DETERMINATION OF THE LOCATION OF THE CENTER, OR CENTERS,
OF PROJECTION IN ANOMALOUS CORRESPONDENCE

Dissertation

Presented in Partial Fulfillment of the Requirements
for the Degree Doctor of Philosophy in the
Graduate School of the Ohio State
University

By

Neal James Bailey, B.S.
The Ohio State University
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Approved by:
ACKNOWLEDGMENTS

The investigations described in this dissertation do not reflect the efforts of a single individual working alone. For more than three years, the generous contributions of time, knowledge, and encouragement of Professor Glenn A. Fry provided the incentive and the experimental insight which have made this report possible. Many obstacles which, from the author's point of view apparently blocked further progress completely, were accepted by his adviser not as hindrances but as challenges and as opportunities to learn. Professor Fry's devotion to his students and his work cannot be forgotten.

In addition to the help individually provided by his adviser, the author was the recipient of a fellowship from the American Optometric Foundation from September, 1950 through June, 1954 when this work was completed. The author owes a large debt of gratitude to the many optometrists and optometric organizations whose generous contributions made this financial support possible.
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I. INTRODUCTION

Crossed eyes, squint, and strabismus are synonymous terms denoting an inability to direct both eyes to a single object. Although this condition almost never causes any real pain and probably interferes little with the performance of most every day tasks, it has been the subject of investigation by workers in the field of vision for centuries.

Two reasons probably best explain this interest: first, an understanding of how a squinter sees is necessary for a complete understanding of binocular vision and secondly, this clearly visible defect imposes upon the possessor the stigma of inferiority. Hence persons who have this defect want it corrected.

Methods of treating this condition have taken many forms principally because its real nature and its causes have been so poorly understood. In addition, the physical appearance of the eyes gives little or no clue to the visual adaptations which may have accompanied the mechanical deviation of one eye relative to the other.

In everyday life, objects seen in the field of view of one eye are perceived in different directions with respect to ourselves. The apparent angular separation of these objects is related to the angular separation of the images of
the objects on the retina, i.e., to each retinal element there is attached a specific directional value which is dependent on the point in the cortex where the impulse impinges. The fovea is the "principal visual direction." Lotze (Boring, 1942) labeled this the visual "local sign."

Normal binocular individuals who are able to direct both foveas to the same object must have retinal elements in one eye which will give rise to the same visual direction as will similarly placed elements in the opposite eye in order for a unitary concept of direction to take place. This fact Hering (1942) referred to as the law of identical visual directions. This law implies that different objects whose images fall simultaneously upon the foveas or other corresponding areas of the two eyes will be seen in a single subjective direction even if they are actually separated in object space. Persons possessing this faculty of "common visual directions" (Tschermak, 1952) are said to have normal correspondence.

Among squinters there are also some who are capable of demonstrating common visual directions with the two foveas, e.g., with the after image test (Bielschowsky). These we refer to as normal correspondence squinters.

The squinters who are of primary concern here, however, are those in which it is usually possible to demonstrate the...
existence of the local sign attribute in each retina when each eye is used alone but in which the two retinæ do not exhibit common visual directions when corresponding areas of the eyes are stimulated simultaneously. On the contrary, considerable evidence exists which seems to indicate that the fovea of one eye is functionally united to an off-foveal area of the opposite eye insofar as directional values are concerned. This latter type of squinter is said to possess anomalous correspondence (Burian, 1947).

Orientation of ourselves and of objects around us depends upon three mechanisms. First, kinesthesis, which in the case of the eyes probably depends mainly on an "innervational sense" (Helmholtz, 1925; Cogan, 1948; Adler, 1950; Ludvigh, 1952; Walls, 1951; Irvine and Ludvigh, 1936), keeps us informed of the position of our eyes with respect to the head. The proprioceptive type of kinesthesis keeps us informed of the position of the head and limbs with respect to the body and their orientation with respect to gravity. The vestibular system aids the kinesthetic sense in keeping us aware of changes in the position of the head and the position of the head with respect to gravity.

Finally, the visual mechanism, which begins in the retina and extends to the occipital lobe of the brain,
gives us information about the relative oculocentric
direction of objects. All three of these kinds of infor-
mation can contribute to one's awareness that an ob-
ject is located in space in a given position with
reference to his head, limbs, and body.

It is customary to describe the visual perception
of space by saying that perceived images of objects are
"projected" out into space from a "center of projection."
It should be pointed out here that the term "projection"
is not used to imply that the observer is first aware of
a point on the retina being stimulated and then uses this
information to construct an image which he "projects"
somewhere into the space surrounding him (Pascal, 1954).
The observer is aware only of an impression of the object
which exists in space in front of him; he is not conscious
of having received coded bits of information which have to
be re-interpreted as an impression of an object.

The term "lines of projection" is used in a geometric
sense to designate the lines in visual space which
are analogous to the lines of sight in physical space.
The point at which these lines of projection converge is
called the center of projection.

Studies have been conducted mainly on normal binoc-
ular subjects (Hering, 1942; Helmholtz, vol. III, 1925;
Roeloff and de Favauge-Bruyel, 1924; Duane, 1925, 1931; Francis and Harwood, 1951), but also on squinters (Duane, 1925; Brock, 1945-46; Carlson, 1950-52; Tschermak, 1952) in an effort to identify this center (or centers) of projection with some anatomical reference point. In the case of remote objects, no problem is presented in assuming this "center" to be anywhere on the observer's body. In the case of near objects, however, and in the special problems associated with the correction of squint, there is a definite need for a more precise localization of the center from which perceived objects are projected.

The determination of the location of the center of projection presents a number of problems. Though nearly all of us operate on the basis that objects are what they "look" like and are located where they "appear" to be located, it is true that the configuration and location of these objects may be quite different from what our subjective impressions would indicate.

Objective space can be measured quite adequately; subjective visual space, however, must be measured by having the individual perform in objective space while using only subjective clues. For example, as in this study, we can ask him to show us with his hands where a particular visible object is located while his hands are kept from his
view by suitable screening devices. If he is unable to see his hands and the object simultaneously, it is not possible for him to correct for a subjective error in direction since he is not aware that an error is being made.

Investigations of visual space using the hands as indicators introduces the variable of hand and eye coordination and, in order for these investigations to be valid, proper integration of the two senses must be present. Under ordinary conditions of seeing, use is made of all possible clues to construct a framework and to place oneself in it. In the parts of the present study where the hands have been used as described above we must then define our results with these facts in mind, i.e., either the direction of visual projection is the direction indicated by the hand, or a method must be found whereby the error introduced by using the hands can be computed out of the data. Further, since primary consideration has been given to monocular experimental situations, it must be assumed that eye-hand coordination is as good using one eye as the other.
II. HISTORY

If one places his right index finger in line with his right eye and a distant object and his left index finger in line with his left eye and the same distant object, he will note that, when he fixates the far object binocularly, the two fingers fuse and appear to be situated in line with the bridge of his nose and the distant object.

The results of this and similar experiments have led Hering, Helmholtz, Tscherning, and others to speak of the "cyclopean eye" or "binocular" and to place it anatomically at about the root of the nose or the midpoint of the line joining the entrance pupils of the two eyes in binocular subjects. These authors claim, however, that a strong dominance or habitual use of one eye, as in microscopy, may lead to a movement toward one eye of this center of visual directions.

Roeloff and de Favaugé-Bruyel (1924) conducted a study using methods which depended upon the hands for localizing objects. They used only two binocular subjects and concluded that the center of projection in monocular and binocular vision is located rather far behind the eyes, perhaps in the region of the atlas-axis articulation. If this were so, they said, monocular experiments using targets displaced toward the side of the eye used would produce projection lines cross-
ing the interpupillary line well toward this same eye, but
would converge at the atlas-axis articulation in common
with lines from points straight ahead in binocular vision.
They claimed, therefore, that the apparent shift in the cen-
ter of projection with monocular vision was an experimental
artefact.

Duane (1925) stated that in binocular use of the eyes,
"projection by the binocular is performed just as it would
be by each eye, if each were transferred to the root of the
nose." Convergence is the function which "transfers the two
visual axes to the midline." This would also be true in the
case of squinters, even those with anomalous correspondence,
so long as both eyes were open and they were "under the dom-
inination of the sensations set up by convergence", i.e.,
there would be a single center of projection.

In certain types of squinters, however, the "deviating
eye escapes more or less from the influence of ... conver-
gen" and, even when both eyes are apparently used simul-
taneously," acts ... as though governed ... by the impress-
ions" of monocular vision. In this case, each eye would pro-
ject with reference to its own visual axis. He would expect
the center of projection to be in or near the eye used, its
actual site depending on how much the eye has "escaped" the
influence of convergence.

Tschermak (1952) believed that a single center of pro-
8.
jection existed midway between the eyes at the root of the nose, but in predominant use of one eye - "for instance, in squinters" - it may be shifted toward the dominant eye.

"The sensory anomaly (anomalous correspondence) represents not merely two parallel independent egocentric localizations of the two eyes, but a genuine unity - in spite of the un-equivalence of the cooperating partners", i.e., a single center of projection exists even in anomalous correspondence. Tschermak was an anomalous correspondence squinter himself.

Brock (1945-46) observes: "We may conclude that one of the essential differences between our form of vision and that of the confirmed squinter is that in normal binocular vision the line of gaze of the right eye and that of the left eye are cortically united to form a single projection axis, whereas in the squinter the line of gaze of each eye forms its own projection axis."

More recently, Francis and Harwood (1951) conducted experiments with binocular subjects only and concluded that the center of projection varies laterally with changes in image brightness, moving toward the side of the eye with the brighter image.

Substantial agreement appears to prevail regarding a single center of visual directions at the midpoint of the baseline in normal binocular individuals; as to the situation
in squinters, marked disagreement seems to argue for further investigation.
III. GENERAL PLAN OF STUDY

In view of the fact that experimental methods for determining the center of visual directions have never been standardized, it was first necessary to use a variety of techniques on normal subjects in order to have a standard by which to evaluate the responses of the squinters.

The studies which formed the major part of this investigation were those in which images of objects seen with the eyes were localized with the hands. The subjects were permitted to see objects on top of a table and were required to localize them with the hands which were kept hidden from view under the table.

In one of the studies a single near target was placed on the table in the subject's midsagittal plane while he bifixated a distant target. The points where the diplopic images of the near target were localized were used to determine the location of the center of projection.

Previous studies by other investigators had indicated that normal binocular subjects might be expected to use a separate center of projection for each eye in a monocular situation (Roeloff, 1924; Tschermak, 1952). As a preliminary investigation of this problem, two near targets were
placed equal distances on either side of the primary line of sight of one of the eyes; the other eye was occluded. The uncovered eye fixated a distant target. The images of the two near targets were localized in the same manner as in the binocular experiment. A center of projection for each eye was determined from this data. During this phase of the investigation a method was discovered for assessing the error made by the hands in localizing the perceived objects at the right distance.

The technique of fixating a distant target while trying to localize near targets, as was done in the two studies already mentioned, makes it difficult to perceive the distance of the near targets. Consequently in the next study the subject was permitted to fixate on the center one of three targets arranged on an arc of 40 cm radius concentric with the midpoint of the interpupillary line. This arrangement has an advantage in that the three targets appear in the apparent fronto-parallel plane and the subject can localize the images of each of the three objects by moving a pointer along a straight line tangent to the arc at the center target.

Each of the targets was localized by the subject (using his hands as previously described) while he looked at the center target. Monocular fixation with the opposite eye completely occluded, binocular fixation with the
center target visible to both eyes and the remaining targets visible to only one of the eyes, and unobstructed binocular fixation were all used in this series of experiments. For each of these situations, the location of the center of projection was determined in the case of normal binocular subjects.

Two other advantages were also present with the 40 cm arc: (1) targets to be localized were within arm's reach, yet the distance was great enough so that small errors in localization would not unduly influence the results; (2) the accuracy of localization with foveal versus peripheral targets was immediately comparable. The conclusions arrived at in this study lean heavily upon this basic experimental arrangement.

This particular study was supplemented by one in which five targets were used instead of three. This arrangement makes it possible to evaluate the extent to which the eyes can perceive correctly the angular displacement of objects in the periphery of the field of view and the extent to which the hands can estimate the position of images which are seen to the right or to the left of the midline.

One of the fundamental assumptions made in this study was that a normal binocular individual using one or both eyes would see a foveally fixated object in a direction...
parallel to the bisector of the angle of convergence. The correctness of this assumption was tested by two experiments. One of these experiments utilized plus and minus lenses in conjunction with the 40 cm arc.

In the second experiment, the subject was required to walk toward a distant object. All clues to direction except the target itself were removed from the subject's field of view by the use of special "peephole" goggles.

Attempts to use binocular experiments in the study of squinters were unsuccessful. The 40 cm arc apparatus using monocular fixation was employed to collect data relative to the location of the center of projection in these subjects. Esotropes and exotropes, including both monolateral and alternating types, were used in this phase of the study. A few of these squinters possessed normal correspondence, but the majority exhibited responses characteristic of anomalous correspondence.

The direction of projection of these same subjects was tested by means of the walking experiment and the 40 cm arc in conjunction with plus and minus lenses.

Since vision in strabismus appears to have features somewhat similar to that in one-eyed persons, a few one-eyed subjects were tested with the same procedures as those
used for the squinters.

Supplemental studies relating to an individual's ability to demonstrate a knowledge of the position of his head, shoulders, arms, and body with reference to objects placed in front of him were also carried out with binocular subjects, one-eyed subjects, and squinters.
IV. WALKING EXPERIMENT

One of the basic assumptions that has been made in the interpretation of the data is that the direction of projection is parallel to the bisector of the angle of convergence. In order to test the validity of this assumption, a walking experiment was carried out.

This investigation was conducted on a large open field. One eye of the subject was covered and he was placed with the center of his back touching a vertical string suspending a plumb bob. He was instructed to walk toward a target 1000 yards away. The experimenter told him to stop after he had walked 50 yards "toward the target."

The angular deviation of his path from the direction of the target was determined by mounting a two-meter stick behind the string. The two-meter stick was horizontal and was bisected by a line through the string and the distant target. By moving the eye along the two-meter stick to sight on the string and the subject, one could determine the angular deviation of the subject's path from the target in 1/20 prism diopter steps.

The subject made five trials with one eye covered and then five trials with the other eye covered. The average
deviation in each of these sets of five trials was used to evaluate the correctness of his projection using either eye.

In Table I are shown the data collected by the above method. It can be seen that the subjects walk quite straight toward the target using both eyes or one eye alone when no prisms are placed before the eyes. However, when an effort was made to check the accuracy with which they followed fixational movements to the right or left using prisms placed before one eye alone or both eyes together, it was found that the path of the subject deviated less than would be predicted on the basis of the power of the prism used. It seemed probable that clues other than the target itself were being used as an aid.

To prevent the subject from seeing the ground and to confine his clues as to direction almost entirely to the target itself, special goggles with a two mm opening placed two cm in front of each of the eyes were devised. The subject wore these over his customary Rx (Fig. 1).

Table II shows data for H. B. taken without the special goggles, and Table III, with the special goggles. It can be seen that when the goggles are worn, deviations in path direction are almost exactly as predicted by the power of the prism used.

17.
Table I. "Walking experiment" data for three normal binocular subjects. No peephole goggles were used. Deviations to the right are indicated by a plus sign (+); to the left, by a minus sign (-). All measurements are in prism diopters.

<table>
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<th>Prism</th>
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<th>Average Deviation</th>
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Fig. 1. A subject wearing the special "peephole" goggles used in the "Walking Experiment."
Table II. "Walking experiment" data for subject N. B., a normal binocular subject. No peephole goggles were used. Deviations to the right are indicated by a plus sign (+); to the left, by a minus sign (-). Measurements are in prism diopters.

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Table III. "Walking Experiment" data for subject N. B., showing the more precise agreement between prism power and the subject's path deviation when the special goggles were used. Deviations to the right are indicated by a plus sign (+); to the left, by a minus sign (-). Measurements are in prism diopters.

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</tr>
<tr>
<td>L</td>
<td>0</td>
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<td>+3.1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>L</td>
<td>18</td>
<td>R</td>
<td>-16.0</td>
<td>-14.9</td>
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<tr>
<td>L</td>
<td>18</td>
<td>L</td>
<td>+21.2</td>
<td>+21.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>
Data for five binocular subjects wearing the special goggles but without prisms are presented in Table IV. Errors made in walking are small enough so that it may be concluded that projection is along the bisector of the angle of convergence as assumed.

In the case of D. S., it is probable that a binocular instability by which the left eye is suppressed frequently during ordinary seeing has interfered with the projection ability of this eye. This will be discussed further in connection with this subject's errors in localization on the 40 cm arc.
Table IV. "Walking experiment" data for five normal binocular subjects showing the path deviation when one eye was covered and the special goggles were worn. Phoria and path deviations are measured in prism diopters. A plus sign (+) indicates a deviation to the right; a minus sign (-), to the left.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Phoria</th>
<th>Deviation Right Eye</th>
<th>Deviation Left Eye</th>
</tr>
</thead>
<tbody>
<tr>
<td>F. B.</td>
<td>ortho</td>
<td>+0.6</td>
<td>+0.6</td>
</tr>
<tr>
<td>J. E.</td>
<td>6 exo</td>
<td>-0.5</td>
<td>+2.1</td>
</tr>
<tr>
<td>H. G.</td>
<td>5 eso</td>
<td>+0.3</td>
<td>-0.9</td>
</tr>
<tr>
<td>J. H.</td>
<td>4 exo</td>
<td>+1.4</td>
<td>-1.0</td>
</tr>
<tr>
<td>D. S.</td>
<td>1 exo</td>
<td>-1.1</td>
<td>-4.6</td>
</tr>
</tbody>
</table>
A. Apparatus and Procedure

The subject was seated at a comfortable height before a specially constructed table which was 120 cm high, 115 cm wide and 90 cm deep (Fig. 2). His forehead and chin were held in position by rests provided (F). He was permitted to see objects placed on top of the table and was required to localize them with his hands which were kept hidden from view under the table (Fig. 3).

Along the edge nearest the observer, a translucent sheet of plastic (BB') which projected 5.5 cm above the table top served as a screen to prevent the subject from seeing any part of the table top when the pupils of his eyes were positioned six cm behind the screen and about one mm above its top edge. This arrangement prevented him from seeing how or where on the table top the targets were attached.

Accurate localization of the right eye in anterior-posterior positioning of the head was provided for by placing the cornea of the right eye in line with the straight edges S and D. The interpupillary line of the subject was kept perpendicular to the line between the near target P and the distant target P̅.
Lateral positioning of the head was managed by lining up the pupil of each eye and the fixation target with the sighting device, LL'. The pointed rod, L, was suspended just above the pupil of the left eye and was placed one-half the subject's P.D. to the left of the line through the near target P and the far target P. L' (also a pointed rod) was suspended just above the pupil of the right eye and was placed one-half the P.D. to the right of this same line so that this line coincided with the midsagittal plane of the subject. During each run the subject periodically checked to see that with the right eye he saw L' above and in line with the fixation target, P.

Binocular fixation was maintained on a target, P, placed 5.7 meters in front of the observer (Fig. 4).

A second target, P, was placed in the midsagittal plane of the observer within arm's reach at two different positions. For one position (P₁), the target P was placed so that the angle $\gamma_R$ or $\gamma_L$ between the line of sight and the target for the right eye or left eye respectively was equal to $7^\circ 15'$ at the entrance pupil of each eye. In the second position (P₂), the target P was placed so that $\gamma_R$ and $\gamma_L$ were each equal to $4^\circ 15'$. The distances of the near target from the eyes were so chosen that the angles $\gamma_R$ and $\gamma_L$ for a given target position remained constant.
Fig. 4. Schematic top view of the Binocular Diplopia Method. The principal line of sight of each eye is directed toward the distant target, P. This drawing also illustrates one method of locating the center of projection, S, from the perceived positions of PR and PL. The midpoint of the interpupillary line is at C.
Angle of Convergence
Bisector

Fig 4
for various interpupillary distances.

The near target \( P \) was seen by each eye on the opposite side of the bisector of the angle of convergence, and the apparent location of each of the images (\( P_R^l \) and \( P_L^l \)) of the target was indicated by the subject by placing the pointer \( A \) under the table directly beneath the apparent position of the object.

The two rods \( R \) and \( C \) were loosely joined to the pointer \( A \). (Fig. 2). These rods pivoted around the points \( M \) and \( N \) and could be displaced in a longitudinal direction. Longitudinal movements of rod \( R \) were communicated to an indicator on the meter stick \( R' \) via a system of pulleys, and longitudinal movements of rod \( C \) were likewise communicated to an indicator on the meter stick \( C' \). Both meter sticks (\( R' \) and \( C' \)) were placed close together at one side of the table for easy reading. The position of \( A \) was recorded as "\( x \) cm from \( N \)" and "\( y \) cm from \( M \)." The actual position of \( A \) with reference to the subject was then plotted on a graph drawn to scale. The coordinate lines were arcs (\( aa' \) and \( bb' \)) centered at \( M \) and \( N \). From this graph one could determine the fore and aft displacement of the pointer from the interpupillary line, and the lateral displacement from the midsagittal plane. The subject had complete freedom to place the pointer at the distance and direction from his
eyes where he felt the image was really located.

Five trials on each image for a total of ten trials constituted one "run." The average of the five trials on each image was taken to plot the apparent position of $P'_R$ or $P'_L$ for each eye. It was assumed that the image $P'$ of the fixation point $P$ was projected from the center of projection parallel to the bisector of the angle of convergence. The two points $P'_R$ and $P'_L$ were then assumed to be perceived in directions displaced from $SF'$ through angles $\psi'_R$ and $\psi'_L$ respectively which are equal to the angles $\psi_R$ and $\psi_L$ between the primary lines of sight and the actual direction of the target, $P$, at the centers of the entrance pupils. Since bifixation of the target $P$ was maintained by the subject, it was not necessary to make any correction for a localization error due to the phoria.

Using these assumed relationships, lines were drawn through the two points $P'_R$ and $P'_L$ so that $\psi'_R = \psi_R$ and $\psi'_L = \psi_L$. The center of projection for this experimental situation is assumed to lie at the point of intersection of these two lines.

B. Results

Fry (1950) discussed this method as one which is valid for locating the center of projection in binocular in-
individuals. As a preliminary investigation, thirteen binocular subjects, ages 21 to 35, were run to determine whether, in a group of normal binocular individuals, this method located a center of projection which agreed with the generally proposed notion that this center was at the midpoint of the line connecting the entrance pupils of the two eyes.

Figure 5 shows the data for the thirteen subjects plotted for center of projection for target $P_1$. Three subjects were run twice; the open circles were first runs. An arrow joins the same subject's first run to his second run (filled circles). This graph illustrates that when the data for all subjects for target $P_1$ are grouped together, the average center of projection is found to be located 6.2 cm in front of the interpupillary line and 0.9 cm to the left of the midline.

Figure 6 is a plot of the average center of projection when the data for target $P_2$ are similarly grouped. The average center of projection for $P_2$ is found to be eight cm in front of the interpupillary line and 1.2 cm to the left of the midline. Note that the center of projection located by this method is generally well in front of the entrance pupil line.

The small differences in the average location of the center of projection for these two target distances can
Location of the Center of Projection
Fig. 5. Target P₁
Location of the Center of Projection

Fig. 6. Target P₂
probably be accounted for primarily on the basis of experimental error introduced by the variance in hand-eye coordination of these subjects.

Attention should also be called to the study by Brown (1953) in which six subjects tested during a period of two to nine weeks were required to judge when a horizontal or vertical line was exactly bisected while using only one eye. Trends were found which indicated that apparent size in a given part of the visual field sometimes varies gradually but markedly with respect to time. Since judgments of target location depend essentially on estimation of visual angles in a similar sense to those of Brown's study, it is conceivable that factors acting in the "half-meridional difference" report of his are also factors here.

In Figs. 7 and 8, the changes in perceived lateral separation of the diplopic images with changes in the average perceived distance of the images for targets $P_1$ and $P_2$ respectively are shown. The sloping line, MN, in each graph represents the predicted change in separation of the diplopic images with change in perceived distance based on the assumption that the angle between the two images measured at the midpoint of the interpupillary line should be equal to $14.5^\circ$ in the case of Fig. 7, and $8.5^\circ$ in the case of Fig. 8. Figure 7 for $P_1$ shows almost 33.
Fig. 7

13 Subjects
Target P₁

Perceived Distance of Images Compared to Actual

Perceived Separation of Images Compared to Actual Separation
Fig. 8

Perceived Distance of Images Compared to Actual

13 Subjects
Target P₂

Perceived Separation of Images Compared to Actual Separation

35.
no correlation between perceived separation and perceived distance; Fig 8 for $P_2$, however, shows that some agreement does exist.

These data show rather clearly that the perceived separation of the images is, in general, less than would be mathematically predicted, i.e., most of the points fall to the left of the mathematically derived vertical line, ST. In addition, the perceived distance of the target is different from its actual distance.

At a later date, N. B. was used as a subject, and made ten runs over a week's time. The locations of his center of projection for target $P_1$ are shown in Fig. 9. The average of these data shows his center of projection for target $P_1$ to be located 3.9 cm in front of the entrance pupil line and 0.5 cm to the left of the midline. For target $P_2$ (Fig. 10), the center of projection is found 3.7 cm in front of the entrance pupil line and 0.7 cm to the left of the midline. Changing the target distance, then, has almost no effect on the location of the center of projection for this subject.

Plots of the perceived locations of the diplopic images of target $P_1$ and $P_2$ are shown in Figs. 11 and 12 respectively. The two parallel lines on one side of each graph meet the two parallel lines on the opposite side of 36.
Subject: N. B.
Target P1

Location of the Center of Projection

Fig. 9
Subject: N. B.
Target P₂

Fig. 10

38.
Fig. 11 Target $P_1$

Localization of Diplopic Images

Fig. 12 Target $P_2$
each graph and form an angle of $14.5^\circ$ in the case of Fig. 11 and $8.5^\circ$ in Fig. 12. The points are grouped closely enough between these lines to suggest that there is some connection between perceived separation and perceived distance.

On the basis of the combined data for 13 subjects and the cumulative data for one subject (N. B.), it seems probable that the center of projection is near the mid-sagittal plane when both eyes are used. The discrepancy between perceived and actual separation of the diplopic images may be due to one or more of the following possibilities:

(1) The fore and aft shift of the center of projection.

(2) An error in the visually perceived angular displacement of the target from the midline.

(3) An error in estimating with the hands the position of the visually perceived image.

This experiment, however, brings out the fact that a great deal of data must be collected to obtain averages which have significance. This is shown by the spread of points indicating the center of projection for N. B. and also by the unpredictable shifts in center of projection locations for the 13 subjects with changes in target distance. If any two center of projection locations for 40.
targets \( P_1 \) and \( P_2 \) for N. B. were taken consecutively, this same erratic shift in center of projection location would also show up.

Attempted trials with the binocular diplopia method using squinters who had anomalous correspondence made it clear that a different method, probably a monocular one, must be used with squinters. When they attempted to fixate the distant target \( \overline{P} \) with the eye preferred for fixation, a diplopia of the near target \( P \) was obtained, at best, for only short periods. Also, in their efforts to see the target \( P \) as two images even for these short periods, it was frequently found that the eye used for fixation of \( \overline{P} \) changed, i.e., alternation occurred. In addition, even when two near images of \( P \) were seen, it was nearly impossible for the squinters to make a judgment as to the location of more than one of the diplopic images.
VI. MONOCULAR TWO TARGET METHOD

A. Apparatus and Procedure

This is one of several monocular methods devised for testing squinters because the binocular method was not successful with them. In this particular section, the results obtained with a normal subject have been described. The purpose has been to find whether it makes a difference in normal subjects whether one or two eyes are used.

The specially constructed table described under "Binocular Diplopia Method" was used here with similar precautions observed relative to head and eye positioning.

In the case of the one subject, N. B., to be reported on here, the following procedure was used. The subject fixated with one eye a target, \( \overline{P} \), 5.7 meters in front of him; the other eye was occluded (Fig. 13). Two near targets, \( P_1 \) and \( P_2 \), were set up on the right and left side respectively of the line of sight of the fixing eye so that the angle between each target and the line of sight at the entrance pupil, \( R \), of the fixing eye was \( 15^\circ \) i.e., \( P_1 \) and \( P_2 \) were placed \( 30^\circ \) apart. Two distances were used: in one case, the two targets \( P_1 \) and \( P_2 \) were placed 20 cm in front of the line through the entrance pupils of the
Fig. 13. Schematic top view of the Monocular Two Target Method. Esophoria is indicated by the crossing of the visual axes in front of the distant target, P. This drawing also illustrates one method of locating the center of projection, S, from the perceived positions of P₁ and P₂. The midpoint of the interpupillary line is at C.
Primary Line of Sight (OD)

Primary Line of Sight (OS)

Angle of Convergence

Phoria Bisector

Fig 13
two eyes; in the second case, P₁ and P₂ were placed 40 cm in front of the entrance pupil line.

The locations of the images (P'₁ and P'₂) of these two objects were indicated by the subject by means of a pointer, A, held in both hands under the table. Five trials on each image for a total of ten trials constituted a "run." The average for the set of five trials for each target, after a correction for the distance phoria had been made, was used as a measure of the apparent displacement of the target.

The phoria at distance was measured using a single letter of 20/30 size as a target. Sufficient vertical prism was placed over the left eye to dissociate the eyes. A Risley rotary prism with its base-apex line horizontal was placed over the right eye. The lateral prism was varied while the left eye was intermittently exposed until the subject reported the two targets in vertical alignment.

The correction for the phoria is based upon the assumption that when innervation is supplied to the eye muscles, it is supplied in equal quantity to each eye (Hering's Law of Equal Innervation). If an esophoria is present, as in Fig. 13, the eyes are assumed to make a convergence movement first which causes both lines of sight to intersect at the midline closer to the subject than P. Each
eye would over-converge an amount equal to one-half the phoria. If neither eye were covered, innervation of equal amount to each eye would be furnished which would cause each eye to execute a divergent fusional movement equal to one-half the phoria and P would be seen singly and still on the midline.

If, however, the left eye were covered, as in this experiment, and the eyes had over-converged so that the right eye was looking to the left of P, a fixational movement would be substituted for the fusional movement. Sufficient innervation to turn the right eye to the right through an angle equal to one-half the phoria would be furnished to the right eye and the left eye so that a conjunctive movement to the right would occur. Since fixational movements are interpreted by the subject to imply that the object fixated has moved laterally a distance equal to the mean change in direction of gaze of the eyes, P would now be seen to the right of its actual position by an amount equal to one-half the phoria.

If P is fixated at 40 cm and the total esophoria is 10 prism diopters, the image P' will be seen two cm farther to the right than if the esophoria were not present, since a prism diopter at 40 cm equals 0.4 cm. The apparent localization of P' would be indicated by the subject by plac-
ing the pointer under it but, in plotting its localization for our purposes, this point would be moved two cm to the left of where the subject has placed the pointer during the experiment in order to correct for the error due to the phoria.

In the case of exophoria with the right eye fixing the target, localization too far to the left would be predicted, hence the correction applied would be to move the point indicated by the subject with his pointer two cm to the right.

Plotting the location of the center of projection depends upon two assumptions. (1) The image of the fixation point is projected from the center of projection in a direction parallel to the bisector of the angle of convergence. (2) The point in Fig. 13 is perceived in a direction displaced from through the angle which is equal to angle between the primary line of sight and the actual direction of the target at the center of the entrance pupil of the eye used. This same assumption applies in the case of target , and angles and . Using these assumed relationships, lines are drawn through the two points ( and ) so that and . The center of projection for the eye used in this experimental situation is assumed to be at the point of 46.
intersection of these lines.

B. Results

In order to determine where the center of projection would be found in binocular subjects using this method, N. B. served as a subject. Five runs were made for the right eye and five for the left eye at the 20 cm setting. Figure 14 is a plot of the locations of the center of projection found for this observer at this setting. Averaging the right eye findings together shows its center of projection to be 1.2 cm to the right of the midline and 3.4 cm behind the entrance pupil line. For the left eye, the "average" center of projection is to the left 1.4 cm and 4.3 cm behind the entrance pupil line.

Figure 15 shows the center of projection data for \( P_1 \) and \( P_2 \) placed 40 cm in front of the subject. Five runs were made for the right eye and five for the left. The "average" center of projection for the right eye is 1.2 cm to the right of the midline and 7.7 cm behind the entrance pupil line. For the left eye, the average is 0.9 cm to the left of the midline and 10.4 cm behind the entrance pupil line.

The "average" separation of the centers of projection for the right eye and left eye at the 20 cm setting is 47.
Subject: N. B.  
No Stop Used

Fig. 14. $P_1$ and $P_2$ at 20 cm

Location of the Center of Projection

Fig. 15. $P_1$ and $P_2$ at 40 cm
2.6 cm; for the 40 cm setting, these centers are 2.1 cm apart. In both cases, the centers are behind the midline, i.e., the perceived angular separation of the images of targets P_1 and P_2, as indicated by the hands, is greater than the actual separation of these targets.

The method of analyzing the data illustrated in Figs. 14 and 15 is based upon the assumption that the hands locate the visual images correctly and that the eyes see relative visual directions correctly. In order to account for the discrepancy between the perceived and actual angular separations measured at the midpoint of the interpupillary line, it is necessary to assume that the center of projection lies in front of or behind the interpupillary plane.

If by various methods the center of projection always appeared to be located at a fixed distance in front of or behind the interpupillary line, this might be used as evidence that the center of projection can lie in front of or behind this line. In Figs. 14 and 15 it can be seen that the fore and aft displacement of the center of projection behind the interpupillary line varies with the distance of the target. In the binocular method, the center of projection was in front of the interpupillary line. It is improbable that a person's center of projection actually varies in such a manner.
Instead of trying to explain the apparent discrepancy between perceived separation of the targets and their actual separation by assuming that the center of projection is displaced in front of or behind the interpupillary line, one can assume at the outset that the center of projection lies on the interpupillary line and attempt to account for the discrepancy between perceived and actual separation in some other way.

Since individuals in their daily life appear to see objects in their right directions, it follows that visual angles are quite correctly estimated. Also, the visual mechanism makes its size judgments on the basis of perceived angles, i.e., for a given perceived distance, the larger the visual angle, the larger the visual size.

However, when an individual uses his hands to demonstrate how large a fish he caught, he spreads his hands apart the same distance whether he holds his hands close to the front of his body or well out away from himself. This might imply that the hands estimate size on the basis of linear units instead of angular separation at some reference point.

In Fig. 16, the targets \( P_1 \) and \( P_2 \) are visually perceived in one plane (AB) and an estimate of linear size is made based on the visual angle. The subject (whose hands are in the plane FG), believing that his hands under the

50.
Fig. 16
are in the same plane as the visually perceived targets, will place the pointer A under the point F and then G and these points will be separated an amount which is linearly equal to \( \overline{AB} \). If the subject realized that there was a discrepancy between the perceived locations of the visual plane and the plane of his hands, he would place the pointer at L and then M. Hence, the error made is not one of lateral size or angle, but one dependent on the difference in the perceived planes of visual versus haptic localization.

Another possible error is the misjudgment of the lateral position of the hands when they are believed to correspond to the visually perceived targets. These two errors combine to produce the discrepancy between the perceived separation and the actual separation. A measure of the total error can be obtained by plotting the data as shown in Figs. 17 and 18.

These graphs are based on the same data as used for Figs. 14 and 15. The average of five runs is taken to plot each point. In constructing these graphs, it is assumed that the displacement of the pointer from the mid-sagittal plane is a measure of the apparent displacement of the target and that the angular separation of the targets is correctly perceived visually. Allowance for the phoria is made here as in the previous graphs. The ab-
Fig. 18.  $P_1$ and $P_2$ at 40 cm

Subject: N. B.
scissa represents actual displacement of the target from the midsagittal plane; the ordinate represents perceived displacement of the image of the target from the midsagittal plane.

A line drawn between the two points, \( P_1 \) and \( P_2 \), for the right eye crosses the vertical line depicting the line of sight of the right eye at \( M \). For the left eye, the line drawn between the two points, \( P_1 \) and \( P_2 \), crosses the line of sight of the left eye at \( N \). The displacements of \( M \) and \( N \) from the midsagittal plane represent the measured displacements of the center of projection from the midsagittal plane since it has been assumed that a target (if one existed at \( M \) or \( N \)) seen with the fovea of either eye is projected out from the center of projection along a line parallel to the bisector of the angle of convergence.

The slope of each line indicates the ratio of the perceived distance to the actual distance of the targets, i.e., the ratio of \( a \) to \( b \) in Fig. 16.

In Fig. 17, it is seen that the average center of projection for the right eye is still 1.2 cm to the right and for the left eye, it is 1.4 cm to the left of the midline. In Fig. 18, the center of projection for the right eye is 1.2 cm to the right and for the left eye is 0.9 cm to the left of the midline. The lateral dimensions found by this

55.
method agree with those found by the method used for Figs. 14 and 15.

Considering both the 20 cm and the 40 cm target distances, a center of projection for the right eye is found about one cm to the right, and for the left eye, about one cm to the left of the midline.

Analysis of the data collected with the arc system using the two rods joined by the pointer was very tedious. In order to simplify the procedure for the remainder of the experiments, a stop was put under the table in the plane of the targets against which the subject could hold the pointer and along which this pointer could be moved laterally. This allowed the use of a single recording indicator since only lateral displacements of the pointer from the midsagittal plane had to be recorded.

It is possible that some of the subjects did not perceive the stop as lying in the same plane as the targets. In analyzing the data it was assumed that, if the stop and the target were perceived in different planes, then the subject perceived the target as lying in the correct direction and placed the pointer so that it would be at the same distance from the midsagittal plane as the target.

Figs. 19 and 20 show the locations of the center of projection found under identical conditions as in Figs. 14 and 15 except that a stop was now being used. N. B. again
Subject: N. B.
Stop Used

O.D.
O.S.

Fig. 19. \( P_1 \) and \( P_2 \) at 20 cm

Location of the Center of Projection

Fig. 20. \( P_1 \) and \( P_2 \) at 40 cm
served as the subject. For the targets placed at 20 cm, the average center of projection for the right eye was two cm to the right of the midline and 1.8 cm behind the entrance pupil line; for the left eye, 0.2 cm to the left of the midline and 1.6 cm behind the entrance pupil line. For the 40 cm setting, the center of projection for the right eye was found two cm to the right and 5.1 cm behind; for the left eye, 0.5 cm to the left of the midline and 5.3 cm behind the entrance pupil line.

Comparison of Figs. 19 and 20 (using the stop bar) with Figs. 14 and 15 (no stop bar used) would indicate that the centers found in either case are identical if allowances for experimental error are made; using the stop has little effect on the measurement of the position of the center of projection.

These monocular data would indicate that a separate center of projection is used for each eye when the opposite eye is removed from action. It is possible that the displacement of the center of projection from the midline can be accounted for on the basis of the phoria being different under these experimental conditions than under the conditions existing when it was measured. Blurring of the distant target \( P \) was sometimes noticed during the experiment. Since a full correction was worn by the subject, this might indicate accommodation for a plane nearer 58.
than the target $P$ was occurring. Esophoria, induced by the change in accommodation, would have the effect of making the center of projection appear to be displaced toward the eye used.

Roeloff and de Favauge-Bruyel (1924) discuss the fact that, in monocular studies, localization of objects in the temporal half of the visual field is always approximately correct. In the nasal half of the field, however, "a typical error in localization always occurs" in which objects are localized too far to the left with the right eye and too far to the right with the left eye. This "error" is clearly demonstrated in the data of N. B. in Fig. 17 by the slope of the line joining $P_1$ and $P_2$. If this "error" were not present, the line $P_1P_2$ would be parallel to line $AB$. The difference in the slope of the line $P_1P_2$ compared to the slope of line $AB$ has already been explained as being due to the difference in the visually perceived plane of the targets as compared to the actual plane of the targets and therefore represents the ratio of the visually perceived distance of the target plane to that of the actual target plane.
VII. FIVE TARGET ARC AT 30 CM

A. Apparatus and procedure

The specially constructed table described under "Binocular Diplopia Method" was used here with similar precautions observed relative to head and eye positioning. In addition, a uniform white background was provided in the form of a cylindrical arc, E, of white poster board (Fig. 21). This arc had a radius of 40 cm concentric with the midpoint of the observer's interpupillary line and formed a semi-circle 30 cm high on the table. Two lamps, F and G, mounted on the arc were positioned so as to give uniform illumination over the whole inner arc surface.

Each of the five targets consisted of 1.5 mm drill rod 10 cm long placed along the arc of a circle of 30 cm radius concentric with the midpoint of the interpupillary line. Each target was separated from the adjacent one by an angle of 10° measured at the center of the arc between the two eyes. Table V gives the physical location of the targets in cm.

The targets, numbered from one through five starting at the left, were placed simultaneously on the arc of 30 cm radius and the subject maintained clear fixation on...
Five Target Arc at 30 cm
Fig. 21
Table V. Locations of targets one through five along the 30 cm arc. Lateral dimensions are measured along a perpendicular from the midline of the subject. Anterior-posterior dimensions are measured along a perpendicular from the interpupillary line. Distances to the right of the midline are indicated by a plus sign (+); to the left, by a minus sign (-).

<table>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>x</td>
<td>-11.0</td>
<td>-5.3</td>
<td>0</td>
<td>+5.3</td>
<td>+11.0</td>
</tr>
<tr>
<td>y</td>
<td>30.0</td>
<td>30.0</td>
<td>30.0</td>
<td>30.0</td>
<td>30.0</td>
</tr>
</tbody>
</table>

*A = True location of targets on arc.
B = Target location projected from a point midway between the two eyes to the plane of the stop bar under table.

x = Lateral distance to the target.
y = Anterior distance to the target.
three letters of five minutes visual angle (20/20) each. These letters were attached to target number three (center target). If the subject's visual acuity was too poor to see these letters clearly, larger ones were substituted or he was instructed to look only at the number three rod. Stability and exactness of accommodation presented real problems. A subjective optometer arrangement was set up, but was not used since it appeared to afford too much distraction to the subject in his localization efforts.

Fixation was at 30 cm, hence the phoria was measured at 30 cm with the eyes dissociated vertically. One eye maintained clear fixation on a row of 20/20 letters placed 30 cm in front of the interpupillary line while the other eye was intermittently exposed. Lateral prism before the latter eye was varied until the subject reported the two images in vertical alignment. The phoria correction for the parts of this experiment where monocular fixation was used was based on one-half the phoria as described under "Monocular Two Target Method."

A stop bar, H, was placed under the table in the plane of the number three target at 30 cm and the subject held the pointer against this stop bar in localizing all five targets. The lateral location of the pointer was communicated to an indicator on the meter stick, R. The proced-
ure consisted of fixating the letters on the number three rod and localizing each rod in turn five times, starting with the number one rod. After rod five was localized in this run, the subject moved away from the apparatus and rested three to five minutes. After again positioning himself at the apparatus, he localized all five rods five times each once more, this time starting with number five and proceeding through rod number one.

By the above procedure, each rod was localized by the subject ten times. The average of these ten trials for each rod was used to plot the apparent location of the rod.

The above described procedure was followed using three different fixation arrangements:

(1) Binocular fixation of target three.
All of the targets were seen simultaneously with both eyes.

(2) Monocular fixation of target three.
One eye was occluded and the covered eye was presumed to assume its phoria position. A correction for the phoria at 30 cm was applied before the center of projection was plotted.

(3) Binocular fixation with shield.
This was accomplished by using a "shield" of translucent plastic with a hole three mm in
diameter drilled in it and positioned in front of the "covered" eye so that only target three was visible to this eye. The uncovered eye, of course, saw all five targets. Convergence was thereby controlled, hence no phoria correction was necessary, and it was possible to check localization of the center target using both eyes as compared to localization of the remaining four targets using only the uncovered eye.

B. Results

Experimental procedures used prior to this had been carried out with the subject fixating a target 5.7 meters away. Since subjects normally are concerned more directly with the location of objects in or near the plane of accommodation, it was felt that information based on such experiments would be of value in this study. In addition, on the graphs used with the Monocular Two Target Method, a straight line was drawn between $P_1$ and $P_2$ because only two points were known. Using five targets should help determine whether this is really a straight line.

Tschermak (1952, p. 165) states: "For moderate distances of observation, particularly for a distance of 65."
30 cm, the horopter coincides approximately with the equidistant circle, i.e., a circle whose center is at the root of the nose and which passes through the fixation point." When the 30 cm arc experiments were carried out, most of the subjects claimed they saw the targets as single and lying approximately in a straight line with binocular as well as monocular fixation of the center target.

Analysis of the data for this procedure was accomplished by the use of the graphical method in which actual displacements of the targets from the midsagittal plane are shown on the abscissa and perceived displacements of the targets from the midsagittal plane are shown on the ordinate. "Actual" displacements of the targets from the midsagittal plane, however, are based on the assumption that the targets on the arcs were perceived as lying in a straight line in the plane of target three which is the plane in which the stop bar was placed (Table V).

Figures 22, 23, and 24 show binocular and monocular data for the 30 cm arc plotted for N. B. The binocular data for three runs indicate good repeatability (Fig. 22).

The straight line between \( P_1 \) and \( P_2 \) in the Monocular Two Target graphs is now seen to be an ogive. The same tendency of the curves for the right eye to be parallel to those for the left eye is evident in Figs. 22 and 23,
Subject: N. B.

Run 1
Run 2
Run 3

Monocular
(Occlusion)

Monocular
(Sheild)

Fig. 22

Fig. 23

Fig. 24

67.
indicating that the discrepancy between the perceived and actual distance of the targets is about the same for both eyes. However, a change toward less slope with this experimental arrangement as compared to the Monocular Two Target Method is noticed which would indicate a change in the perceived distance as compared to the actual distance of the targets. Other subjects' data did not reflect this change in slope with the change in fixation distance. The fact that the right and left eye curves using the shield (Fig. 23) are closer together than those with occlusion (Fig. 22) may indicate that the phoria with occlusion is different from the one measured prior to the experiment.

The location of the center of projection is determined by the localization of target three since this is the target seen by the subject along his principal line of sight using either eye. This object should be seen straight in front of his nose, or on the graph, at the intersection of the vertical and horizontal zero lines if his center of projection is at the midpoint of the interpupillary line.

Table VI shows the locations of the center of projection of the five subjects used in this experiment.

Three possible explanations for the fact that with
Table VI. Location of the center of projection for five binocular subjects using the Five Target Arc at 30 cm. A plus sign (+) indicates a location to the right of the subject's midline; a minus sign (-), to the left. Dimensions are in cm.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Fixation</th>
<th>Center of Projection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Binocular</td>
</tr>
<tr>
<td>N. B.</td>
<td>Binocular</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Binocular</td>
<td>+0.9</td>
</tr>
<tr>
<td></td>
<td>Binocular</td>
<td>+0.2</td>
</tr>
<tr>
<td></td>
<td>Occlusion</td>
<td>+0.5</td>
</tr>
<tr>
<td></td>
<td>Occlusion</td>
<td>-0.4</td>
</tr>
<tr>
<td></td>
<td>Shield</td>
<td>+0.4</td>
</tr>
<tr>
<td></td>
<td>Shield</td>
<td>+1.1</td>
</tr>
<tr>
<td>F. B.</td>
<td>Binocular</td>
<td>-0.8</td>
</tr>
<tr>
<td></td>
<td>Binocular</td>
<td>-0.5</td>
</tr>
<tr>
<td></td>
<td>Occlusion</td>
<td>-0.3</td>
</tr>
<tr>
<td></td>
<td>Shield</td>
<td>-0.3</td>
</tr>
<tr>
<td>J. R.</td>
<td>Binocular</td>
<td>-0.4</td>
</tr>
<tr>
<td></td>
<td>Occlusion</td>
<td>-2.8</td>
</tr>
<tr>
<td></td>
<td>Shield</td>
<td>-2.1</td>
</tr>
<tr>
<td>J. H.</td>
<td>Binocular</td>
<td>+1.8</td>
</tr>
<tr>
<td></td>
<td>Occlusion</td>
<td>+2.1</td>
</tr>
<tr>
<td></td>
<td>Shield</td>
<td>+1.0</td>
</tr>
<tr>
<td>D. S.</td>
<td>Binocular</td>
<td>+2.1</td>
</tr>
<tr>
<td></td>
<td>Occlusion</td>
<td>+2.9</td>
</tr>
<tr>
<td></td>
<td>Shield</td>
<td>+0.1</td>
</tr>
</tbody>
</table>

69.
monocular viewing the central target is not always localized on the midline present themselves: (1) a change in the phoria from that measured prior to the experiment may have occurred during the experiment; (2) the direction of projection using one eye may be in error or; (3) a different anatomical point may be used as a center of visual directions depending on the eye used for fixation. The fact that findings using the shield compare so closely with those found with complete occlusion of one eye, and the fact that walking data (Table IV) indicate that projection is good using either eye (except in the case of D. S.), it is probable that there is a real change in the center of projection when one eye is used.

The terminal curves in the lines joining the five target localizations may be due to changes in the kinaesthetic perception of distances due to the fact that the two hands joined together at the pointer A exert increasing "stretch" on the contralateral arm and shoulder as movements away from the midsagittal plane toward targets one and five are made. It is apparent that the ogives shown have their terminal curves bent toward the perceived zero line; this would indicate that the subject believed his pointer was further out into the periphery than
it was actually.

A second possibility for such errors in judgment is the chess-board illusion pointed out by Helmholtz (1925, vol. III, pp. 174-185), by which it is demonstrated that peripheral angles are perceived as smaller than they actually are. It is possible that a combination of these two effects will account for the curves shown.

Reference has been made to the variance in hand localization efforts when the hands are kept out of sight by suitable screening devices. Figure 25 shows one set of data for the right eye, with the left eye covered with the shield, for J. R. Each point is the average of five trials. The abscissa indicates the actual target position; the ordinate, the perceived target position. The open circles indicate the perceived target positions for the run in which J. R. located target 1, 2, 3, 4, and 5 in that order; the filled circles show the perceived target positions when J. R. located the targets in the reverse order starting with target five.

An "adaptation" effect is evident in this subject's data, as well as in the data of most subjects used in the hand localization experiments. This effect is demonstrated by the fact that the average target localization for run two (when the target order is 5, 4, 3, 2, 1) is progressively more toward the right. Run two is thus relatively 71.
Fig. 25. Five Target arc at 30 cm

Subject: J. R.

Right Eye

○ Run 1-5
● Run 5-1
higher on the graph at target one than at target five.

The range of localization for each point for run 1-5 is shown by the short horizontal lines to the right side of each point; the ranges for run 5-1 are shown to the left of each point. Overlapping is very evident for target five, but no overlapping occurs for target one.

It seems probable that the relation between visual and kinesthetic space changes throughout the experiment.
A. Apparatus and Procedure

Three targets only, targets 2, 3, and 4, were used on an arc of 40 cm. The center of this arc was placed on the midpoint of the interpupillary line and each target was separated from the adjacent one by an angle of 10° measured from the center of the arc. Fixation was held on target number three as described under "Five Target Arc at 30 cm," but the shield of translucent plastic was not used; only binocular fixation without the shield and monocular fixation with the opposite eye occluded were employed. The targets were placed against the 40 cm cylindrical white arc previously described (Fig. 26).

Localization was carried out as in the 30 cm arc experiment, using five trials on each target in turn from number two through number four, then a rest period, then five trials on each target from number four through number two.

Following the above procedures and using only monocular fixation with the opposite eye occluded, a +2.50 lens was placed before the right eye and the same localization procedure described above was carried out. The
Fig. 26. A subject localizing target four on the Three Target Arc apparatus.
right eye was then occluded and the +2.50 lens placed before the left eye and again the same localization procedure was carried out.

A -2.50 lens was then centered before each eye in turn with the opposite eye occluded and localization was carried out as with the +2.50 lens described above.

Since the center target with the 20/20 fixation letters was located 40 cm in front of the midpoint of the observer's interpupillary line, the +2.50 lens would place the letters at infinity and the -2.50 lens would place the letters at 20 cm on an optical basis. Convergence demand in either case would be the same as with a target at 40 cm with no lenses in front of the eyes.

B. Results

1. Normal Binocular Subjects

Data for subject N. B. with monocular occlusion and using no lenses are shown in Fig. 27. Since targets 2, 3, and 4 only were used, the line joining the localization points should be relatively straight as this would be the middle section of the ogive shown in the 30 cm arc data previously described.

Plotting the data as in Fig. 27, one can determine precisely the perceived lateral displacement of target
Subject: N. B.

Actual Position of Target
Three Target Arc at 40 cm

Fig. 27.
three from its true position. This displacement can be analyzed as follows (Fig. 28 a, b). If the eye under cover is deviating, one can assume that the direction of projection is parallel to the bisector of the angle of convergence and one must assume therefore, that the center of projection lies on the line through the perceived image which is parallel to the bisector of the angle of convergence. This line crosses the interpupillary line at the center of projection. One can determine the amount that the eye under cover is deviating from the phoria data.

Phoria data were taken for at least three different distances for each binocular subject. For most of the subjects these data were taken on two different days. From the information obtained the accommodative convergence associated with accommodation, the ACA ratio, could be determined.

The phoria at distance was taken using a regular refractor with a single letter of 20/30 size used as the target. Sufficient vertical prism was placed over the left eye to break fusion and this eye was then occluded. A Risley rotary prism placed over the right eye with its base-apex line horizontal was then varied while the left eye was intermittently exposed until the subject reported the images in vertical alignment.

Using the 20/30 line on a reduced Snellen chart held
Bisector of the Angle of Convergence

Midline

Projection Error Due to Esophoria.
Center of Projection at S.

Fig. 28 (a)

Correct Projection.
Center of Projection at S.
Fig. 28 (b)
40 cm in front of the subject, the procedure just described was followed to obtain the phoria with a stimulus to accommodation of 2.50 diopters.

For the 20 cm phoria, the 20/15 line on the reduced Snellen chart was used and, by the same procedure as above, the phoria for a stimulus to accommodation of 5.00 diopters was obtained.

Computation of the ACA was then based on the phoria findings plus the interpupillary distance (the P.D.). Mathematically, the ACA is the ratio found by using as the numerator the difference between the prism diopters of phoria found at near and the prism diopters of phoria found at six meters. The denominator would be the difference between the diopters of accommodation used at the same near distance and the diopters of accommodation used at six meters.

Referring back to Fig. 27, and assuming that the phoria under these experimental conditions is the same as that measured prior to the experiment, the center of projection for N. B. is found 0.8 cm to the right for the right eye and 1.1 cm to the right for the left eye after a correction for the phoria has been made. Figure 28 (b) would illustrate the analysis of the center of projection for this subject. It may be true that a single center of
projection exists about one cm to the right of the mid-
line, but walking data show an error in projection for
either eye toward the right (Table III). It is possible
then that this subject's center of projection is at the
root of the nose, (See Table VI for 30 cm Arc data).

The locations of the center of projection for a num-
ber of binocular subjects is shown in Table VII after be-
ing analyzed by the method described for N. B.

In the case of F. B., a common center of projection
is found at or slightly to the left of the midline in
this experiment and in the 30 cm arc (Table VI).

For subject J. E., this common center is probably
about one cm or more to the left of the midline since
walking data indicate an error in projection to the right
when using the left eye. No other data on this subject
are available.

Two runs were made by subject J. F. with rather diff-
erent results, but it appears probable that a single cen-
ter of projection could be placed about 1.5 cm to the
right of the midline.

Results for subject G. F. are quite possibly due to
accommodative difficulties since he is a beginning pres-
byope. Though his correction for myopia is usually not
worn, it was used during this experiment. A correction
for his small exophoria at this distance was made, but it
Table VII. Location of the center of projection in normal binocular subjects using the Three Target Arc at 40 cm. A plus sign (+) indicates a location to the right of the midpoint of the interpupillary line; a minus sign (-), to the left of the interpupillary line. Dimensions are in cm.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Right Eye</th>
<th>Left Eye</th>
</tr>
</thead>
<tbody>
<tr>
<td>N. B.</td>
<td>+0.8</td>
<td>+1.1</td>
</tr>
<tr>
<td>F. B.</td>
<td>-0.3</td>
<td>-0.6</td>
</tr>
<tr>
<td>J. E.</td>
<td>-0.6</td>
<td>-1.9</td>
</tr>
<tr>
<td>J. F.</td>
<td>+2.5</td>
<td>+0.7</td>
</tr>
<tr>
<td>J. F.</td>
<td>+1.1</td>
<td>+0.8</td>
</tr>
<tr>
<td>G. F.</td>
<td>-1.0</td>
<td>+1.6</td>
</tr>
<tr>
<td>H. G.</td>
<td>-1.1</td>
<td>+2.3</td>
</tr>
<tr>
<td>D. S.</td>
<td>+5.4</td>
<td>+4.4</td>
</tr>
</tbody>
</table>
is quite possible accommodation was relaxed more during the experiment than when the phoria was measured prior to this test. His ACA of about six would mean that a relaxation of accommodation of one diopter would move the apparent location of the center of projection for the eye used 1.2 cm toward the opposite or covered eye.

Subject H. G. has a variable ACA of 5.4 to 8.2. In his case also, a small lag of accommodation could produce this apparent shift of centers of projection toward the opposite eye.

Walking data for D. S. indicated that projection ability was not as good using his left eye as when he used his right eye (Table IV). He was also run on the 30 cm arc and the center of projection for each eye was found at or very near the right eye using both eyes together or one eye at a time. It is probably reasonable to conclude that his center of projection is in or very near the right eye whether he is using the right or the left eye.

A further investigation of the theory that projection in binocular persons proceeds parallel to the bisector of the angle of convergence can be obtained through a study using plus and minus lenses. The experiment using
monocular fixation and the 40 cm arc was repeated with the subject wearing a +2.50 lens over one eye at a time and again with the subject wearing a -2.50 lens over one eye at a time.

If the ACA ratio is greater than zero, we would expect the +2.50 lens to produce a change in the relative position of the two eyes toward less convergence than when no lens is used at the 40 cm distance. Using a -2.50 lens should produce a movement of the eye under cover toward more convergence than with no lens. The change in direction of localization produced should be equal to one-half the convergence change. If the convergence change is measured in prism diopters and the target distance is 40 cm, then the change in apparent lateral displacement of the target from its true position should be 0.4 cm multiplied by one-half the convergence change in prism diopters.

Figure 29 for subject N. B. gives the apparent lateral displacement of target three using plus and minus lenses. The ordinate shows the phoria position or relative convergence of the two eyes with and without lenses; the abscissa gives in cm the apparent lateral displacement from this target's true position. No correction is made for the phoria. The dotted line gives the predicted
error in localization based on one-half the change in convergence; the solid line, the actual error in localization. Note that the changes in localization using the right eye are much less than would be predicted. The graph for the left eye, however, shows rather good agreement with the predicted change in localization.

Figures 30 through 34 show the results for five other binocular subjects using this graphical method. Agreement of the change in localization of target three with that predicted is fairly good for the most part; disagreement in some parts of these graphs may be due to the fact that the subject was unable to maintain precise accommodation for the stimulus levels demanded by the auxiliary lenses used. It should be noted that the deviations from the predicted changes in localization were most apparent when the minus lens was used. F. B., for example, was unable to maintain clear vision of the target at 40 cm even when a -1.50 lens was used. Her data would indicate that the addition of the -1.50 lens to the right eye was accompanied by relaxation of accommodation rather than further contraction of the ciliary muscle (Fig. 30).

In addition to information on our own problem, it was hoped that this approach would throw some light on
Target Localization

Fig. 31

Target Localization
Fig. 32  Target Localization
Fig. 33

Target Localization
Fig. 34 Target Localization
the theory of Walls (1951, p. 14-18) regarding visual directions and the dominant eye. Walls has stated that movements of the environment would not be expected to occur with changes in convergence of the two eyes unless the dominant eye was under the cover and hence free to change its direction of turn with changes in convergence. That is, if the dominant eye were covered and accommodation (and hence convergence) were changed by means of lenses (as in our experiment) or by changing the target distance, a lateral displacement of the object fixated with the non-dominant eye would take place. If, under these same circumstances, the non-dominant eye were covered and the dominant eye were the fixing eye, an apparent lateral movement of the target would not be expected to take place.

As can be seen from the data presented in Figs. 29-34, localization of target three appears to have changed with accommodative convergence in the direction predicted by our assumptions no matter which eye was used as the fixing eye, even though the change was not always in complete agreement with that predicted.

The data collected using the Three Target Arc at 40 cm appear to confirm the findings of other investigators as well as the findings of parts of this study which have already been discussed: normal binocular in-
dividuals have a single center of projection usually located near the midpoint of the interpupillary line; under monocular conditions this center moves toward the eye used for fixation. In some binocular subjects the center of projection may be in or very near one of the eyes whether one or both eyes are used.

In addition, it seems reasonably certain that projection in normal binocular subjects proceeds parallel to the bisector of the angle of convergence.

2. Squinters

In order to determine the type and amount of strabismus existing in each subject used for this part of the study, at least two tests were used. In all cases, as with the normal subjects, their customary Rx (if worn) was used throughout all testing.

The objective angle of squint with relaxed accommodation and with various amounts of accommodation in play was measured on the Wottrting Troposcope if visual acuity in each eye was 20/40 or better. In the case of amblyopes with less than 20/40 in either eye, this same information was obtained using the table troposcope described below. From the data collected, the objective ACa was computed for each subject.

The measurement of the angle of squint in amblyopic
subjects presents a problem since fixation of the amblyopic eye is frequently off-foveal. It is, therefore, usually necessary to make use of a corneal reflex method of measurement.

A type of synoptophore or troposcope was devised which allowed for measurement of the change in squint angle to about one tenth of one degree accuracy. An eight inch Circline fluorescent tube, C, served as a corneal reflex light source (Fig. 35).

The subject's head was held in position by means of a chin and forehead rest placed along one edge of the table. In front of the amblyopic eye, R, was a back surface mirror, M, by means of which the light from the fluorescent tube C was reflected onto the eye. The light reflected from the cornea traveled back along this same path and the corneal reflex was observed through the telescope, F, placed one meter from the subject on the side of the amblyopic eye and at the center of the circle formed by the Circline tube. If a vertical deviation of the eye was noted, the height of the Circline tube and telescope was changed so that the corneal reflex was centered. No measurements of the vertical deviation were made.

The fixation target, P, was a photographically reduced Snellen chart. It was mounted on a rod, N, which
Table Troposcoope
Fig. 35
rotated about an axis placed in vertical alignment with the center of rotation of the fixating ("good") eye, L. This target was placed at distances from one meter to 20 cm from the eye and, by placing a plus one diopter sphere in the lens holder, H, a stimulus to accommodation was produced which varied between zero and five diopters. Rotation of the target through an angle of 40 degrees on each side of the straight forward was possible. A scale, AA', mounted on the table top, calibrated in one degree steps on a one meter arc allowed easy estimation of the angle of turn to about one tenth of a degree.

Clear fixation on the smallest letters possible was maintained by the subject while the rod upon which the target was mounted was rotated until the corneal reflex was centered in the amblyopic eye. An allowance of five degrees toward greater esotropia (or less exotropia) due to the Angle Kappa* of Landolt was arbitrarily made. Since our primary consideration was the change in convergence with the change in accommodation, the error introduced by the assumption that the angle Kappa was always

*Angle Kappa of Landolt: the angle formed by the intersection of the line passing from the point of fixation to the fovea and the line normal to the cornea passing through the center of the pupil. (Peter , pp. 43-44)
equal to 5° would be negligible except in the differentiation of normal from anomalous correspondence.

Five measurements were made with the subject fixing the target through the plus one diopter sphere while the target was one meter in front of the spectacle plane. The one diopter sphere was removed and five measurements were made with no lens at the one meter fixation distance. The target was moved to 40 cm and then to 20 cm in front of the spectacle plane and five measurements made at each of these distances without any auxiliary lens. In each case, the average of the five trials was taken to indicate the squint angle under those experimental conditions. During all trials the subject wore his customary spectacles. (also see Figs. 36 and 37)

This apparatus was used only for amblyopes and the dominant eye was always used for fixation of the reduced Snellen chart.

The subjective angle for infinity was also obtained on one of the instruments described above. If the subjective and the objective angles of squint differed by more than 10°, anomalous correspondence was inferred.

Each subject was checked with the after image test (Bielschowsky) as a further aid to the differential diagnosis of normal versus anomalous correspondence.
Fig. 36. Front view of a subject seated at the Table Troposcope. The fixation target is at the one meter setting.

Fig. 37. Side view of a subject seated at the Table Troposcope. The fixation target is at the one meter setting.
In all cases used, the objective angle versus the subjective angle, and the after image test were in agreement as to the state of retinal correspondence.

Since true binocular cooperation for localization purposes is not presumed to exist in squinters, corrections similar to those made for the phoria in binocular subjects in order to compensate for the deviation of the eye under cover were not made for the squinters except as noted in the discussion of normal correspondence squinters. Walking data for the normal correspondence squinters show rather clearly that projection cannot proceed parallel to the bisector of the angle of convergence when the dominant eye is used alone since no error in walking is made under these circumstances. The error in walking that is made when the non-dominant eye is used for fixation suggests a change in the projection pattern when this eye is used alone.

In locating the center of projection for squinters, it would hardly be reasonable to use the same analysis as was used for normal binocular subjects. A normal subject who has a high phoria does not use his eyes dissociated but uses them binocularly with the phoria compensated for via fusional convergence, and he sees both the dextrocular and sinistrocular images in the same direct-
tion. If he were to wear an occluder over one eye to make himself similar to a normal correspondence squint-er who suppresses vision in one eye, the large deviation of his covered eye would at first cause errors in localiza­tion. Such a person usually learns readily to perceive the fixated object in its correct direction.

If the occluder were worn constantly over one eye until he had learned to project correctly with the un-covered eye, and then the occluder were switched to cover the "trained" eye, one would expect him to see objects in the direction in which the trained eye were pointing.

Similarly, in the case of a squinter who normally uses a particular eye to guide his activities, one might expect when the normally used eye were covered that an object fixated by the normally deviating eye would be seen in the same direction as the normally used eye were pointing.

It is not inconceivable that, if a normal binoc-ular individual with a high phoria had an occluder switched from one eye to the other at regular inter­vals, he would learn to project correctly with either eye. This is analogous to the case of the alternating squinter.
The center of projection data for squinters were plotted on the same type of graph as was used for the normal binocular subjects described in the previous section.

a. Normal Correspondence Squinters

Subject: R. B. Male, Age 18

The objective and subjective angle of squint measured 12 to 15 prism diopters of exotropia, with an ACA of about four. The after image response showed normal correspondence. To the subject's knowledge, only one eye was used at a time; he claimed he could use either eye, but preferred the right eye. Visual acuity was 20/15 in either eye. There was no history of surgery, though the squint was discovered when he was six years old.

Two runs were made on the 40 cm arc using no auxiliary lenses. When he used the right eye, target three was seen 3.1 cm to the left of its actual position in the first run, and 3.9 cm to the left in the second run; for the left eye, it was seen 3.1 cm to the right of its actual position in the first run and 1.8 cm to the right in the second run.

If we analyze cases of this type on the basis of the assumption that projection proceeds parallel to the line 101.
of sight of the dominant eye, then a line parallel to this eye's line of sight through the apparent position of target three should intersect the interpupillary line at the center of projection for the eye used.

According to this analysis, a center of projection for the right eye was found approximately at the root of the nose in the case of R. B.

When the left eye fixated, the principal line of sight of the right eye was directed about 20° or 8 cm farther to the right than the left eye's line of sight at the 40 cm testing distance. For the first run, a line drawn parallel to the line of sight of the right eye through the apparent location of target three met the interpupillary line about 2 cm to the left of the midline. For the second run, this line intersected the interpupillary line near the entrance pupil of the left eye.

Data supplied by using each eye separately to direct his walking showed that with the right eye he walked toward the target with a deviation of only 1.3° to the right. Using the left eye, however, an error of 21.3° to the right (with a range of 16° to 30°) was made. This would imply that, after turning in the left eye to fixate foveally, very imperfect knowledge existed as to the direction of the line of sight of the right or left eye.
eye and hence, variance in localization efforts would be expected when the left eye was used alone.

These findings suggest, however, that the subject appreciated the fact that the left eye was being used and perhaps used it as a center of projection even though the line of sight of the right eye was used as the direction line.

Figure 38 shows the effects on localization produced by the plus and minus lenses for subject R. B. The dotted lines show the slope of the full ACA. Since projection is assumed to proceed parallel to the line of sight of the right eye, little consistent change in localization using plus or minus lenses with this eye as the fixating eye would be expected. Using a plus lens did produce a shift which appears to indicate that the line of sight did actually change. A small change in the reverse direction occurred with the minus lens. Possibly the addition of either of these lenses altered his space perception sufficiently to cause the apparent shift in localization regardless of the lens power itself.

The left eye appears to follow the slope of the ACA almost perfectly, which would appear to support the analysis used for this case.
Target Localization

Fig. 38
Subject: L. H. Male, Age 18

The objective and subjective angles of squint at six meters agreed at $24^\circ$ to $28^\circ$ of exotropia. The after image showed normal correspondence, also. Accommodation had no effect on the relative position of the two eyes: the ACA was zero.

This subject frequently used both eyes together and stereopsis was evident. Divergence to the squinting position was common at any fixation distance, but was most likely to occur at near since the squint angle then increased to about $60^\circ$ of exotropia due to the zero ACA. Visual acuity was good in both eyes, but the right eye was preferred for fixation in the squinting position. The age of onset was unknown, but no eye surgery had ever been done.

This subject was also run twice on the 40 cm arc apparatus using no lenses. Target three was localized 1.2 cm to the right in the first run, and 0.3 cm to the right in the second run when the right eye fixated. Assuming that the same analysis as was used for subject R. B. applies here, this would mean that the center of projection for this eye was located approximately in the right eye.

Using the left eye, target three was localized 7.7 cm
to the right of its true position in run one and 7.9 cm to the right in run two. The right eye turned to the right about 43° when the left eye fixated at this distance; this means that the right eye was looking about 17 cm farther to the right than was the left eye. A line drawn parallel to the right eye line of sight and through the apparent location of target three would strike the interpupillary line about 2 cm to the left of the left eye.

Walking data showed that L. H. projected correctly with the right eye. With the left eye fixating the target straight ahead, however, he walked 12° toward the right. This amount of error in the perceived "straight ahead" direction when he uses the left eye as the fixating eye is equal to one-half of his distance phoria. Since L. H. frequently uses both eyes simultaneously and fixates with the right eye when monocular vision is used, it is possible that, when the left eye is used alone, projection proceeds parallel to the bisector of the angle of convergence as it would in a normal binocular subject who had a high exophoria.

Using the above analysis, the center of projection for the left eye would fall about one cm to the left of the midpoint of the interpupillary line.
Figure 39 shows the effects of plus and minus lenses on the direction of projection. Rather erratic shifts appeared in run one, but run two showed some consistent effect for the left eye in a direction which would indicate a change in localization due to an ACA greater than zero. Since his ACA is zero, this effect must be due to some disorientation in direction produced by the lenses.

Subject L. H. was used as a subject twice on the five target arc at 30 cm. Figure 40 shows this data. Note the fairly wide range over which identical targets were localized, even though these runs were all made with not more than ten minutes rest intervening. Other subjects also showed rather wide variance: the combination of hand-eye coordination and the relation between physical and perceived space probably accounts for this (Fry, 1950; Roeloff, 1924; Freeman, 1951; Boring, 1942). Since experimental conditions are similar to those for the Three Target Arc at 40 cm, the same analysis may be applied.

Using both eyes simultaneously, target three was localized 1.7 cm too far to the right. Using the left eye as the fixating eye, projection appeared to proceed parallel to the bisector of the angle of convergence when the 40 cm arc was used; this may have been the case also in the binocular situation. However, whether we use this as-
Fig. 39

Target Localization

Subject: L. H.

O. D.

O. S.

Exotropia

pl = no lens

Run 1

Run 2

Target Localization
Fig. 40. Five Target Arc at 30 cm
sumption or assume that projection parallels the line of sight of the right eye, the center of projection was located near the right eye. In the monocular situation also, the center of projection for the right eye was very near the right eye since target three was localized about 0.5 cm to the left of its true position.

With the left eye, target three was seen about 4.2 cm too far to the right. The right eye was looking about $48^\circ$ to the right of target three; at the 30 cm target distance this would be about 14.4 cm further to the right than the line of sight of the left eye. On the assumption that a binocular projection pattern existed in this situation, the center of projection for the left eye was in the left eye.

In the two normal correspondence cases discussed, a separate center of projection appeared to be used for each eye. This center is located in or very near the eye used.

Projection in these squinters appears to proceed parallel to the line of sight of the dominant eye.

b. Anomalous Correspondence Squinters

Table VIII shows that the anomalous correspondence squinters in every case project quite correctly using
Table VIII. "Walking Experiment" data for eight anomalous correspondence squinters showing the path deviation when one eye was covered and the "peephole" goggles were worn. The amount of tropia and the path deviation are in prism diopters. A plus sign (+) indicates a deviation to the right; a minus sign (−), to the left.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Tropia</th>
<th>Right Eye</th>
<th>Left Eye</th>
</tr>
</thead>
<tbody>
<tr>
<td>C. D.</td>
<td>23 eso</td>
<td>+3.5</td>
<td>+6.6</td>
</tr>
<tr>
<td>S. G.</td>
<td>30 exo</td>
<td>+1.4</td>
<td>+4.8</td>
</tr>
<tr>
<td>D. K.</td>
<td>20 eso</td>
<td>+2.6</td>
<td>+3.8</td>
</tr>
<tr>
<td>R. L.</td>
<td>32 eso</td>
<td>+3.5</td>
<td>+8.4</td>
</tr>
<tr>
<td>W. M.</td>
<td>14 eso</td>
<td>+1.4</td>
<td>+3.9</td>
</tr>
<tr>
<td>J. M.</td>
<td>42 eso</td>
<td>+0.7</td>
<td>+3.5</td>
</tr>
<tr>
<td>D. W.</td>
<td>21 eso</td>
<td>+0.7</td>
<td>+0.5</td>
</tr>
<tr>
<td>W. H.</td>
<td>-</td>
<td>+0.8</td>
<td>-0.7</td>
</tr>
</tbody>
</table>
either eye in the walking experiment. This would eliminate any discussion in each subject's case as to projection: it must proceed very nearly along the line of sight of the eye used regardless of the squint angle and not, as in binocular subjects, parallel to the bisector of the angle of convergence.

Subject: C. D. Male, Age 22

The objective angle of squint was esotropia; subjective angle, 2° exotropia. An objective ACA of about five could be demonstrated. Visual acuity was good in either eye, but the right eye was preferred. There was no history of surgery; the date of onset was unknown.

Using no lenses, target three was seen 0.3 cm to the right of its true position; the center of projection for this eye was in the right eye itself. The left eye localized target three about 0.8 cm to the left of its true position; for this eye the center of projection was in the left eye.

Figure 41 shows a very small inconsistent shift in apparent localization using plus and minus lenses with either eye. Localization probably is based upon a learned association between accommodation and the perceived distance of the target without consideration of the change
Target Localization

Fig. 41
in the squint angle.

Subject: S. G. Female, Age 17

About $30^\circ$ exotropia was measured objectively; subjectively, the angle was $10^\circ$ exotropia. The objective ACA was 2.4. Visual acuity was good in either eye and alternation occurred readily, but the left eye was preferred. The squint angle had been surgically reduced by an unknown amount in 1947. She has squinted since birth.

Two runs were made on the 40 cm arc. In the first run, the right eye saw target three about 1.3 cm to the right; on the second run, about 2.7 cm to the left. For the left eye, run one showed the center of projection to be to the left of the left eye about 0.5 cm, and for run two, 2.2 cm to the left of the left eye.

Note that in the second run, the apparent location of target three for each eye has shifted to the left. However, if the data for each eye is averaged, the center of projection for the right eye appears very close to the right eye and that for the left eye, close to the left eye.

Figure 42 indicates no appreciable change in localization with plus or minus lenses for run one. For run two, some consistent shift is noticeable with the right
Fig. 42
eye, but not the left eye. As in the case of C. D., localization was based upon a learned association between accommodation and the perceived distance of the target rather than an ACA effect. Any small slope in the line shown could agree with the ACA since the ACA is so small.

This subject took part in the Monocular Two Target experiment also. These data show that the centers of projection were separated by about the same amount as her interpupillary distance at 6.4 cm although both centers were shifted noticeably to the right.

If the data for the 20 cm and 40 cm distance of the Monocular Two Target experiment are plotted together so that the midpoints between the localization of the nasal and temporal targets for each eye are used to determine projection lines, the center of projection for each eye does fall very nearly in the eye used. This method of plotting indicates an error in projection of about $10^\circ$ toward the right for each eye under these experimental conditions.

The separation of the two centers, whether one or the other analysis is used, is marked enough, however, to indicate that a separate center was used for each eye.

The Monocular Two Target data were taken on a single
day. Each run for the 40 cm arc data was completed on a separate day. This adds to the evidence already presented in this study and the studies of others that visual space is subject to variations with the passage of time. Using the hands to indicate the location of objects increases this variation.

Subject: W. H.  Male, Age 18

This subject was a post-surgical exotrope whose objective squint angle varied between about $5^\circ$ and $40^\circ$ with relaxed accommodation. Following the surgery six years ago, diplopia was noticed for some months and is still occasionally present. The variable angle prevented an ACA estimation and therefore no graph showing the effects of plus and minus lenses is shown, although this test was done and will be discussed. Visual acuity in the right eye was 20/200 with no evident pathology; in the left eye, 20/20. His parents noted the squint when W. H. was two years old.

Target three was seen 0.4 cm to the right using the right eye. This places the center of projection in this eye. With the left eye, target three was localized 2.7 cm to the left of its true location. This appears to indicate that the center of projection for this eye was to the left of the left eye; however, visual acuity with 117.
this eye was so poor that this could be an artefact. It seems probable, however, that two centers of projection were present since walking data showed that projection was good with either eye.

Using plus and minus lenses did not produce any consistent shift in localization, although it was apparent that localization was more correct using the left, or dominant, eye than when the right eye was used.

Subject: D. K. Male, Age 23

An esotropia of 20° was measured objectively at infinity; the ACA was 4.6. There was no history of surgery. Visual acuity in the right eye was 20/15; in the left eye, 20/25. The right eye was preferred for fixation. He has squinted since birth.

The center of projection for the right eye was in the right eye since target three was localized 0.7 cm to the left of its true location. Using the left eye, target three was seen 0.9 cm to the left, hence this center of projection was in or very near the left eye.

No consistent shift was seen with either eye when plus or minus lenses were used (Fig. 43).

Subject: R. L. Male, Age 26

This subject was an alternating esotrope of 32° with 118.
relaxed accommodation; his ACA was five. There was no history of surgery. Visual acuity was 20/15 in each eye, but the left eye was preferred for fixation.

Using the right eye, target three was seen to the right of its true location about 1.8 cm. The center of projection was either in the right eye or to the right of this eye.

When the left eye was used, target three was localized 0.1 cm to the left of its true location; the center of projection was in the left eye.

No shifts in localization were apparent when plus or minus lenses were placed before either eye (Fig. 44).

Subject R. L. participated in the Monocular Two Target experiment. Analysis of this data showed the center of projection for each eye approximately in the eye used, with the centers of projection separated by about seven cm. His P.D. was 6.6 cm.

Subject: W. M. Male, Age 18

Objectively, the squint angle for infinity was 14° esotropia, with an ACA of 1.6. This subject normally wore no Rx, although he required a +3.50 sphere on each eye as a full correction. Findings were taken without glasses. Visual acuity: right eye, 20/40; left eye,
Subject: R, L O S

Target Localization

Fig. 44
20/25. The left eye was preferred for fixation.

When using the right eye, target three was localized 1.3 cm to the right. This eye's center of projection was in or to the right of his right eye.

Using the left eye, target three was seen 3.2 cm to the right. This would place the center of projection for the left eye at the midpoint of the baseline.

The addition of plus or minus lenses showed some shift in localization especially in the left eye (Fig. 45).

Subject: J. M. Male, Age 22

Objectively the squint measured 42° esotropia, with an ACA of eight. Visual acuity with the right eye was 20/15 and with the left, 20/25. The right eye was dominant, although alternation occurred readily. Surgery performed in July, 1953 reduced the squint from 70° esotropia to the present angle. The subject has squinted since birth.

Target three was seen 0.8 cm to the left of its true location using the right eye; the center of projection was in the right eye. For the left eye, the target was seen 0.8 cm to the right of its true position. This indicates that the center of projection for the left eye was in the left eye.
Subject: W. M.

Fig. 45
A small consistent shift in localization is seen when plus and minus lenses are used, though it is so small it could hardly be attributed to the ACA (Fig. 46).

Subject: D. W. Male, Age 26

The objective angle of squint was 21° esotropia; the ACA five. Visual acuity in the right eye was 20/400 with no pathology evident; in the left, 20/20. There was no history of surgery.

Two runs were made, about one month apart. In the first run, the right eye saw target three to the left 1.1 cm. The second run, target three was localized 0.5 cm to the left. The center of projection for the right eye was in the right eye.

Using the left eye in run one, target three was seen 2 cm to the right of its true position and in the second run, it was seen 0.5 cm to the right. The center of projection was in the left eye or about 1 cm toward the mid-line from the left eye.

Using plus or minus lenses produced no consistent change in target localization (Fig. 47).

It is interesting to note that even though fixation with the right eye was eccentric by at least five degrees, localization and walking were very good using this eye.

In the case of anomalous correspondence squinters, some changes in localization do occur when plus and minus
Fig. 47 - Target Localization

O.D. Subject: D.W. O.S.

F. sotropia

Target Localization

-2.50
+2.50
lenses are used in this experimental arrangement, but these changes usually do not indicate a consistent relationship to the accompanying change in squint angle. This means that the direction of the line of sight of the fixing eye is reasonably well known to the subject and that changes in accommodation, so long as they do not alter the direction of the line of sight of this eye, will not greatly affect the perceived direction of the object. Addition of these lenses can distort the distance judgment, however, and it is possible that some of the apparent shifts in localization are due to errors in perceived distance.

Results indicate that anomalous correspondence squinters do have two centers of projection and that these centers are usually in, or very close to, the eye used for fixation.

3. One-Eyed Subjects

Two one-eyed individuals were included in this study because it was felt that responses obtained from subjects in which there was no possibility of binocular cooperation might aid the comparative analysis of squinters who rarely, if ever, use both eyes together in the same sense as binocular individuals do.
Measurements on one-eyed individuals were, of course, limited to visual acuity and motility checks, and analysis of their center of projection must proceed, as a first choice, on the basis that projection is along the line of sight of the eye used.

Subject: D. R. Female, Age 22

The left eye had been destroyed by a hand grenade about five months before our experiment was done. Visual acuity without glasses was 20/15 in the right eye and motility of this eye was normal.

Using the 40 cm arc, target three was localized 0.4 cm to the right of its true position. This would place the center of projection in the right eye on the basis of the above analysis. However, when this subject attempted to walk toward the target 1000 yards away she made an error of 7.4° toward the right.

Convergence for the center target at 40 cm would demand a turn to the left of this right eye of about 7.5°, but target three was localized correctly. This means that projection at near from a center at the root of the nose was correct, i.e., the subject saw objects imaged on the fovea of her remaining eye as being straight in front of the center of projection which was at the root of the
nose just as though her two eyes were converging on
the target. Only five months had passed since the loss
of the left eye and she was still using the projection
pattern of a two-eyed person.

When the subject looked at a target 1000 yards away,
no correction was made for the previously present ACA
and projection was in error by $7.4^\circ$ to the right. An
error in projection at near would be noticed by the sub­
ject and therefore correct projection would be learned;
distance projection errors would not even be recognized
and hence would go uncorrected.

The graph used for two-eyed subjects showing changes
in the perceived lateral location of target three with
changes in accommodation could not be used for one-eyed
subjects since the ordinate indicated the relative posi­
tion of the two eyes. For the two one-eyed subjects dis­
cussed here, the ordinate on the graph has been changed
to show the stimulus to accommodation. The abscissa is
the same, i.e., it indicates the perceived lateral posi­
tion of target three. A positive slope of the line connect­
ing the perceived positions of target three for the three
stimulus levels would be expected if accommodation affect­
ed localization.

Figure 48 for D. R. shows that plus and minus lenses
produce no change in the visual direction of target three. This shows that, if an ACA had existed prior to the accident in which the left eye was lost, no effects due to the ACA were now evident. It is possible, of course, that the ACA had been zero when both eyes were intact. However, since a zero ACA is not common, it is more probable that a new localization pattern had been learned in which the former ACA relationship was ignored.

Subject: D. W. Male, Age 24

Visual acuity in the remaining right eye was 20/15 using his Rx and motility was normal. The left eye had been removed two years prior to this experiment following an accident.

Target three was localized by this subject 1.3 cm too far to the left. Walking data showed that this subject projected correctly at distance using his one eye, hence this subject used a center near the right eye and projected along the line of sight of this eye.

Plus and minus lenses had no effect on localization, so it appears evident that here, as in the case of D. R., any effects of a prior ACA relationship were being ignored (Fig. 49).

The data of two subjects do not warrant positive conclusions. However, it seems that when an eye is first
lost, the binocular pattern of projection is used, i.e., projection parallel to the bisector of the angle of convergence from a center of projection at the root of the nose; but the effects of any previously existing ACA must be ignored insofar as near objects are concerned.

With the passage of time, a new center of projection is established in the remaining eye and projection proceeds along the line of sight of this eye.
IX. SUPPLEMENTAL STUDIES

A. Shooting Experiment

An optical pointer with a red filter was mounted on a pistol handle and equipped with a trigger for turning on the light in "shooting" at the target (Bailey, 1951). In order that visual clues as to the hand or arm position could not be used to help direct the pointer toward the target, a rectangular board, four by five feet, was placed parallel to the floor. The subject's chin rested well over the edge of the board to prevent the subject from seeing any part of his own hands or arms (Fig. 50). A lens holder with a red-free filter was mounted in front of the fixing eye so that the subject was able to see the target but was unable to see whether he "hit" the target when he pulled the trigger. The opposite eye was occluded.

The target consisted of a central black cross (Fig. 51). Ten vertical lines of one degree separation on either side of the cross allowed responses to be recorded in degrees to right or left of the central cross. A projector was used to project this target on to a screen six meters in front of the observer.

Each observer was allowed to practice pointing the "pistol" and "shooting" at various points on the target.
Fig. 50. Side view of subject and apparatus used for the Shooting Experiment.
Fig. 51. Target used in the Shooting Experiment.
using either hand he preferred, or both hands, without using the filter until he was familiar enough with the arrangement to feel that he could shoot with reasonable accuracy without sighting.

In order to prevent the subject from repeating errors or correct responses on the basis of kinesthesis alone, i.e., shooting repeatedly in a particular direction on the basis of the muscle sense of the arm and shoulder, each recorded "shots" was preceded and followed by one or two "shots" at some point on the target with the filter removed from the fixing eye. Five recorded shots constituted one "run."

One or more runs were made using (1) no lens, (2) a -2.50 diopter sphere, and (3) a -5.00 diopter sphere in the spectacle plane of the uncovered or fixating eye.

It was hoped that a "shooting" experiment of this type would give us information first, on the direction of projection using one eye at a time; and secondly, on changes in the direction of projection with changes in convergence associated with accommodation. In addition, it was felt that this procedure might add some useful information to that already obtained with plus and minus lenses on the 40 cm arc in connection with the theories of Walls' (1951) regarding egocentric localization and the dominant
The predicted change in perceived visual directions was based upon the premise that in binocular subjects visual projection should be parallel to the bisector of the angle of convergence. Since one eye was occluded, the "angle of convergence" was assumed to be equal to the phoria measured prior to the experiment under conditions similar to those existing during the experiment. No check on accommodation was made except the subject's statement that the target was seen clearly; it is admitted that accommodative inaccuracies during the experiment may be a factor in the results obtained.

Figure 52 shows averaged data for five separate runs with the right eye for subject N. B. for each of three stimuli to accommodation. Table IX gives this subject's complete data for the same five runs. Even though N. B. was more consistent in his settings than any of the other subjects used, a rather large range is noted within each run and between successive runs. His results are, however, in the expected direction, i.e., the addition of minus lenses rotates the perceived direction of the target to­ward the right.

Four other subjects were used (two binocular and two squinters). The magnitude of the variance in successive
Figure 92: Shooting Experiment

Stimulus to Accommodation

Perceived Direction of Target

Subject: N.B.
Table IX. "Shooting Experiment" data for subject N. B. for the right eye only. Phorias were measured through lenses with the subject fixating on a target at six meters. A plus sign (+) indicates that the subject "shot" too far to the right; a minus sign (-), too far to the left.

<table>
<thead>
<tr>
<th>Date</th>
<th>Lens</th>
<th>Trial 1</th>
<th>Trial 2</th>
<th>Trial 3</th>
<th>Trial 4</th>
<th>Trial 5</th>
<th>A</th>
<th>B</th>
<th>C</th>
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* A - Average of five trials in degrees.
  B - Average of two or three runs in degrees.
  C - Average of B converted to prism diopters.
trials and between successive runs indicates that this method of determining the effects of accommodation on the direction of projection and on the relative projection of each eye is rather ineffective. By averaging a great deal of data, significant results might be obtained.

B. Accommodation with Headlamp

1. Apparatus and Procedure

A room 13.5 meters long and about seven meters wide was used. The subject was seated on a rotatable stool placed 7.5 meters from the front wall of the room, and confined his attention to a target made up of a single vertical black line 150 cm long and four cm wide straight in front of him on the wall. Six meters behind him on the rear wall was a tangent scale calibrated in one prism diopter steps (Fig. 53).

A surgeon's headlamp was mounted on the subject's head by means of a head band. The lamp projected a focused beam on to the tangent scale behind him. It was not possible for the subject to see the beam at any time (Figs. 54 and 55).

The headlamp was positioned initially by having the subject attempt to look at the vertical line target so
Accommodation with Headlamp

Fig. 53

141.
Fig. 54. Front view of a subject seated behind the screen used in the Accommodation with Headlamp experiment. The tangent scale can be seen against the back wall.

Fig. 55. Rear view of a subject seated behind the screen wearing the headlamp used with the Accommodation with Headlamp experiment. The headlamp is held on the head by means of a plastic headband. On the wall toward which the subject is facing can be seen the vertical black strip used as the fixation target.
that he felt that this target was straight in front of him, i.e., in line with his mid-sagittal plane. This was done two or three times in order to adjust the headlamp beam so that it fell on or near the midpoint of the tangent scale.

The left eye was then occluded and the subject made five attempts to look straight at the vertical line target with the right eye without any accommodative effort.

Following this, a 50 mm lens blank of -2.50 diopters was placed in the subject's spectacle plane before the straight foreword right eye. The subject was instructed to wait until he could see the vertical black target clearly through this lens. Five attempts to look straight at the target were then made under this experimental arrangement.

The -2.50 lens was removed and a two mm mesh screen 70 cm wide and 50 cm high was placed 40 cm in front of the subject.

He fixated the screen with his right eye and saw a blurred vertical black line "through" the screen. Five attempts were made to look straight at this blurred line while maintaining accommodation on the screen 40 cm away.

The screen was removed and a -5.00 diopters lens blank of 50 mm diameter was placed in front of his right
eye. When he could see the vertical black line clearly, five trials to look straight at it were made.

This -5.00 diopter lens was removed and the screen described above was placed in front of the subject at a distance of 20 cm. Five attempts to look straight at the blurred vertical line which was visible "through" the screen were made while maintaining accommodation in the plane of the screen.

The above procedure was carried out twice on the right eye and twice on the left eye, so that ten trials with each eye were made for each experimental set-up. The average of each set of ten trials was used to plot the subject's concept of the apparent "straight forward" under each experimental situation.

2. Results

This experiment was undertaken as a further attempt to determine how projection is accomplished. Three binocular subjects will be discussed first.

Figure 56 shows the data plotted for subject N. B. The abscissa shows the subject's head turn in prism diopters. Plus on the scale indicates a head turn to the right; minus, a head turn to the left.

The ordinate indicates in diopters the stimulus to
Subject: N.B.

Head Turn in Prism Dipters

Fig. 56
accommodation provided either by lenses or the screen previously described.

No phoria correction has been made since we are concerned mainly with changes in head turn when accommodation is altered.

On the right side of the graph, the sloping dashed line indicates the predicted head turn with accommodation when the right eye is used if projection proceeds parallel to the bisector of the angle of convergence. The dashed line on the left side of the graph gives the same information for the left eye.

The solid line shows the head turn using lenses, and the broken line shows the head turn when accommodation is held in the plane of the screen.

For the right eye, the head turn of N. B. followed the predicted rather closely using either the lenses or the screen. There was, however, a head turn of 5° to the right when fixation was changed from the right eye to the left eye even though accommodation was supposedly relaxed in both cases. N. B. has an exophoria of only 1° with relaxed accommodation.

The left eye followed the slope of the dashed line well when N. B. accommodated for the screen. No change occurred when the -2.50 lens was used, but with the -5.00
lens an excessive head turn took place, so that the total head turn agreed rather well with that predicted.

Two other binocular subjects were also run using this apparatus. In general, rather good agreement between the slope of the predicted and the actual head turn was obtained. However, even though little or no heterophoria was present with relaxed accommodation, head turns of \(5^\Delta\) to \(8.5^\Delta\) did occur when these subjects changed from fixation of the target straight ahead with the right eye to the same fixation point with the left eye even though accommodative conditions appeared to be identical.

The head turn when the fixing eye was changed may be the result of choosing a particular criterion upon which to base a judgment of "straight ahead" when each eye was first used. This criterion may be the same for either eye, in which case no head turn would result unless a heterophoria were present or projection were faulty. If a different criterion, based on the internal or external environment were used when the fixing eye was changed, a head turn would result without regard to the phoria or projection fault.

This change in apparent "straight forward" when there is no heterophoria or projection error to account for it makes this method a questionable one to use for any purpose.
except to show relative changes in the perceived "straight forward" position of the head. Individuals are apparently not as aware of the position of his eyes, head, torso, etc., as they are of the direction of objects in space.

Figure 57 is a plot for R. B., a normal correspondence exotrope whose right eye was dominant. The slope of the predicted head turn was based on the change in direction of the line of sight of the covered eye. It can be seen that only very small and erratic changes occurred when the right or dominant eye was the fixing eye. Using the left eye, the changes in direction were also rather erratic, but the overall change followed the slope of the dashed line. This is in agreement with the analysis of R. B. presented in the section describing the Three Target Arc at 40 cm (p. 101).

Figure 58 shows the data for R. L., an anomalous correspondence esotrope. No auxiliary lenses were used with this subject. The right and the left eye each showed a consistent deviation in the direction predicted, but the amount of change was only $4.5^\Delta$ for the right eye and $3.8^\Delta$ for the left eye using five diopters of accommodation. A change of $22.5^\Delta$ based on this subject's objective ACA of 4.5 would be predicted if the fixating eye followed the line.
Subject: R. B.

Fig. 57
Figure 58

Subject: R.L.

Dioptry of stimulus to accommodation

Predicted Slope

Screen

Head Turn in Prism Dioptries

Fig. 58

-20 -10 0 +10 +20

Right Eye
Left Eye
of sight of the covered eye, or 11.25° if projection were parallel to the bisector of the angle of convergence. It is evident that accommodation caused a change in the perceived straight ahead, but this subject appeared to rely primarily on the direction of the line of sight of the eye used for fixation. (See Three Target Arc at 40 cm, p. 118)

In the case of the one monocular subject, D. W., used in this experiment, accommodation for the plane of the screen was used. His data are shown in Fig. 59. Note that no change in the apparent straight forward took place when accommodation changed. The analysis for this subject presented with the Three Target Arc at 40 cm would predict the results shown here, i.e., this subject's projection depends upon the direction of the line of sight of his remaining eye.

The three binocular subjects, two squinters, and one monocular subject described in this section were the only subjects whose data were complete enough to be discussed. Definite conclusions can hardly be based on results using this method on so small a group, but this evidence should be considered along with that previously discussed in this paper.
Subject: D. W.

Screen only

Right Eye only

Diopeters of Stimulus to Accommodation

Head Turn in Prism Diopeters

Fig. 59
C. Visual Midline

An aluminum channel slide 30 cm long and one cm wide was mounted on a meter stick and placed parallel to the subject's objective frontal plane on top of the special table previously described. At each end of the slide a horizontal pulley allowed the subject to move a vertical bolt laterally in the slide by means of a string until he felt the bolt was in the midsagittal plane of his head. He was unable to see his hands, the channel slide, or the string during the experiment; only the upper part of the vertical bolt was visible to him.

The slide was placed 20 cm, 28.6 cm, and 50 cm in front of the entrance pupils in three different experimental situations. Five trials were made at each distance with each eye and with both eyes together fixating the bolt. The average of each set of five trials, after a correction for the phoria had been made, was used to plot the visual midline for each of these experimental situations.

This procedure eliminated the hand-eye coordination problem since the subject had to estimate on a visual basis alone when a single target was located on his subjective midsagittal plane.

In the binocular situation, the midline was very closely approximated by both subjects (Figs. 60 and 61). When
Fig. 60

Binocular
O.D.
O.S.

N.B.

28.6 cm

Visual Midline

50 cm

20 cm

Fig. 61

Binocular
O.D.
O.S.

F.B.

154.
one eye was used alone, however, there was a noticeable shift of the visual midline toward the eye used. This is in agreement with the apparent shift in the center of projection noticed in all monocular data described in this study.
X. SUMMARY AND CONCLUSIONS

In this study, data are presented which relate to the location of the center of projection of visual impressions. Normal binocular individuals, one-eyed persons, and squinters have been considered.

When a normal binocular subject fixates with both eyes a target placed 5.7 meters in front of him along his midsagittal plane, and is then asked to localize each of the diplopic images produced by a single target also placed in his midsagittal plane but within arm's reach, the results indicate that there is a single center of projection close to the root of his nose.

On the other hand, when one eye fixates a distant target while the opposite eye is occluded and two targets, spaced equally on either side of the primary line of sight, are localized, the center of projection moves toward the eye used. This is in agreement with results reported by Tschermak (1952), Roeloff (1924), and others, although some of these investigators do not agree that this indicates a movement of the center of projection. Their disagreement is centered around the fore and aft position of the center of projection. The relationship between perceived angular and linear size and perceived
distance is, however, a rather stable one under normal circumstances. It seems reasonable, then, to presume that the center from which we localize objects should be located along the interpupillary line.

Studies in which five targets were equally spaced on arcs of 30 cm and 40 cm radii centered at the root of the nose and with fixation maintained on the central target appeared to produce similar results, i.e., with binocular fixation of the center target, a center of projection was found near the root of the nose; with monocular fixation, this center shifted toward the eye used.

Two possible reasons for the apparent shift in the center of projection with monocular fixation were considered. First, when one eye is occluded, changes in convergence due to accommodative inaccuracies might occur; the phoria correction applied before plotting the center of projection may be in error. Secondly, the direction of projection of either or both eyes may be incorrect. In either of the above cases, a single center of projection might still be at the root of the nose or near one of the eyes.

In an effort to check the effect of the phoria change on projection and the apparent center of projection, a translucent "shield" was employed. A small hole
in the shield allowed the "covered" eye to see the center target only; the uncovered eye was able to see all the targets, including the center one. This arrangement eliminated the need for a phoria correction since no heterophoria should be manifest under these conditions. Only a small effect toward moving closer together the two centers of projection found with monocular fixation was evident. It was assumed, therefore, that the phoria was of the same magnitude during the monocular experiments as when it was measured prior to these experiments.

Walking experiments indicated that the subjects were, in general, able to guide themselves adequately using either eye, which indicated that projection was correct.

With the elimination of these two factors, it was concluded that a separate center of projection is used with each eye in monocular situations. This ability is based, perhaps, on a knowledge of which eye is being used. When one eye is closed, the "oblong" from which we view our surrounds is suddenly changed to a "rounded off square" displaced noticeably toward the open eye. Some subjective response to this phenomenon would not be unexpected.

As an additional check on projection, three targets placed on a 40 cm arc concentric with the midpoint of the interpupillary line were localized using monocular fix-
ation with and without auxiliary lenses placed before the uncovered eye. The changes in direction of localization, while erratic in many cases, appear to bear out the assumption that projection in normal individuals proceeds along a line parallel to the bisector of the angle of convergence.

After results to be expected in normal subjects had been determined, a group of 10 squinters was subjected to experimental situations in which monocular vision could be used.

Two of the squinters had normal correspondence and appeared to project in a direction parallel to the line of sight of the dominant eye. The center from which they projected was determined by the eye used, i.e., when using the right eye, this eye or a point near this eye was the center; when using the left eye, the left eye or a point near the left eye was the center of projection.

The eight squinters with anomalous correspondence used the line of sight of the fixating eye as the projection axis and appeared to use this eye or a point near it as the center of projection.

Two one-eyed subjects were run on the same 40 cm arc apparatus. One of these who had lost an eye only recently indicated that projection proceeded from the midpoint...
of the interpupillary line but that any ACA relationship which may have existed prior to the removal of the eye was now ignored.

The other one-eyed subject had lost his eye two years prior to this experiment. He demonstrated that the remaining eye was used as the center of projection and also indicated that any prior ACA relationship no longer had any effect on localization.

When normal subjects or squinters are put into situations in which a precise knowledge of the position of the head and body or the hands and body in relation to the direction in which the eyes are pointing must be known, it was shown that only a very imperfect knowledge of this kind is present. Experiments involving "shooting from the hip" while the "gun" was out of sight of the eyes showed that subjects could not be relied upon to indicate with any consistency the direction in which objects were localized by the eyes. A second method employing a focused light attached to the head by a headband showed somewhat better results, but there is still a question as to this method's validity. The rather erratic responses obtained would seem to eliminate both of these as good approaches to the problem of projection.

Experiments in which fixation is held in the plane
of the distant targets and those in which fixation is maintained at near yield results which conform to the same general principles.

The following general conclusions have been drawn from the data obtained:

(1) Binocular individuals in a binocular situation have a single center of projection located rather near the midpoint of the interpupillary line. These subjects project parallel to the bisector of the angle of convergence.

   (a) Some apparently binocular subjects may have this center very close to, even in, one of the eyes. Projection in these cases may be faulty in the non-dominant eye.

   (b) Binocular individuals when placed in a monocular situation appear to shift their center of projection toward the eye used.

(2) One-eyed individuals who have completely adapted themselves to the use of the remaining eye have a center of projection in this eye and project along the line of sight of the functioning eye.
(a) Those who have only recently lost an eye appear to use as the center of projection a point near the previously used binocular center of projection, but rapidly learn to ignore effects of accommodation on near localization.

(3) Squinters appear to have a center of projection located approximately in the eye used for fixation.

(a) Normal correspondence squinters project parallel to the line of sight of the dominant eye.

(b) Anomalous correspondence squinters project parallel to the line of sight of the eye used for fixation.

In general, it appears that localization in a monocular situation is more precise in the case of one-eyed individuals or squinters (using their dominant eye) than is that of normal binocular subjects. This is probably to be expected. From a practical standpoint this would indicate that jobs requiring monocular viewing might best be reserved for such individuals.
XI. REFERENCES


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XII. AUTOBIOGRAPHY

I, Neal James Bailey, was born in Gardenville, New York, November 6, 1917. I received my secondary school education in the public schools of the city of Detroit, Michigan. My undergraduate training was obtained at the University of Detroit and at The Ohio State University. I received the degree Bachelor of Science (Optometry) from The Ohio State University under the advisership of Dr. Glenn A. Fry. During my graduate training I held the position of Associate in Optometry. In addition, I was the recipient of an American Optometric Foundation Research Fellowship which continued in effect until completion of the requirements for the degree Doctor of Philosophy.