direction of convergence. They were found
on every type of record obtained in the experiments, independently of whether fusion stimuli were present.

Although the neurological origin of the convergence peaks could not be implied, the author suggested the possibility of their representing some sort of tonic innervation to convergence.
VII. REFERENCES


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VIII. AUTOBIOGRAPHY

I, Charles Reese Stewart, was born in Oklahoma City, Oklahoma, October 20, 1918. I received my secondary education in the public schools of Oklahoma City. My undergraduate training was obtained at The North Texas State College, The Oklahoma University and The Ohio State University, from which I received the degree Bachelor of Science (Optometry) in 1948. All of my graduate training was obtained at The Ohio State University under the advisorship of Dr. Glenn A. Fry. The degree Master of Science was received in 1950. During the period of my graduate training I held the position of Associate in Optometry. In 1950 I was awarded an American Optometric Foundation Research Fellowship which continued in effect until completion of the requirements for the degree Doctor of Philosophy.