Vision Res. Vol. 33, No. 5/6, pp. 777–789, 1993
Printed in Great Britain. All rights reserved

0042-6989/93 $6.00 + 0.00

Optical Flow from Eye Movement with Head Immobilized: "Ocular Occlusion" Beyond the Nose

GEOFFREY P. BINGHAM*

Received 27 February 1992; in revised form 4 August 1992

The point of observation translates with eye movement because it is not coincident with the center of rotation in the eye. "Ocular occlusion" results. The amount of optical structure revealed by eye rotation depends on the distances of the occluding and occluded surfaces. The method of adjustment was used in Expt 1 to investigate the amount of structure detected at distances up to 1 m. In Expt 2, a forced-choice method was used to confirm predictions based on the assumption that the point of observation is in the entrance pupil at 11 mm from the center of rotation. (The location of the point of observation in the eye had not been measured previously.) Experiment 3 investigated the use of ocular occlusion to detect separation of surfaces in depth.

Optic flow   Eye movement   Occlusion   Nodal point

INTRODUCTION

Gibson (1961) formulated the notion of the optic array using a single abstract property of the eye, namely the point of observation. The array consists of the pattern in light projected from all directions to a point of observation. When the point of observation is translated through the environment, the optical pattern projected to the eye changes producing patterns of optical flow. For instance, when the point of observation is translated over a level ground surface, the optical flow pattern includes inverse patterns in hemispheres on opposite sides of the point of observation. On one side is radial outflow from a fixed point that corresponds to the direction of heading (Gibson, 1950, 1955, 1958; Lee, 1980; Warren, 1976). On the opposite side is radial inflow to a fixed point corresponding to the departure direction. In cluttered surroundings, the change of optical pattern includes accretion or deletion of optical structure at edges corresponding to the occluding edges of surfaces in the surround (Gibson, 1979; Nakayama & Loomis, 1974).

Although translation of the point of observation produces flow in the optic array, no flow results from rotation around the point of observation. The pattern in the array itself does not change. Nevertheless, when an eye rotates, the pattern projected to the back of the eye does change. Gibson (1979) suggested that an eye, occupying a potential point of observation, could scan the static pattern of the array projected to that point. Although the pattern of the array would sweep across the back of the eye, in this account, no flow in the optic array itself would be associated with eye movement. Neither radial flows nor accretion and deletion of optical structure would result. Only with head movement would the point of observation begin to translate causing change in the optic array.

Recent studies of optical flow have included the effect of eye movement (Cutting, 1986; Regen & Beverley, 1982; Rieger & Toet, 1985; Warren & Hannon, 1990; Warren, Mestre, Blackwell & Morris, 1991; Warren, Morris & Kalish, 1988). The analysis in these studies has been consistent with Gibson's. Eye movement has been treated as generating only rotational effects on the flow pattern reaching the retina (Koenderink, 1986; Lee, 1980; Rieger & Toet, 1985; Warren & Hannon, 1990; Warren *et al.*, 1991). Thus, for instance, Warren and Hannon (1990) have studied perception of heading with eye movement used to track a point on the ground. They have characterized the problem as a matter of decomposing the flow on the retina into a rotational component, associated with the pursuit movement of the eye, and a component of flow generated by translatory locomotion of the observer.

In these accounts, eye movement has been distinguished from all other movements of the observer as causing no alteration in the distances to various surfaces in the surround and as, therefore, producing no parallax. Accordingly, eye movement would provide no information about the structure of the surround. The only effect would be a rigid translation of pattern across the retina. This analysis, however, requires the assumption that the point of observation and the center of rotation

---

*Department of Psychology, Indiana University, Bloomington, IN 47405, U.S.A.

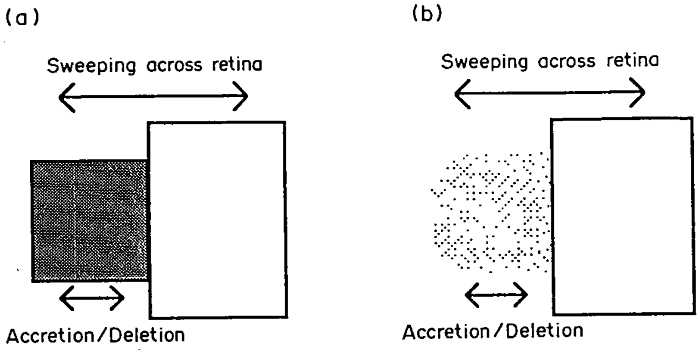

FIGURE 1. Forms of accretion and deletion of optical structure accompanying the sweep of structure across the retina with eye rotation. Note that the forms actually projected on to the retina would exhibit perspective transformations as well. (a) Change of size and shape of a homogeneous area. (b) Change in the visible number of contrast elements.

in the eye are coincident. They are not. The center of rotation is located near the center of the eye, approx. 1 mm nasalward of the center of the primary globe (Bennett & Rabbetts, 1989; Fry & Hill, 1962; Le Grand & El Hage, 1980; Park & Park, 1933; Verrijp, 1930). In contrast, the point of observation in the eye is located in the optics at the front of the eye. If located at the nodal point of the lens, then the point of observation would be at a distance of about 6.5 mm from the center of rotation. However, the more relevant structure for defining the point of observation is the entrance pupil because this ultimately constrains and determines the bundle of rays allowed to enter the eye (Bennett & Rabbetts, 1989; Nakayama & Loomis, 1974; Westheimer, 1986). The location of the effective point of observation in the eye has never been determined empirically. However, if it is at the entrance pupil, then the point of observation is at a distance of 11 mm from the center of rotation.

In their seminal 1974 paper on optical flow, Nakayama and Loomis recognized that the center of rotation and the point of observation are separated and that rotation of the eye therefore translates the point of observation producing "ocular parallax" (Brewster, 1844) or "ocular occlusion". However, Nakayama and Loomis assumed that the effects would be small and could be ignored in an analysis providing a good first approximation. Nevertheless, it has long been known that the effects of "ocular parallax" are strong when the nearer of two locii separated in depth is within a few centimeters of the point of observation (Brewster, 1844; Mapp & Ono, 1986). This can be demonstrated readily as follows. Close your left eye and while looking with the right eye past the bridge or tip of your nose, use your nose to occlude some object in the surround. Without moving your head, look straight ahead and the occluded object should come back into view in the periphery. Another demonstration, described and illustrated by Mapp and Ono (1986), shows that the effect of "ocular parallax" with nasal occlusions remains strong when the occluded surface is close to the eye and nose. While looking straight ahead with the right eye and with the left eye closed, bring your left finger forward from your left ear until it first comes into view past the bridge of your nose. (Wiggling the finger helps to make it obvious in the periphery.) Once again, without moving your head, look towards the finger and it should disappear from view behind the bridge of your nose.

Mapp and Ono (1986) measured the parallax between the nose and an object at a distance of 30 cm from the eye's center of rotation. Eye rotation of about 45°, i.e. from looking straight ahead to looking past the nose, produced parallax of about 10°. The size and direction of parallax varied with the size and shape of the observer's nose.

How general is the effect of ocular parallax or ocular occlusion? Is it detectable when the nearer point is farther away than the nose? Given a separation between the point of observation and the center of rotation of 11 mm, an eye rotation of 45° translates the point of observation sideways by about 8 mm. This is potentially a large distance depending on the acuity of the eye. Are the transformations noticeable when generated by eye movement? The difference is that the optical transformations sweep back and forth across the retina as the eye moves back and forth and the transformations are locked in phase with the sweeping. Furthermore, the excursion across the retina takes the transforming pattern from foveal regions into the retinal periphery and back. Thus, peripheral acuity is relevant to the question.

With translation of the point of observation in cluttered surrounds, the global flow structure in the optic array includes a distribution of locations at which accretion and deletion of optical structure occurs. Ultimately, in evaluating ocular occlusion, one should investigate such global flows. However, this study will focus on the local transformation at a single occluding edge. This transformation can exhibit a variety of forms. In all cases, translation of the point of observation via eye movement sweeps the transformation across the retina in phase with the transformation itself. Although the sweeping and transformation can occur along any given direction and extent defined on the retina, we will restrict consideration to eye movement along a horizontal direction that moves an occluding edge between the fovea and the temporal periphery. Depending on whether the occluding edge faces to the left or to the right, the accretion of structure would occur with a sweep from fovea to periphery or vice versa. We restrict our investigation to the former.

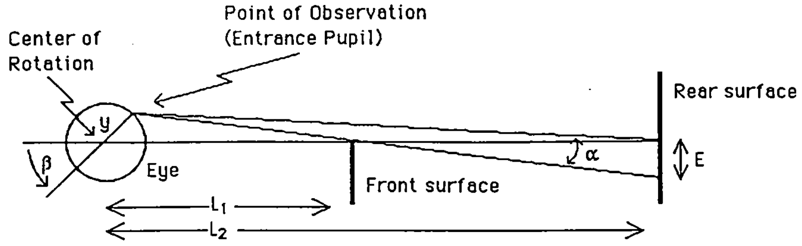

FIGURE 2. The geometry of optical occlusion. See text for explanation.

One form of the transformation, shown in Fig. 1(a), involves the growing and shrinking and change of shape of a distinct, internally homogeneous area that contrasts with neighboring regions. For instance, a homogeneous red square on a white ground being occluded by a white surface would yield the transformation of the projected square into the projection of an increasingly narrow rectangle that would shrink in width down to a red line, finally disappearing from view.* Accretion would yield the reverse. Another form, shown in Fig. 1(b), involves the disappearance (or appearance) of a distribution of optical contrasts and a frequency of disappearances (or appearances). The current investigations focused on the first form of the transformation because it was suited to unequivocal measurement of the magnitudes of detectable structure revealed by eye movement with surfaces at different distances and simultaneous measurement of the location of the point of observation in the eye. We used the clearest case to establish the geometry and fundamental detectability of ocular occlusion.

Using the viewing geometry, we will derive estimates of the variation in the transformation with variations in the distances of occluding and occluded surfaces. Next, we will compare these magnitudes with established measures of acuity to predict the potential significance of the effect. Finally, we will report experiments in which we have measured both the location of the point of observation in the eye and the detectable magnitudes of ocular occlusion with various surface distances. In a final experiment, we began to investigate the use of this information to detect separation of surfaces in depth.

Predicting magnitudes of structure revealed in ocular occlusion

The geometry of ocular occlusion is shown in Fig. 2 from a perspective above a horizontal plane which cuts the eye and two surfaces separated in depth from the eye. As the eye rotates counter clockwise about its center through an angle β, the point of observation is translated to the left revealing an extent, E, along the rear surface. The corresponding visual angle of the revealed extent is α. The magnitude of α is determined by the distances from the center of rotation of the front, L_1, and rear, L_2, surfaces together with the angle of rotation, β, and the distance, y, between the center of rotation and the point of observation. Assuming $y = 11$ mm, a predicted α_p can be computed by using the following equation (2) to derive a predicted $E = E_p$ which can be substituted into equation (1) to yield $\alpha = \alpha_p$.

$$\alpha = \arctan\left[\frac{E + y \sin\beta}{L_2 - y \cos\beta}\right] - \arctan\left[\frac{y \sin\beta}{L_2 - y \cos\beta}\right] \qquad (1)$$

$$E_p = \frac{(L_2 - L_1) y \sin\beta}{L_1 - y \cos\beta} \qquad (2)$$

Similarly, a measured extent on the rear surface, $E = E_m$, can be plugged into equation (3) to derive a measured $\alpha = \alpha_m$. A comparison of α_p and α_m yielding $\Delta\alpha(=\alpha_p - \alpha_m)$ should provide some indication whether our estimate of y is accurate. [See Hadani, Ishai and Gur (1980) for a more general formulation of ocular parallax without a focus on occlusion.]

α_p was computed for front surface distances from 20 to 40 cm and for rear surface distances from 25 cm to 1 m. The near and far front surface distances correspond roughly to a close reading distance and maximum reach distance respectively. The amounts of optical structure revealed by eye rotations of 20, 30, and 40° were plotted in Fig. 3. α_p ranged from 12′ to 1°10′. α_p decreased with L_1 distances and increased with L_2 distances. An α_p surface for eye rotation of 40° was plotted in Fig. 4 for L_1 distances up to 5 m and L_2 distances up to 20 m. Most of the decrease in α_p with increasing L_1 occurred at distances within 1 m. Potentially significant α_p values remained at an L_1 distance of 5 m, where, for instance, with L_2 at 10 m, α_p was 2.5′. α_p increased with increases in L_2 (beyond L_1) rapidly reaching an effective maximum value that changed little with additional increases in L_2. With L_1 at 20 cm, α_p reached an effective ceiling of 2° for L_2 distances beyond 3.5 m.

The progressive accretion or deletion of optical structure appeared in Fig. 3 as the separation between 20, 30, and 40° curves at a particular configuration of surface distances. The rate of accretion for a given configuration of L_1 and L_2 was essentially constant. At $L_1 = 20$ cm and $L_2 = 42$ cm, the rate of accretion was about 15′ per 10° of eye rotation or about 2.5%. At $L_1 = 40$ cm and $L_2 = 80$ cm, the rate of accretion was about 7′25″ per 10° of eye rotation or about 1.2%. The velocity or time rate of accretion is a function of the velocity of eye rotation. For a given configuration of surfaces, the constant rate of accretion with eye rotation yields a proportionality

---

*A square on a surface in the environment would not project to a square on the retina, but rather to some rhomboid form with curved sides. The transformations in question would be of this projected form, but we will describe it in terms of the viewed form for ease of expression.

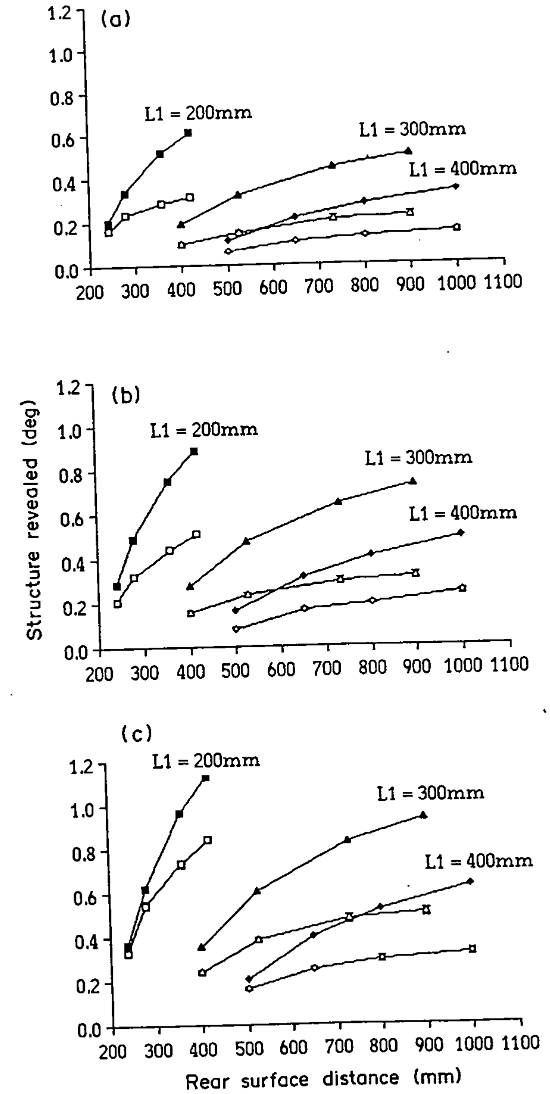

FIGURE 3. Visual angles of structure revealed with eye rotations of 20° (squares), 30° (triangles), and 40° (diamonds) with four rear surface distances for each of three front surface distances, L_1. Predicted α_p together with mean α_m (with standard error bars). Values of α_p predicted using equations (1) and (2) and assuming $y = 11$ mm. α_m, open symbols; α_p, solid symbols. (a) 20° of eye rotation. (b) 30° of eye rotation. (c) 40° of eye rotation.

constant that takes eye velocity to accretion velocity and determines the relation between differential velocity (of parallax) and absolute velocity (of sweep) across the retina. The proportionality constant increased rapidly with increasing L_2 distances up to about twice the L_1 distance and increased more gradually thereafter. With $L_1 = 20$ cm, the slope reached 3′ of accretion per 1° of eye rotation at an L_2 of 3.5 m (yielding 2° accretion with 40° of rotation: $\frac{2}{40} = 0.05$). This differential velocity is 5% of the absolute velocity of eye rotation. Given the ceilings reached in Fig. 4, we deduced that a proportionality constant of 5% or greater could only be achieved at L_1 distances of 20 cm or less (as well as at L_2 distances of 3.5 m or greater). To evaluate the potential significance of these predicted magnitudes, we next compared them to established levels of acuity.

Comparing predicted magnitudes with established levels of acuity

Acuity is measured in a variety of ways each of which yields a different estimate. The difficulty is that few of these measurements are strictly comparable to ocular parallax. The two most studied measures of acuity are minimum angle of resolution and minimum angle detectable. Minimum angle of resolution is the subtense of the separation between two dots or lines (perhaps in a grating pattern) that allows the two items to be distinguished. This measure would be relevant for determining whether an accreted optical contrast and the edge from which it has emerged might be resolved. Resolution acuity drops rapidly from 33″ at the fovea to about 3′ at 10° eccentricity and then decreases less steeply to 5–8′ at 30° (Kerr, 1971; Thibos, Walsh & Cheney, 1987b; Wertheim, 1980; Westheimer, 1981). These values for peripheral resolution compare favorably with α_p values shown in Figs 3 and 4, although as L_1 approaches 5 m and beyond, α_p values fall below these thresholds. Although variation in luminance can affect resolution acuity, Kerr (1971) found that variation in luminance values above 1 mL ($= 3.18$ cd/m^2) had no effect at eccentricities beyond 10°.

Detection acuity would be relevant when optical contrasts emerge in an otherwise homogeneous field. Wertheimer (1981) cited acuity values of a few seconds of arc in peripheral regions. These values predict detection of nearly all α_p values described in Figs 3 and 4. In particular, an L_1 distance of 5 m would not represent a limit.

Both resolution acuity and detection acuity are static measures of acuity. Brief exposures (≈ 200 msec) are usually employed in these measures to avoid "Troxler's effect" in which a constantly illuminated peripheral field quickly tends to fade and disappear (Kerr, 1971). This effect suggests that the periphery is designed primarily to handle changing optical patterns. Because the fading of "stabilized retinal images" is not restricted to the periphery (Riggs, Ratliff, Cornsweet & Cornsweet, 1953), the inference applies as well to the entire retina. In ocular occlusion, a single element of optical structure may appear as an occluding edge passes a locus on the retina. As the edge follows the sweep produced by eye movement, it takes the newly accreted optical element with it. The result is a brief exposure of the retinal locus to a newly appearing optical contrast. Thus, both resolution and detection acuity may well reflect performance levels of a sensory system designed to handle accretion (or deletion) of structure in optical flows.

With the head stabilized, change would result from both saccadic and pursuit movement of the eye. At the terminus of successive saccades, we might expect detection of the result of optical flow generated by eye movement. Hadani, Gur, Meiri and Fender (1980) found thresholds of 2–6″ for detection of differential displacements in random-dot displays. On this basis, they predicted "some level of monocular depth perception" generated by small involuntary eye movements (Hadani *et al.*, 1980, p. 950).

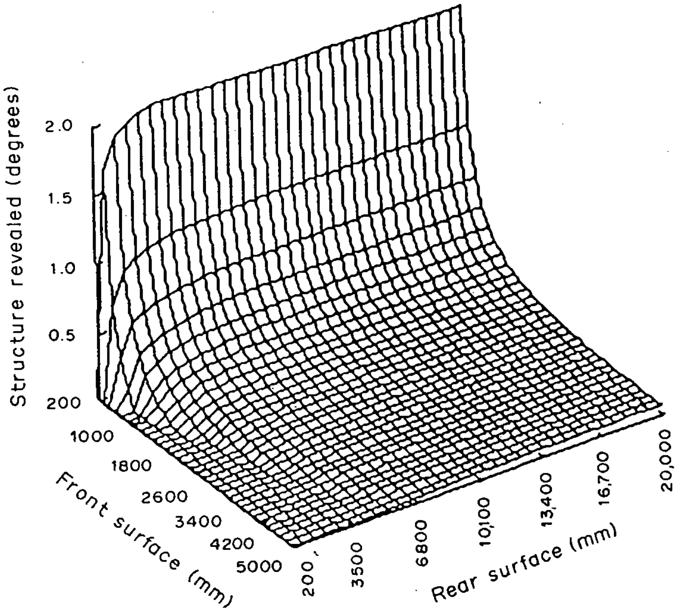

FIGURE 4. An α_p surface generated for an eye rotation of 40° with the front and rear surfaces at distances up to 5 and 20 m respectively.

The detection of change during a saccadic movement is not likely. Saccadic eye movement is extremely rapid with velocities of 100–300°/sec. Dynamic resolution acuity becomes poor at these velocities as does sensitivity for motion (Burr, Holt, Johnstone & Ross, 1982). On the other hand, pursuit movement of the eye, performed to track an object moving in the surround, would occur at much lower velocities where dynamic resolution acuity and motion sensitivity may be relevant.

"Dynamic acuity" has been studied by translating a rigid pattern across the retina at specific velocities to determine resolution or detection acuities. Resolution acuity is relatively unaffected by velocities up to about 2–4°/sec (Anstis, 1983; Fahle & Poggio, 1981; Westheimer, 1981; Westheimer & McKee, 1975). At greater velocities acuity drops to values of about 1–2′ at velocities of 60°/sec (Schiff, 1980). If acuity for the accretion of structure in ocular occlusion requires the ability to resolve the emergent structure and the occluding edge while they sweep together across the retina, then assuming large amplitude contrasts, dynamic resolution acuity is sufficient to detect (during relatively fast pursuit movements of the eye) all α_p values appearing in Fig. 3. At an L_1 distance of 5 m, all α_p values corresponding roughly to $L_2 \geqslant 1.5L_1$ should be detectable.

The sweeping pattern in ocular occlusion is not rigid, however. By definition, parallax yields different velocities for the optical edge and the optical structures revealed at the edge. Accreted structure might be detected during pursuit movement in terms of a differential velocity. Using the results of studies by McKee (1981), Nakayama (1981) and van Doorn and Koenderink (1982, 1983), Nakayama (1985) has estimated a Weber fraction for the detection of differential velocity as 5%. This means that, to be detectable, differential velocity must exceed a common velocity component by 5%. We had estimated that ocular parallax would only reach or exceed this value for L_1 distances of 20 cm or less and L_2 distances of 3.5 m or more. Only in these limited conditions should accretion in ocular occlusion be detectable in terms of differential velocity.

Although sensitivities for differential velocities are inadequate to detect ocular occlusion beyond near space, both detection and resolution acuities certainly place predicted α_p values, for surfaces beyond near space, within a detectable range, both at the ends of successive saccades or during pursuit movement.

EXPERIMENT 1: MEASURING OCULAR OCCLUSION

Using a method of adjustment with surface configurations as shown in Fig. 2, we measured the detectable extents, E_m, along the rear surface that were revealed by 20, 30, or 40° of eye rotation. We tested the twelve surface configurations shown in Fig. 3 and Table 1. α_m values, computed by substituting E_m values into equation (1), were compared to corresponding α_p values.

Method

Apparatus. As shown in Fig. 5, the distances of front and rear surfaces were adjusted along a 2 m optical bench. Both surfaces were oriented in a fronto-parallal plane relative to the observer. The front surface was

TABLE 1. Surface configurations

	Front surface distance		
	200 mm	300 mm	400 mm
Rear surface distance	240 mm	400 mm	500 mm
	280 mm	525 mm	650 mm
	360 mm	730 mm	800 mm
	420 mm	899 mm	1000 mm

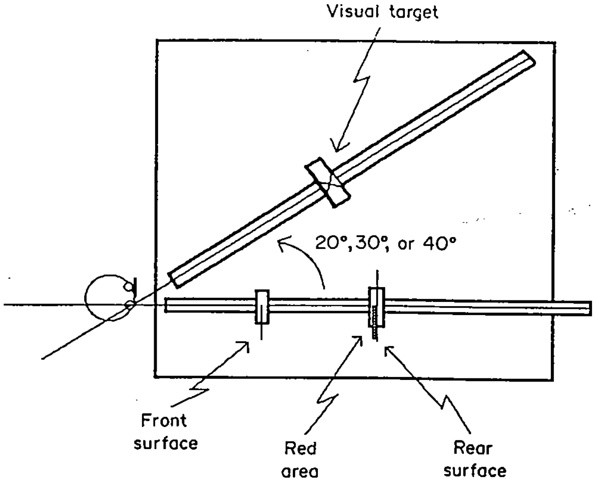

FIGURE 5. Apparatus and viewing conditions for Expt 1. See text for explanation.

white and extended to the right of the midline of the bench. The left edge was sharp and clean. This surface was 10 cm in width and 20 cm in height. The rear surface extended 10 cm to either side of the midline of the bench. The left half of this surface was white. The right half was red. The border between white and red was sharp and lay over the midline of the bench. The rear surface was 20 × 20 cm. Both surfaces were smooth. The rear surface sat on a translation platform that allowed us to translate the surface to the left or right of the bench. The platform was instrumented with a micrometer used to move the surface and to measure its position to the nearest 0.0002 cm. The optical bench was attached to a steel table (painted flat black) so as to allow precision adjustment of its height and its orientation about the long axis. A meter stick was attached to the bench so that pointers extending from the surface mounts indexed the surface distances.

A second 2 m bench was attached to the table so as to form an angle with the first bench with the apex at the center of rotation of the observer's right eye. A cross hair sight was mounted on this bench at the same distance from the observer as the rear surface on the first bench and at a height equal to the middle of surfaces. The second bench could be adjusted to form an angle of either 20, 30, or 40° with the first bench.

A biteboard was attached to the table at the apex of the angle formed by the two benches. The room wall behind the apparatus was hospital yellow cinderblock and was at a distance of 2.5 m from the observer. Standard overhead fluorescent lighting was used with the bulbs running the length of the first bench. The luminance from the white front surface and from the white and red areas of the rear surface were measured from the observer's position using a Minolta LS-100 luminance meter. Measurements were made in all twelve surface configurations used. Four readings were taken in each case. Luminance increased and then decreased slightly with distance. Luminance varied much less for the red than for the white surfaces. For the white rear surface, luminance ranged between 65 and 100 cd/m^2. The average difference between the white and red areas of the rear surface was 68.7 cd/m^2 (SD = 9.4 cd/m^2). The luminance of the cross hairs and of the wall behind the apparatus were within the same range as for the white surface. All of the readings were well above the value cited by Kerr (1971) at which luminance might begin to affect resolution acuity in the periphery.

Observers. Seven optometry students at Indiana University participated in the experiment. Six were male and one female. All had good uncorrected vision and all were right eye dominant. Participants were paid at the rate of $4.25 per hour.

Procedure. Sights were mounted on the two ends of both benches. Before the observer arrived, threads were attached to the rearmost sights and to a post temporarily fixed to the biteboard. These were used to set the benches relative to one another at the desired angle with the apex over the biteboard. The post and threads were then removed. With his left eye covered with a patch, the observer on the biteboard attempted to sight down the first bench with his right eye. The biteboard was adjusted left to right to achieve accurate alignment. Next the observer attempted to sight down the second bench. The biteboard was adjusted front to back (without altering left to right position) to achieve alignment. This fixed the center of rotation of the observer's right eye at the apex of the angle formed by the two benches. This procedure was expected to introduce small error in positioning the center of rotation because, according to the results of Fry and Hill (1962), it is located 1 mm to the temporal side of the line of sight. However, given the additional results of Park and Park (1933) and Verrijp (1930), there is bound to be some error in locating the center of rotation due to individual differences in its location and behavior. Generally, errors on the order of 1 mm must be expected.

Twelve configurations of front and rear surface distances were tested. Distances were measured from the observer's center of rotation. For each of three front surface distances, four rear surface distances were used as shown in Table 1. Each configuration was tested at three angles of rotation, 20, 30, and 40°. Three trials at each configuration and angle were run in each of three different repetitions. The separate repetitions in different sessions were used to guarantee the reproducibility of the measurements and alignment procedures. Nine measurements (3 trials × 3 repetitions) by twelve configurations and three angles yielded a total of 324 measurements per observer. This took each observer about 18 hr spread over nine 2 hr sessions. The order of testing was completely randomized within repetition and angle.

At the beginning of each trial, the lateral position of the rear surface was adjusted so that the red portion of the surface was just occluded by the front surface as the observer looked straight past the left edge of the front surface to the rear surface. The position, x_1, on the micrometer was recorded. The observer was then asked to look towards the cross hairs on the second bench, while noticing whether a red area on the rear surface came into view. The observer was allowed to visually explore the interval between the surfaces and the cross hairs without going farther to the left than the cross hairs. If the observer detected a red area, the rear surface was translated under the observer's guidance until he could no longer see red. The rear surface was to be adjusted to that point at which the red just disappeared from view while the observer looked at the cross hairs. The observer was free to indicate that the surface should be moved to the left or right. When, on being translated to the right, the red area disappeared, observers often moved the surface slightly to the left and then right again before indicating that the position was final. The position, x_2, on the micrometer was again recorded. E was computed as $x_2 - x_1$.

(A few "ascending" trials were run starting with the red area out of view so that the rear surface had to be translated left until the red just began to come into view. The results were identical to those for "descending" trials, so the method was not used systematically.)

Color sensitivity shifts towards the shortwave in the periphery. Most observers reported that the red area appeared black when viewed peripherally.

Results and discussion

One of the participants, the only female, apparently was unable to perform the task. Her data were excluded from analysis. Two other participants only performed judgments at the 30° angle. Data reported for 30° eye movement included that from six participants while data for 20 and 40° included only four participants. The data are expressed as α_m values.

The results of repeated judgments in different sessions were checked to ensure that alignment procedures were stable and reproducible. Overall means for the three repetitions of eye movement were within 1.5′ or less of one another when computed and compared independently for each angle of eye rotation. Standard deviations were computed for each of the 36 experimental conditions (three L_1 distances × four L_2 distances × three angles) for each repetition and across all three repetitions. When the mean of the three SDs for individual repetitions was compared to the SD for all three repetitions, the two were nearly identical in all 36 experimental conditions. Only four differed by more than 18″. The overall mean (of the 36 SDs) in the former case was 3′50″ (SD = 1′41″) and in the latter case it was 4′ (SD = 1′44″). Finally, when the data for each repetition were regressed on those for the other repetitions, the slopes were 0.94 or greater, the intercepts were 1′12″ or less, and the r^2 were 0.86 or better in all cases. By comparison, when the data for each of the three trials were regressed on one another, the slopes were 0.98, the intercepts were 25″, and the r^2 were 0.92 or better in all cases. Thus, the alignment procedure added a very small amount of variability to that of trials and observers. Overall, the data were very consistent and the procedures were reliable.

Repeated measures analyses of variance were performed independently on the data for each angle with front surface (1–3), rear surface (1–4), repetition (1–3), and trial (1–3) as factors. In all cases, front surface, rear surface, and their interaction were significant, $P < 0.01$. In no instances were repetition, trial, or any of their interactions significant.

Mean judgments (with standard error bars) were plotted with predicted α_p values in Fig. 3(a–c) for angles 20, 30, and 40° respectively. (The standard error bars were often smaller than the points in the graph.) The form of the data curves is similar to that of the predictions; however, the predictions overestimated measured values. Despite this difference, significant amounts of optical structure were detected in every condition. A multiple regression was performed regressing angle, L_1 distance, and L_2 distance simultaneously on α_m values. The regression was significant, $F(3,140) = 102.8$, $P < 0.001$, and accounted for 70% of the variance (an amount that was somewhat low because the model approximated curves with lines). α_m decreased with L_1 distance, $\beta = -0.85$, partial $F = 158.7$, $P < 0.001$, and increased with L_2 distance, $\beta = 0.44$, partial $F = 43.3$, $P < 0.001$, and with angle, $\beta = 0.55$, partial $F = 137.1$, $P < 0.001$. Even with the front surface at a distance of almost 0.5 m, mean α_m values ranging from 3′43″ to 19′19″ were derived depending on the amount of eye rotation and rear surface distance.

The question remained why did the predictions systematically overestimate the measured values? One possibility was that the estimate of the distance between the center of rotation and the point of observation was too large. To make the predictions, we used an estimate of $y = 11$ mm based on the assumption that the point of observation was in the entrance pupil. The dimensions of adult eyes vary little (Sorsby, 1964), so if the estimate was incorrect, then the assumed location must have been wrong. The alternative possible location was at the nodal points of the eye, placing the point of observation about 6.5 mm from the center of rotation. From equations (1) and (2), we derived an equation which allowed us to derive an estimate of y from the measurements, E_m

$$y = \frac{E_m L_1}{\sin\beta(L_2 - L_1) + E_m \cos\beta}. \tag{3}$$

We used equation (3) to compute estimates of y from each of our measurements. The frequency distribution of computed ys appears in Fig. 6. The mean and mode of the distribution fell at 6.5 mm. Did this mean that 6.5 mm was the better estimate? The upper tail of the distribution fell near our original 11 mm estimate and more than half of the computed ys lay above the 6.5 mm value. This would be unlikely if the point of observation were actually at the nodal points.

A study of the difference between α_p and α_m values, $\Delta\alpha = \alpha_p - \alpha_m$, revealed that the difference was quite systematic. As shown in Fig. 7, mean $\Delta\alpha$ varied linearly with the reciprocal of the L_2 distance. Observers were accommodated to the L_2 distance because they were instructed to look past the edge of the front surface to the rear surface and because the cross hair on the

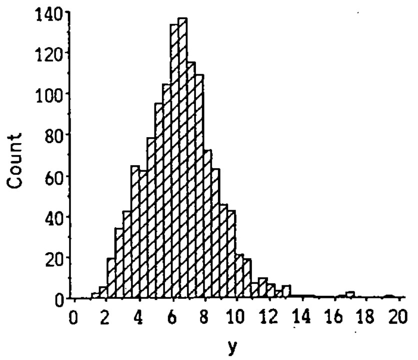

FIGURE 6. Frequency histogram of estimated distances, y, between the center of rotation and the point of observation computed from the data using equation (3). See text for explanation.

second bench was at the distance of the rear surface. Thus, the edge of the front surface would appear blurred. The amount of blur would be a function of the reciprocal of the distance (the dioptric distance) between the two surfaces. The red on the rear surface would have faded gradually into the white blur. Assuming a criterion value defined in terms of a proportion of the original red intensity, a distance from the edge would be determined by the width of the blurred edge. This would vary with dioptric distance depending on the criterion used. This predicted that $\Delta\alpha$ should have approached 0 as L_2 distance approached L_1 distance. Linear regressions were performed on the means in Fig. 7 for each L_1 distance and angle. All regressions were significant, $P < 0.01$, $r^2 = 0.99$. The $1/L_1$ distances ($\times 100$) for the three distances near to far were 0.5, 0.33, and 0.25. The x-axis intercepts for the $L_1 = 200$ cm lines for the three angles were 0.43, 0.46 and 0.43, all close to 0.5; for $L_1 = 300$ mm, they were 0.32, 0.30, and 0.29, all close to 0.33; and for $L_1 = 400$ mm, they were 0.24, 0.25, and 0.22, all close to 0.25.

$\Delta\alpha$ also varied with the angle of eye rotation. Greater angles of rotation placed the edge farther into the retinal periphery dropping the acuity. Figure 7 shows that $\Delta\alpha$ increased with rotation from 20 to 30°, but not beyond, and that the effect of angle interacted with dioptric difference. A multiple regression was performed regressing

$$\left(\frac{1}{L_1}\Big/\frac{1}{L_2}\right),$$

angle, and the interaction on $\Delta\alpha$ values. The result was significant, $F(3,1508) = 570.4$, $P < 0.001$, $r^2 = 0.53$. The dioptric difference was significant, $P < 0.001$, partial $F = 57.8$, $\beta = 0.55$, as was the interaction, $P < 0.02$, partial $F = 5.7$, $\beta = 0.20$, while angle itself was not significant, $\beta = 0.03$. Thus, the extent of the overestimation in predictions varied with the relative distance between the two surfaces and with the angle of eye rotation.†

EXPERIMENT 2: LOCATING THE POINT OF OBSERVATION

Our analysis implied that the red area remained visible at the point where observers judged it to have disappeared. Red may have still been visible to observers, but at a level below a criterion used to make judgments via the method of adjustment. Use of a criterion free method might reduce the difference between α_m and α_p values, lending greater credence to the 11 mm estimate for y. We used a forced-choice task in which observers had to select which of two displays contained the "signal", that is, a red area revealed with eye rotation.

Method

Apparatus. The apparatus was the same as in Expt 1 with the following additions. A wooden barrier was placed between observers and the optical bench so that the surfaces were observed through a 15 × 15 cm window. An LCD window was used so that the view could be obscured between trials without significantly altering the adaptive state of the eye. An axle was attached to the translation platform supporting the rear surface. Two surfaces were attached to the axle so that they could both rotate around the axis and slide along it with a very tight but smooth action. This enabled the alternative positioning of two surfaces with precision and reliability. One surface was completely white while the other was white with red on the right half just as in Expt 1.

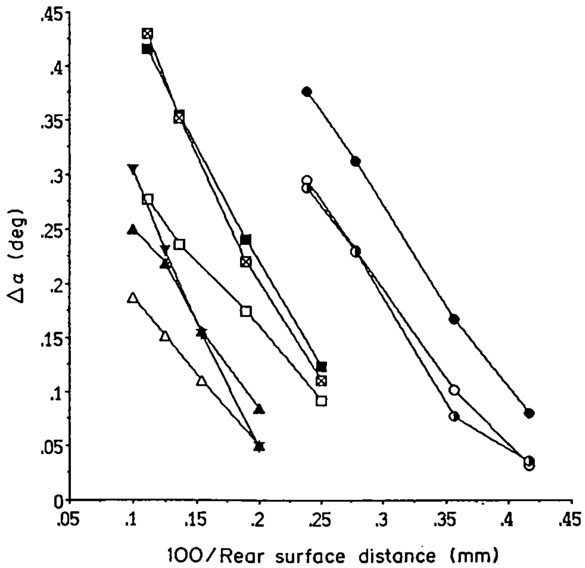

FIGURE 7. Mean $\Delta\alpha$ values plotted against $100 \times (1/L_2)$. Front surface at 200 mm, circles; at 300 mm, squares; at 400 mm, triangles. 20° eye rotation, open symbols; 30° eye rotation, solid symbols; 40° eye rotation, half solid, circle, square and cross, inverted triangle.

---

†L_1 distance also affected $\Delta\alpha$ values. Shorter L_1 distances would place the edge farther into the periphery for a given angle of rotation. However, the effect of L_1 was nonmonotonic. The L_1 distance at 300 mm produced relatively greater $\Delta\alpha$ values, especially for rotations of 30 and 40°. This was puzzling. The only discontinuity available to account for this was the blind spot. This lies at about 15° from the fovea along the temporal retina. How this might interfere with acuity with rotations of 30 or 40° was not clear.

TABLE 2. α_m measured via forced choice

Observer	Configuration 1 $L_1 = 300$ mm; $L_2 = 400$ mm	Configuration 2 $L_1 = 300$ mm; $L_2 = 899$ mm
1	$\alpha_p + 8.97''$	$\alpha_p - 2.99''$
2	$\alpha_p - 2.22''$	$\alpha_p - 20.00''$
3	$\alpha_p - 2.11''$	$\alpha_p - 20.29''$
4	$\alpha_p + 1.85''$	$\alpha_p - 8.35''$

Observers. The four observers who completed all experimental conditions in Expt 1 participated in Expt 2. They were paid at $4.25 per hour.

Procedure. Only a single angle of eye rotation was used, namely, 30°, and only two of the previous surface configurations were used. With L_1 at 300 mm, L_2 was at either 400 or 899 mm. The optical benches were positioned and aligned with respect to the observer's right eye as in Expt 1. In a given surface configuration, E_m was measured on four successive trials. The mean of these values was compared to the mean for the configuration from Expt 1 to be sure that performance was similar. The means were very close in all cases.

Using the values from Expt 1, the rear surface was positioned at the E_m mean value minus 1 standard deviation. The observer was shown two different displays consisting of a rear surface with or without the red area. The order of the two displays was randomized over trials. The LCD window was made opaque while the surfaces were being positioned. Irregular positioning movements were made during each positioning operation. (This precaution was not really necessary because the surfaces rotated and slid silently because the apparatus was precisely machined and well lubricated.) The ISI between the two displays was about 15 sec. Once the surfaces were positioned, the LCD window was made transparent and the observer was instructed, as in Expt 1, to look back and forth between the cross hairs on the second bench and the surfaces on the first bench. The observer was allowed to inspect a given display for as long as desired. Observers usually examined a given display for 5–10 sec. After the observer had viewed the two displays for a trial, he judged which display contained the red area.

Approximately ten trials were run at a given position of the rear surface. Then the rate of correct responding was checked. If the response rate was above 75% correct, then the rear surface was moved towards the predicted $E = E_p$ by another standard deviation unit. (Responses were generally at 100% up to the position at which the 75% response rate was found.) Once an apparent 75% response rate was found, 50 trials were performed to confirm the response rate. Observers were not informed that the rear surface was being adjusted in position nor were they aware when such adjustments were made. In each instance, approx. 90–100 trials were required to establish the position corresponding to the 75% response rate.

The distances between E_p and the E_m mean from Expt 1 in standard deviation units for each of the four observers were 4.95, 3.80, 3.75, and 4.1 for the first configuration and 5.43, 10.00, 24.00, and 3.66 for the second configuration. As is typical for this forced-choice method, observers often felt that they were guessing despite their responding at 100% correct.

Results and discussion

The results for individual observers for the two configurations appear in Table 2. All observers responded at 100% correct until α_m was within a few seconds of arc of α_p. The mean final α_m was $\alpha_p + 1.62''$ in the first configuration (SD = 5.25″) and $\alpha_p - 12.9''$ in the second configuration (SD = 8.64″). These errors were comparable to values for detection acuity in the periphery. Differences from the predictions of the model expressed in equations (1) and (2) would be expected also because the center of rotation is known to lie about 1 mm to the side of the center of the eye and to travel during eye movement, altering the effective y distance by ±1 mm (Park & Park, 1933). Also there are individual differences in the (mean) location of the center of rotation on the order of ±0.8 mm (Fry & Hill, 1962) as well as in the trajectory of the momentary center during eye movement, with more random behavior in some cases where, by inference, the eye sits less snugly in the socket (Fry & Hill, 1933; Verrijp, 1930).

We concluded that 11 mm was an accurate estimate of the distance between the center of rotation and the effective point of observation in the eye. This placed the point of observation in the entrance pupil. This result also shows that optical structure often is revealed with eye movement even though an observer may not be aware of it. As has been found with other forms of optical information (Bingham, Muchisky & Romack, 1991; Bootsma & van Wieringen, 1990; Lee & Aronson, 1974; Lee & Lishman, 1975; Lee, Young, Reddish, Lough & Clayton, 1983; Lishman & Lee, 1973), this information might well be used in guiding behavior despite a lack of awareness.

EXPERIMENT 3: USING OCULAR OCCLUSION

We used surface configurations and contrasts similar to those used in Expts 1 and 2 to investigate the use of ocular occlusion in detecting separation of surfaces in depth. The intent was to create a situation in which the only way to detect separation in depth was via the accretion and deletion of optical structure with eye movement. All other monocular sources of information about separation in depth had to be controlled including differences in luminance, optical texture density, and accommodation.

Three types of displays were used. Two were experimental displays and one was a control. The first experimental display ("Flat") consisted of a single flat surface. The left half was white and the right half was gray. The second experimental display ("red separated") consisted of two surfaces that were separated in depth. The front surface was gray and filled the right half of the display. The rear surface extended across the entire display area and thus, was half occluded by the front surface. The left, unoccluded half was white. The right half was red.

Portions of this became revealed with eye movement as the observer looked to the left away from the white/gray contrast edge. We expected that observers should be able to detect separation in depth when viewing this display. The control display ("white separated") was the same as the "red separated" display except that the rear surface was entirely white. We expected that observers should not be able to detect separation in depth when viewing this display if we had indeed controlled other potential sources of information.

Luminance was controlled by using different surface reflectances in reduced viewing conditions where brightness constancy would not be preserved. Three different grays were used for the front surface and these spanned the gray used for the right half of the "Flat" surface. Differences in optical texture and accommodation were controlled by using extremely smooth surfaces that were lighted (perpendicularly) by a source close in direction to the point of observation. In addition, the surfaces were viewed through an LCD window that itself had a very slight amount of texture which obscured any residual microtexture that otherwise might have been apparent on the surfaces. Without optical structure associated with surface texture, the only contrast in the display was associated with a sharp border formed by a difference in luminance between the left and right halves of the display. This contrast aside, the left and right halves of the display each were Ganzfelds, that is, they were otherwise unfocusable. Only the single contrast, corresponding to the left edge of the right surface could be accommodated. Thus, all displays contained only a single accommodation distance.

Method

Apparatus. The apparatus was largely the same as in Expt 2. However, only a single optical bench was used supporting the front and rear surfaces. A vertical axle was attached to the mount for the front surface. Three different gray surfaces were each attached to a sleeve which fits snugly over the axle guaranteeing precision and reliability in positioning. Three different surfaces were attached to the axle on the rear platform. One surface was half white and half gray. One was half white and half red. The third was all white. A single configuration of surface distances was used with the front surface at 300 mm and the rear surface at 460 mm. The surfaces filled the observer's field of view through the LCD window. The edges of the surfaces were not visible.

Observers. Five optometry students at Indiana University participated in the experiment. Two were male and three female. All were naive concerning the nature of the apparatus and the experiment. All were right eye dominant. Two had good uncorrected vision. Three wore contact lens with wide optical zone. Of these, two were corrected from −3.00 D to 20/20 while the third was corrected from −2.00 D to 20/20. In addition, three of the observers from Expts 1 and 2 also participated in Expt 3. All participants were paid at the rate of $4.25 per hour. The first five observers will be called "naive" while the latter three will be called "experienced".

Procedure. The apparatus was aligned as in the previous experiments. None of the surfaces or the mounts used to support and manipulate the surfaces was in view during the alignment procedure. Once the biteboard and benches were aligned, the observer left the room while the mounts and surfaces were put in place. The observer then returned to his or her seat, unable to see what was on the opposite side of the barrier. The LCD window was opaque at all times except when an observer was observing a display.

After the surfaces had been positioned for each trial, the observer was given notice so that he or she could get into position on the biteboard. Once the observer was ready, the LCD window was made transparent. Observers were instructed to scan a display actively, moving their eye a couple of times rapidly from the contrast edge to the extreme left and back and then, as gradually and smoothly as possible through the same distance. This later instruction should have resulted in a rapid series of short saccades. Additional scanning was encouraged until the observer was ready to make a judgment. Observers were asked to judge whether they were observing a single, flat surface or instead, two surfaces separated in depth. If judged as separated, then observers were asked to judge which surface was nearest to the observer, the gray on the right or the white on the left. Observers made these judgments simultaneously yielding three types of response, "flat", "separated with white in front", or "separated with gray in front". The result was a single three-alternative forced-choice procedure.

The following displays were shown in a completely randomized order. The "flat" display was shown twelve times. The "red separated" display was shown twelve times, with each of the three different gray front surfaces shown four times. The "white separated" display was shown twelve times, again with each of the three gray front surfaces shown four times. A total of 36 trials was performed.

Observers' comments were recorded both during and after these initial sessions. None of the naive observers mentioned seeing the appearance of a red or dark area except for one observer who said that he did not know what it was and that it did not influence his judgments. We began running a second set of sessions with the same naive observers. Halfway through a session, one of the observers, a female, suddenly realized the significance of the appearance of the red area. Her judgments changed accordingly. She performed a full set of trials following this realization. Subsequently, we trained the remaining naive observers before the second set of trials as follows. Observers were positioned before the "red separated" display. They were instructed to move their gaze to the left and to notice the red area coming into view. All four observers reported seeing the red. After this, the experimental session was run as before.

Results and discussion

Judgments of separated vs flat were analyzed by display type independently for naive observers and for the combination of experienced and trained observers.

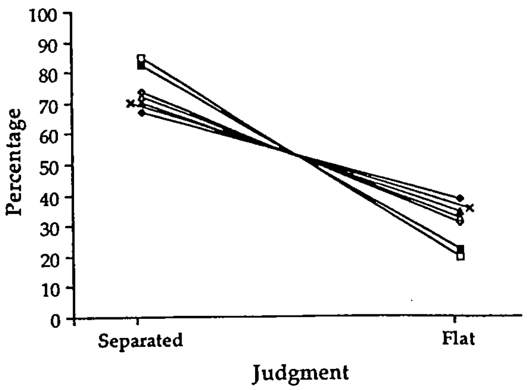

FIGURE 8. Mean percentages for judgments of separated vs flat for "white separated" displays (diamonds), "red separated" displays (squares), and "flat" displays (triangles) with naive observers (open symbols) and experienced/trained observers (solid symbols). Chance level responding (crosses).

The mean percentages of separated vs flat judgments are shown in Fig. 8. Observers chose among three possible judgments, either "separated with white in front", "separated with gray in front", or "flat". Chance responding for each was 33%. Two response alternatives represented judgments of separated while one was flat. Thus, chance responding for separated was at 67% while for flat, it was at 33%.

For both naive and experienced/trained observers, separated vs flat responses were at chance for both "white separated" and "flat" displays. Chance responding indicated that these displays were truly ambiguous, that is, they failed to provide information for flatness as well as for separation in depth. For "red separated" displays, responses were equally different from chance for both groups of observers. Naive observers judged "red separated" displays as separated 83% of the time while experienced/trained observers did so 81% of the time. These were different from chance according to a one-tailed t-test, $t(4) = 2.2$, $P < 0.05$ for the naive observers, and $t(7) = 2.1$, $P < 0.04$ for the experienced/trained observers. Thus, ocular occlusion occurring with surfaces at distances of 30–46 cm enabled observers to detect separation of surfaces in depth. Awareness or lack of awareness of the revealed structure had no effect on the result.

However, awareness of the revealed structure did affect the observers' ability to determine which surface was closer to them. Mean percent correct judgments of the three displays are shown in Fig. 9. In each case, correct responses expected by chance were 33%. Repeated measures ANOVAs were performed separately on the data for naive observers and for experienced/trained observers. Percent correct responses were not significantly different from one another for naive observers and percentages were not significantly different from chance for any of the displays according to one-tailed t-test. However, for experienced/trained observers, the ANOVA was significant, $F(2,14) = 5.9$, $P < 0.02$. In a *post hoc* Tukey (hsd) pairwise comparison, the "red separated" mean percentage was significantly different, $P < 0.05$, from the remaining two means which, in turn, were not significantly different from one another. The "red separated" mean was also different from chance according to a one-tailed t-test, $t(7) = -5.2$, $P < 0.001$, while neither of the other means was different from chance, $P > 0.1$.

The "white separated" display was used as a control to ensure that potential sources of information about separation in depth, other than flows from ocular occlusion, had been eliminated. Chance responding for this display showed that observers were unable to detect separation in depth without accretion/deletion of the red area with eye movement. They also were unable to detect flatness as shown by chance responding for the flat display. Both the flat and control displays were ambiguous. Only when, with eye movement, the simple pattern in the displays was disrupted by the appearance of an additional contrast did observers depart from chance responding, revealing an ability to detect separation in depth. This ability did not depend on the observers' awareness of the disruption. However, their ability to determine the ordinal depth relation between the surfaces did depend on their awareness of the disruption.

Why did naive observers detect separation, but not which surface was in front? The answer is not clear. One possibility is that the coupling between the optical changes and eye movements was not used in making judgments. A naive observer who noticed the red area thought it possible that the experimenters were somehow turning it on and off. This tendency would be strengthened if naive observers could not detect progressive increases in revealed structure. This seems unlikely given the amounts of structure progressively removed by adjustments in Expts 1 and 2. On the other hand, this certainly would be the case if observers moved their eye back and forth with a single saccade in each direction.

We are cautious in generalizing from this specific result because of the reduced and artificial nature of the

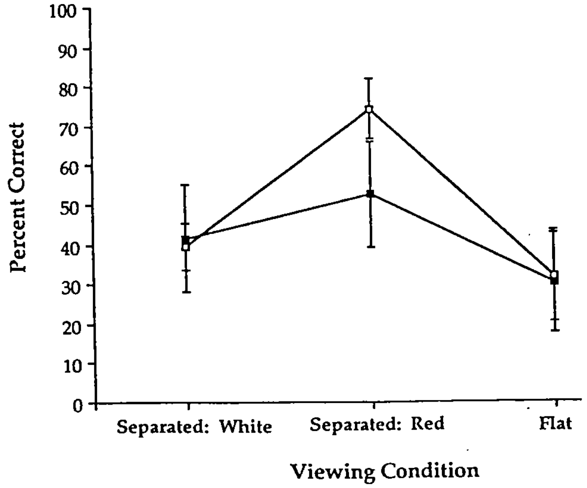

FIGURE 9. Mean percent correct responses (with standard error bars) for each of the three types of displays with naive observers (solid squares) and experienced/trained observers (open squares). Chance level responding was 33% in all cases.

viewing conditions. When observers were asked to describe the arrangement of surfaces in the displays, they described two different arrangements that were both consistent with the information. One was the actual arrangement. The other placed the red area on a surface extending away from the viewer connecting the edge of the front surface to the rear surface. This was as if the observer was looking past the edge of a closed book so that the colored edges of the pages came into view with eye rotation. The situation was indeed ambiguous. In an experiment performed in less ambiguous viewing conditions, Eriksson (1970) found that ocular parallax was sufficient to allow observers to make judgments of ordinal depth relations between two non-overlapping surfaces at distances of 2 and 4 m. Eriksson's observers experienced clear impressions of separation in depth with eye movements. Eriksson noted that "unnatural, voluntary eye movements according to a rigid, predetermined pattern seemed to yield difficulties in size or depth discrimination" (p. 20). We may have committed an error in instructing our observers how to move their eyes.

When motion parallax in general allows estimation of depth order or absolute depth as opposed to mere separation in depth is unclear. Both types of results have been obtained in various viewing conditions (Braunstein, 1976; Gibson, Gibson, Smith & Flock, 1959; Rogers & Graham, 1979). See Rogers and Graham (1979) for additional references and discussion of possible determinants.

GENERAL DISCUSSION

We sought to determine the magnitudes of detectable structure revealed by ocular occlusion with surfaces at significant distances from the eye. Because our goal was to establish the geometry and fundamental detectability of ocular occlusion, we used a display in which a unique high contrast area came into and went out of view with eye rotation. Based on related acuity measures and the geometry of the eye, we predicted that ocular occlusion would be detectable for surfaces at more than 1 m from the eye. In Expt 1 we used a method of adjustment and found that detected amounts of revealed structure were equal to about half of the predicted amounts. On the other hand, we found in particular that ocular occlusion was detectable with an occluding surface at almost 0.5 m from the eye.

In Expt 2 we adopted a criterion free forced-choice method. In this case, we found that detected amounts of ocular occlusion were those originally predicted. We surmised that the difference in results between Expts 1 and 2 was a function of criterion levels used by observers in Expt 1 given blurring of the front edge caused by focus at the distance of the far surface. Our predictions had been made on the assumption that the point of observation was located in the entrance pupil at a distance of 11 mm from the center of rotation in the eye. With confirmation we empirically determined the location of the point of observation in the eye.

Next, we sought to determine whether ocular occlusion might be used to detect the separation of surfaces in depth. Having controlled for other sources of monocular information about depth, we found that observers were able to detect separation in depth, but not depth order. The types of optical structure to which these results might generalize remains to be determined. Judging from other results in studies of motion parallax, displays involving points at many depths may allow perception of depth order in addition to mere separation.

Nevertheless, supposing that ocular occlusion does only yield information about separation of surfaces, how might such information be used? One possibility is in determining whether to explore optical pattern via head movements. Eye movements, which translate the point of observation by small amounts, are nested within head movements, which translate the point of observation by larger amounts. Head movements are nested, in turn, within locomotory movements at yet larger scale. Activity at smaller scales may be used to guide and control activity at larger scale. This strategy would be advantageous because small scale movements are faster and less costly. The most obvious way in which our experiment violated normal viewing is by eliminating head movements. Undoubtedly, the first thing any observer would have done on encountering the somewhat anomalous appearances of a red area at the gray edge would have been to move his or her head to explore the situation. See Bingham (1993) for additional discussion.

The limits on the detectability of ocular occlusion with contrast of progressively lower amplitude and with other forms of the transformation remains to be explored.

REFERENCES

Anstis, S. (1983). Visual coding of position and velocity. In Braddick, O. J. & Sleigh, A. C. (Eds), *Physical and biological processing of images* (pp. 177–195). Berlin: Springer.

Bennett, A. G. & Rabbetts, R. B. (1989). *Clinical visual optics*. London: Butterworths.

Bingham, G. P. (1993). The implications of ocular occlusion. *Ecological Psychology*. In press.

Bingham, G. P., Muchisky, M. M. & Romack, J. (1991). "Adaptation" to displacement prisms is sensorimotor skill acquisition. Presented at a meeting of the Psychonomic Society, San Francisco, Calif. 24 November.

Bootsma, R. J. & van Wieringen, P. C. (1990). Timing an attacking forehand drive in table tennis. *Journal of Experimental Psychology: Human Perception and Performance*, *16*, 21–29.

Braunstein, M. (1976). *Depth perception through motion*. New York: Academic Press.

Brewster, D. (1844). On the law of visible position in single and binocular vision and on the representation of solid figures by the union of dissimilar plane pictures on the retina. *Transactions of the Royal Society, Edinburgh*, *15*, 349–368.

Burr, D. C., Holt, J., Johnstone, J. R. & Ross, J. (1982). Selective depression of motion sensitivity during saccades. *Journal of Physiology*, *333*, 1–15.

Cutting, J. E. (1986). *Perception with an eye for motion*. Cambridge, Mass.: MIT Press.

van Doorn, A. J. & Koenderink, J. J. (1982). Visibility of movement gradients. *Biological Cybernetics*, *44*, 167–175.

van Doorn, A. J. & Koenderink, J. J. (1983). Detectability of velocity gradients in moving random-dot patterns. *Vision Research*, *23*, 799–804.

Eriksson, E. S. (1970). *Unambiguous information from static monocular vision* (Report No. 9). Department of Psychology, University of Uppsala, Uppsala, Sweden.

Fahle, M. & Poggio, T. (1981). Visual hyperacuity: Spatiotemperal interpolation in human vision. *Proceedings of the Royal Society of London B*, *213*, 451–477.

Fry, G. A. & Hill, W. W. (1962). The center of rotation of the eye. *American Journal of Optometry and Archives of American Academy of Optometry*, *39*, 581–595.

Gibson, J. J. (1950). *The perception of the visual world*. Boston, Mass.: Houghton Mifflin.

Gibson, J. J. (1955). The optical expansion pattern in aerial locomotion. *American Journal of Psychology*, *68*, 480–484.

Gibson, J. J. (1958). Visually controlled locomotion and visual orientation in animals. *British Journal of Psychology*, *49*, 182–192.

Gibson, J. J. (1961). Ecological optics. *Vision Research*, *1*, 253–262.

Gibson, J. J. (1979). The ecological approach to visual perception. Boston, Mass.: Houghton Mifflin.

Gibson, E. J., Gibson, J. J., Smith, O. W. & Flock, H. (1959). Motion parallax as a determinant of perceived depth. *Journal of Experimental Psychology*, *58*, 40–51.

Hadani, I., Ishai, G. & Gur, M. (1980). Visual stability and space perception in monocular vision: Mathematical model. *Journal of the Optical Society of America A*, *70*, 60–65.

Hadani, I., Gur, M., Meiri, A. Z. & Fender, D. H. (1980). Hyperacuity in the detection of absolute and differential displacements of random dot patterns. *Visual Research*, *20*, 947–951.

Jennings, J. A. M. & Charman, W. N. (1980). Off-axis image quality in the human eye. *Vision Research*, *21*, 445–455.

Kerr, J. L. (1971). Visual resolution in the periphery. *Perception and Psychophysics*, *9*, 375–378.

Koenderink, J. J. (1986). Optic flow. *Vision Research*, *26*, 161–180.

Lee, D. N. (1980). The optic flow field: The foundation of vision. *Philosophical Transactions of the Royal Society London B*, *290*, 169–17.

Lee, D. N. & Aronson, E. (1974). Visual proprioceptive control of stance. *Perception and Psychophysics*, *15*, 529–532.

Lee, D. J. & Lishman, J. R. (1975). Visual proprioceptive control of stance. *Journal of Human Movement Studies*, *1*, 87–95.

Lee, D. N., Young, D. S., Reddish, P. E., Lough, S. & Clayton, T. M. H. (1983). Visual timing in hitting an accelerating ball. *Quarterly Journal of Experimental Psychology*, *35A*, 333–346.

Le Grand, Y. & El Hage, S. G. (1980). *Physiological optics*. Berlin: Springer.

Lishman, J. R. & Lee, D. N. (1973). The autonomy of visual kinesthesis. *Perception*, *2*, 287–294.

Mapp, A. P. & Ono, H. (1986). The rhino-optical phenomenon: Ocular parallax and the visible field beyond the nose. *Vision Research*, *26*, 1163–1165.

McKee, S. P. (1981). A local mechanism for differential velocity detection. *Vision Research*, *21*, 491–500.

Nakayama, K. (1981). Differential motion hyperacuity under condition of common image motion. *Visual Research*, *21*, 1475–1482.

Nakayama, K. (1985). Biological image motion processing: A review. *Vision Research*, *25*, 625–660.

Nakayama, K. & Loomis, J. M. (1974). Optical velocity patterns, velocity sensitive neurons, and space perception: A hypothesis. *Perception*, *3*, 63–80.

Park, R. S. & Park, G. E. (1933). Centers of rotation in the horizontal plane. *Eye, Ear, Nose and Throat Monthly*, *12*, 371–376.

Regan, D. M. & Beverley, K. I. (1982). How do we avoid confounding the dimension we are looking and the direction we are moving? *Science*, *215*, 194–196.

Rieger, J. H. & Toet, L. (1985). Human visual navigation in the presence of 3D rotations. *Biological Cybernetics*, *52*, 377–381.

Riggs, L. A., Ratliff, F., Cornsweet, J. C. & Cornsweet, T. N. (1953). The disappearance of steadily fixated visual test objects. *Journal of the Optical Society of America A*, *43*, 495–501.

Rogers, B. & Graham, M. (1979). Motion parallax as an independent cue for depth perception. *Perception*, *8*, 125–134.

Schiff, W. (1980). *Perception*: *An applied approach*. Boston, Mass.: Houghton Mifflin.

Sorsby, A. (1964). The nature of spherical refractive errors. In Sorsby, A. (Eds), *Modern ophthalmology* (pp. 3–20). Washington, D.C.: Butterworths.

Thibos, L. N., Cheney, F. E. & Walsh, D. J. (1987a). Retinal limits to the detection and resolution of gratings. *Journal of the Optical Society of America A*, *4*, 1524–1529.

Thibos, L. N., Walsh, D. J. & Cheney, F. E. (1987b). Vision beyond the resolution limit: Aliasing in the periphery. *Vision Research*, *27*, 2193–2197.

Verrijp, C. D. (1930). Ocular movements. *Archives of Ophthalmology*, *4*, 73–83.

Warren, R. (1976). The perception of egomotion. *Journal of Experimental Psychology: Human Perception and Performance*, *2*, 448–456.

Warren, W. H. & Hannon, D. J. (1990). Eye movements and optical flow. *Journal of the Optical Society of America A*, *7*, 160–169.

Warren, W. H., Morris, M. W. & Kalish, M. (1988). Perception of translation heading from optical flow. *Journal of Experimental Psychology: Human Perception and Performance*, *14*, 646–660.

Warren, W. H., Mestre, D. R., Blackwell, A. W. & Morris, M. W. (1991). Perception of circular heading from optical flow. *Journal of Experimental Psychology: Human Perception and Performance*, *17*, 28–43.

Wertheim, T. (1980). Peripheral visual acuity. *American Journal of Optometry and Physiological Optics*, *57*, 915–924.

Westheimer, G. (1981). Visual hyperacuity. In Autrum, H., Ottoson, D., Perl, E. R. & Schmidt, R. F. (Eds), *Progress in sensory physiology I* (pp. 1–29). Berlin: Springer.

Westheimer, G. (1986). The eye as an optical instrument. In Boff, K. R., Kaufman, L. & Thomas, J. P. (Eds), *Handbook of perception and performance: Sensory processes and perception* (pp. 4-1–4-20). New York: Wiley.

Westheimer, G. & McKee, S. P. (1975). Visual acuity in the presence of retinal image motion. *Journal of the Optical Society of America A*, *65*, 847–850.

Acknowledgements—This research was supported by a Biomedical Research Support Grant PHS SO7 RR 7031L, Division of Research Resources, NIH and by the Institute for the Study of Human Capabilities, Indiana University. I greatly appreciated assistance and advice from Arthur Bradley and Larry Thibos of the School of Optometry at Indiana University. I also wish to express my gratitude to Larry Solner, O.D., for insightful advice and long hours spent in collecting the data. Thanks also to two anonymous reviews. Portions of the research were previously reported at the Annual Meeting of the Association for Research in Vision and Ophthalmology, Sarasota, Fla., 29 April, 1991.