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The Implications of Ocular Occlusion

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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. I review studies showing that ocular occlusion is detectable beyond near space and functionally effective in providing information about the separation of surfaces in depth. After discussing the typicality of ocular occlusion in visual experience, I explore the implications for analyses of optical flow for an understanding of depth perception and the mission of the sensory apparatus, and for the notion of efference copy in vision.

Bingham (1993) demonstrated that eye movements performed with the head immobilized translate the point of observation by virtue of the fact that the point of observation is at a distance from the center of rotation in the eye. Surprisingly, the location in the eye of the point of observation had not been measured previously. We determined that the effective point of observation is in the entrance pupil.[1] This placed the point of observation at a distance of 11 mm from the eye's center of rotation (Bennett & Rabbetts, 1989; Sorsby, 1964). This

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[1] This finding may be surprising and confusing to many readers who might expect the point of observation to be equated with the 2nd nodal point of the eye's lens system. The latter would place the point of observation just behind the crystalline lens at a distance of only 7 mm from the center of rotation. However, the nodal points are part of an abstraction used to describe the paraxial or central optics of the eye. (See Bennett & Rabbetts, 1989, Chapter 2, "The eye's optical system," pp. 9–22, for what follows.) The nodal points need not be used to analyze image formation either in the fovea or the periphery (see Bennett & Rabbetts, Figure 2.5, p. 12). In addition, the nodal points become less relevant as the image points occur progressively farther from the fovea. Eventually, the nodal points become totally irrelevant (see Bennett & Rabbetts, Figure 2.13, p. 18). The entrance pupil, on the other hand, determines the bundle of rays allowed to enter the eye (Le Grand & El Hage, 1980). The "chief ray" lies at the center of this bundle and is a much more general—but still not universally precise (Ye, Bradley, Thibos, & Zhang, 1992)—way to locate images.

means that, when the eye is rotated so as to move the gaze from straight ahead to just beyond one's nose (about 40°), the point of observation translates about 8 mm sideways. Translation of the point of observation produces optical flow.

When optical structure is projected to a translating point of observation from surfaces at different distances from the point of observation, motion parallax results. This means that the relative distances between the corresponding optical elements changes as a function of the distances of the surfaces and the distance of translation of the point of observation. This transformation has been shown, in principle, to provide information about the distances of surfaces to within a scale factor. (See, e.g., Koenderink, 1986, who noted that if one had information about the momentary velocity of the point of observation, then the scale factor could be determined.) Because optical elements are projected into the optical flow from substantial surfaces, motion parallax as such is only a partial description of the transformation that results from translation of the point of observation through cluttered surroundings. As loci on more distant surfaces fall directly behind those on opaque surfaces nearer to the point of observation, the more distant loci become occluded and the corresponding structure is deleted from the optical flow. As used in this article, the optical transformation produced by occlusion, namely the accretion or deletion of optical elements at a boundary, is treated as subsuming and including motion parallax.[2]

To obtain some feeling for the potential effect of a translation of the point of observation of 8 mm, try covering one eye and moving your head back and forth by this amount (about the diameter of a large pea) while paying attention to the transformations occurring at occluding edges in the surround. You should notice varying amounts of optical structure being accreted and deleted at occluding edges depending on the distances of the surfaces involved. This should be noticeable even when the nearer surface is at a distance of 3–4 m (depending on the distance of the farther surface). Would such changes be detectable when generated by eye movement?

In ocular occlusion, the edge along which optical structure appears or disappears travels across the retina as the eye moves. With the head immobilized, accretion/deletion of optical structure would occur strictly in phase with the sweep of the optical edge across the back of the eye. Might such ocular

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[2] One might attempt to reserve the deletion of optical elements to occlusion and the change in distances between optical elements (and associated optical velocities) to motion parallax. However, optical elements can only become deleted as they change their relative positions (and some optical velocities are necessarily entailed). Therefore, it would seem that in the context of translation of the point of observation through cluttered surroundings, the only coherent distinction that can be usefully maintained between occlusion and motion parallax is a subsumptive one. Occlusion subsumes motion parallax, which is simply a less complete description. In uncluttered terrain, occlusion would not seem to be relevant. On the other hand, the nose and the boundaries of the orbits of the eye always act to occlude portions of the optic array. In general, therefore, motion parallax may be a locally accurate description, but it is globally incomplete.

occlusion be detected and if so, what configurations of surface distances might allow optical occlusion to be detected? Mapp and Ono (1986) demonstrated that ocular occlusion by the nose of the observer can be detected. This can be demonstrated 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 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. Once again, without moving your head, look towards the finger and it should disappear from view behind the bridge of your nose.

What about occluding surfaces farther from the observer than the nose? Bingham (1993) showed that ocular occlusion was detectable with an occluding surface at .4 m from the observer with the occluded surface at only .5 m, that is, 10 cm beyond an occluding surface at reaching distance. As the occluded surface becomes more distant, the effect becomes increasingly stronger. Clearly, ocular occlusion is not restricted to near space.

After reviewing this study, establishing the phenomena of ocular occlusion, I discuss its relevance and more general implications. The general implications that I draw are not dependent on the extent to which ocular occlusion is actually used. The studies reported in Mapp and Ono (1986) and in Bingham (1993) only demonstrate that ocular occlusion can be detected and used to detect separation of surfaces in certain circumstances. (Although the presence of the nose is a fairly general circumstance.) The generality of use in other circumstances remains for future study. Nevertheless, the fact that ocular occlusion can be detected and used in any circumstances whatsoever means that the sensory apparatus functions successfully to detect optical flow patterns in circumstances where those patterns are being swept across the retinal surface or, alternatively, in circumstances where the retina is traveling laterally under optical flow patterns.

A first implication is that eye movements cannot be described as fundamentally different in respect to motion of the point of observation from other types of movement (e.g., head movements, movements of the trunk, and/or locomotion). All act to translate the point of observation, thus generating optical structure (like progressive accretion or deletion of optical structure at a boundary and motion parallax) specific to the structure of the surround. Furthermore, the fact that such flows are common to all levels of movement, including especially eye movement, implies that the ability to detect such flows is fundamental to the functioning of the sensory apparatus.

Most important are the corresponding repercussions for our understanding of the problem of depth perception. Sensitivity to ocular occlusion may help us to understand why depth perception never completely fails. (The very notion of such complete failure is paradoxical.) The result supports the suggestion that the foundation of vision is the detection of invariance over transformations in optical flow (Gibson, 1979/1986; Koenderink, 1986; Lee, 1980), not the analysis of two-dimensional images. (Here, I mean "fundamental" in the sense that "there is no perception without.") To the extent that the dimensionality of the perceived surroundings is intrinsic to the particular character of such invariants and transformations, then the suggestion that depth is extrinsic to vision and to the fundamental grist of the visual mill is incorrect.

Finally, ocular occlusion tends to undercut the notion that efference copy might be used to sort out optical transformations generated by eye movements as opposed to other sources. The problem is that the optical transformations become contingent upon the momentary structure of the surround rather than being a stereotypcial function of eye movement alone.

THE DETECTABILITY OF OCULAR OCCLUSION

The apparatus that I used to investigate the detection of ocular occlusion appears in Figure 1. The observer sat at a biteboard positioned so that the center of rotation of the right eye lay along the centerline of an optical bench; viewing was monocular. Two surfaces were positioned along the bench so that the observer could look past the left edge of the front surface to the rear surface. The

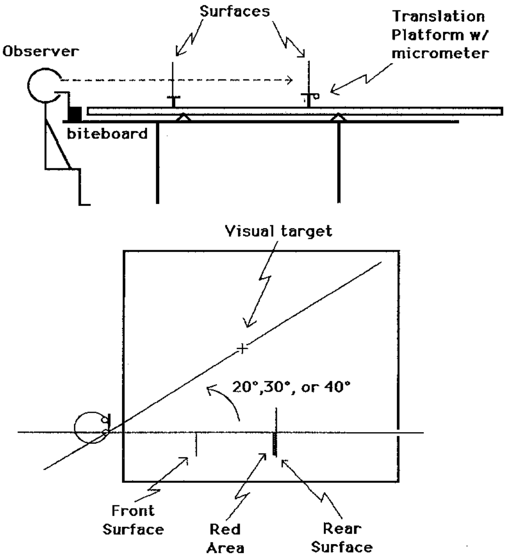

FIGURE 1 Apparatus used to measure extents of surface structure revealed in ocular occlusion with occluding and occluded surfaces at distances ranging from 20 cm to 1 m. See text for details.

left edge of the front surface lay above the centerline of the bench. The lateral position of the rear surface was adjusted via a micrometer on a translation platform so that a red area on an otherwise white surface was just occluded by the front surface as the observer looked directly past the edge of the front surface. As the observer moved his eye to the left, the red area came into view.

How far the observer was to move his eye to the left was constrained by a target on a second optical bench that also was aligned with the eye's center of rotation. The target was at the same distance as the rear surface. In three different conditions, the second bench was placed at angles of 20°, 30°, or 40° from the first bench. Observers were allowed to move their eye freely within the given angle to detect the revealed red area (which appeared blackish when viewed peripherally in this way).

Detection was tested at 12 different surface configurations, including 3 different front surface distances of 20 cm, 30 cm, and 40 cm, and 4 different rear surface distances for each front surface distance. (See Bingham, 1993, for additional technical specifications, including surface extents, luminance levels, calibration procedures, etc.) Using the viewing geometry and assuming a distance between the center of rotation and the point of observation of 11 mm, the visual angle of revealed optical structure was predicted at each configuration of surfaces for each angle of eye movement. These predictions appear in Figure 2. These amounts are well beyond limits determined by various measures of acuity as discussed by Bingham (1993). The progressive accretion of structure as the eye is swung progressively farther to the left is represented by the progressively higher points for increasingly greater angles of eye movement at a given configuration. Figure 3 shows a surface representing angular extents of revealed structure with increasing angles of eye movement (i.e., the rate of accretion with the change of angular eye position). With the front surface fixed at 20 cm, the effect on the relative rate of accretion of increasing the rear surface distance is shown. Increase in the relative rate of accretion rapidly levels out just beyond twice the front surface distance. (The slope of this surface is nearly constant at a given rear surface distance. At the given configuration, this constant scales the time rate or velocity of eye movement to the time rate of accretion, which is, given the concurrent sweep across the retina, a differential velocity.)

In Experiment 1, the amount of structure detected with different amounts of eye movement at given configurations was determined for 4 observers via the method of adjustment. As observers looked back and forth to the left, the rear surface was translated to the right until the red area could no longer be detected. The distance was measured via the micrometer. The mean amounts of detected structure are shown in Figure 4. (Standard error bars were about the size of the filled points in the figure.) Mean detected amounts were about two-thirds of the predicted amounts. Using the detected amounts and the geometry, the corresponding distances were computed between the center of rotation and the point

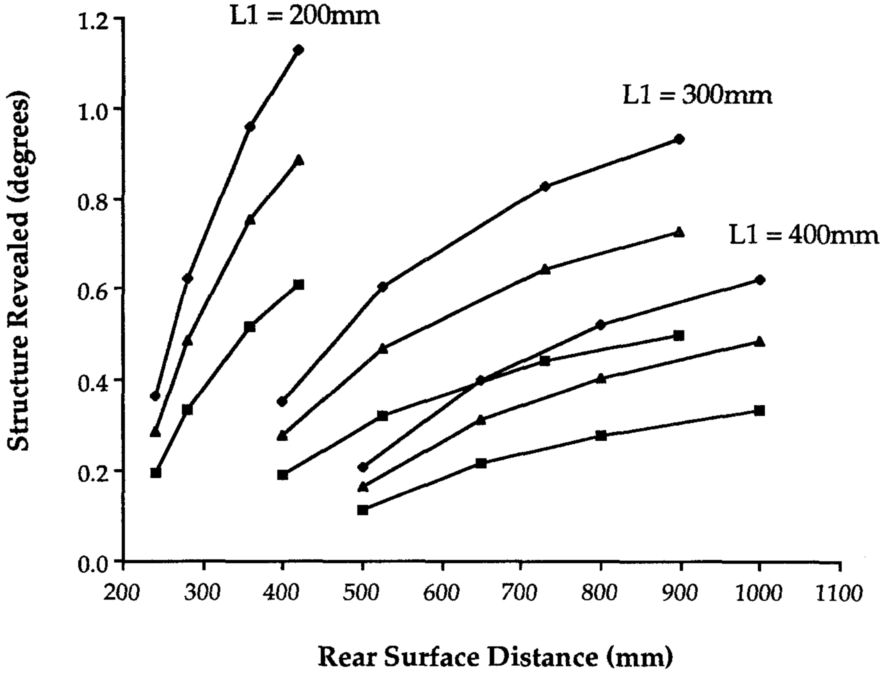

FIGURE 2 Predicted visual angles of surface structure revealed via eye movement with the front occluding surface at three different distances (200 mm, 300 mm, and 400 mm) with the rear occluded surface at four different distances for each front surface distance. Predictions for eye rotations of 20° (squares), 30° (triangles), and 40° (diamonds).

of observation (assuming that the estimates reflected perfect detection of all revealed structure). The result was a frequency distribution with a peak at about 6.5 mm. Had the distance to the point of observation been misjudged?

In Experiment 2, a criterion free forced-choice method was used at two of the configurations previously tested, that is, with the front surface at 30 cm and the rear surface at either 40 cm or 90 cm. Observers, with 30° of eye rotation, had to decide which of two displays contained the red area as the rear surface was translated progressively to the right over trials. The result for the same observers was that visual angles of detected structure were within a few seconds of arc of the predictions. This occurred despite the observers conviction that they were merely guessing, as is typical for this method. The implication was as follows. Because observers in Experiment 1 were focused at the rear surface distance, the front edge would have been blurred. Observers originally adopted a criterion for determining when the red was red enough within the blur area. Thus, they quit in the first experiment while visible red remained. However, given the difference in method, judgments only dropped to chance in the second experiment when

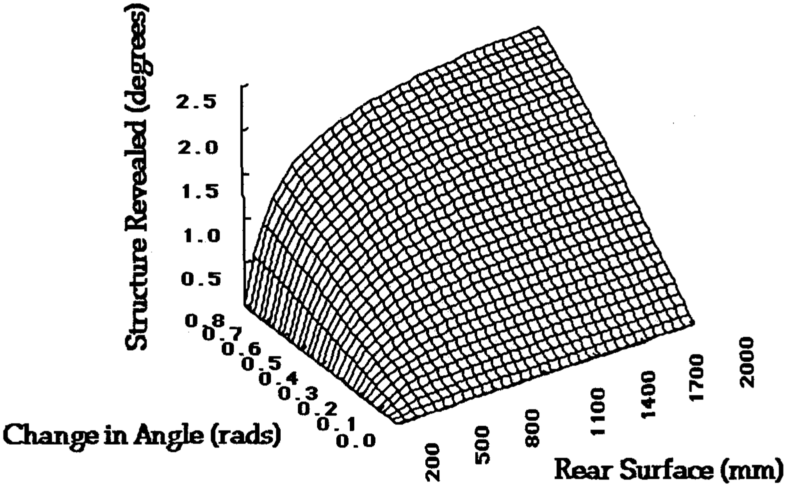

FIGURE 3 Surface representing predicted visual angles of surface structure revealed by eye movement of progressively greater amplitude. The increased height of the surface from the front to the back of the surface represents the accretion of optical structure. The front surface distance was fixed at 20 cm. The surface revealed the effect of increasing the rear surface distance beyond 20 cm. The change in angle of the eye is from a line of sight straight past the edge of the front surface. (The three curves for L1 = 200 mm in Figure 2 run left to right in this figure with 20° = 0.35 rad, 30° = 0.52 rad, and 40° = 0.70 rad.)

the visible red was entirely gone. The differences between predictions and mean estimates in the first experiment were systematic and the pattern was consistent with this interpretation. (See Bingham, 1993, for further description and discussion of this systematicity.)

The overarching conclusion was that 11 mm was an entirely correct estimate of the distance between the center of rotation in the eye and the point of observation, placing the point of observation in the entrance pupil. Furthermore, the amounts of optical structure revealed in ocular occlusion as predicted via the viewing geometry were confirmed. Ocular occlusion was detectable with occluding surfaces well beyond the nose.

The next question was whether ocular occlusion could be used to detect separation of surfaces in depth. Investigation of this question required that ocular occlusion be isolated as potential information about the separation of surfaces. All other monocular sources of information about separation had to be controlled, including differences in luminance, optical texture density, and accommodation. This was achieved via reduced-viewing conditions that did not preserve brightness constancy. Observers viewed the surfaces through a barely fogged liquid-crystal display (LCD) window that obfuscated any potentially visible texture on extremely smooth surfaces. As observers looked straight ahead, the (left) edge of the front surface appeared through the window as the

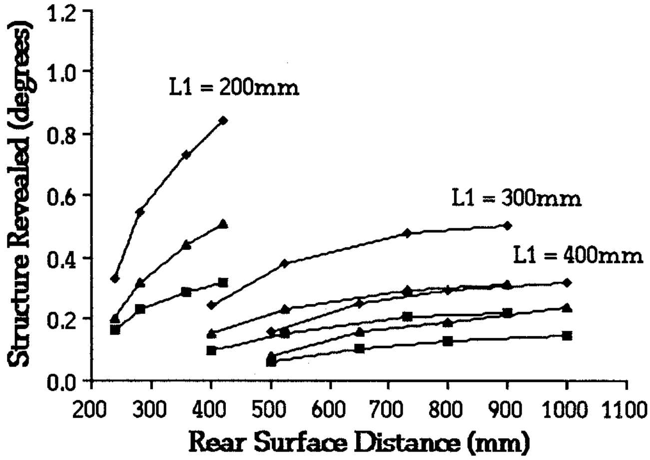

FIGURE 4 Mean measured visual angles of surface structure revealed via eye movement with the front occluding surface at three different distances (200 mm, 300 mm, and 400 mm) with the rear occluded surface at four different distances for each front surface distance. Means for eye rotations of 20° (squares), 30° (triangles), and 40° (diamonds). Compare with Figure 2.

only focusable contrast. In this way, both accommodation and texture-related information were controlled. Luminance differences were controlled by using an assortment of grays for the front surface.

Three different displays were used, two experimental and one control. The first was a flat surface with the right half gray and the left half white. The second display consisted of two surfaces configured, as in the first experiment, at distances of 30 cm and 46 cm, respectively, with a red area on the rear surface just occluded by the (gray) front surface as the observer looked straight past the left edge of the front surface. The third display was the same as the second except that no red appeared on the rear surface. If alternative sources of information about separation in depth had been successfully controlled, then the observers should not have been able to detect separation in this last control display. No optical structure would have been accreted as the observer moved his or her eye to the left, so if alternative sources of information for separation in depth were eliminated, then observers should not have been able to detect the existing separation in depth, and responses should have been the same as for the flat display.

Although the flat and control displays were designed to provide no information for separation of the left and right surfaces in depth, neither was any information provided for the flatness of the displays. The displays were entirely ambiguous in this regard. The lack of information about separation in depth did not entail specification of flatness by default. The expectation was, therefore, that responding for the flat and the control displays would be at chance. Success would have entailed that determination of either separation or flatness would have been impossible. Only with the accretion of optical structure in the red-separated condition should observers have been able to make a determination.

With monocular viewing, observers were instructed to move their eye back and forth to the left. They were asked to judge whether the display was flat, separated with gray in front, or separated with white in front. The result was that, in detecting separation, observers responded at chance (67% separated, 33% flat) with the flat and control displays while correctly responding at rates different from chance (85% separated, 15% flat), with the display yielding detectable ocular occlusion. The latter difference was statistically significant and the results were reliably reproduced with two different groups of observers. One set of observers were naive and unaware of the accretion of the red area both before and after the experiment. They were unable to determine the depth order of the surfaces despite their ability to detect separation. Once observers were trained in specifically attending to the accretion of the red area, they were able to determine depth order.

THE GENERAL RELEVANCE OF OCULAR OCCLUSION

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, I focused on the local transformation at a single occluding edge. Even this local transformation can exhibit a variety of forms. The form I studied involved the growing, shrinking, and change of shape of a distinct, internally homogeneous area that contrasted with neighboring regions. Another possible form involves the disappearance (or appearance) of a distribution of optical contrasts at a single edge yielding a frequency of disappearances (or appearances). I focused on the first form because it was suited to unequivocal measurement of the magnitudes of detectable structure revealed by eye movement and simultaneous measurement of the location of the point of observation in the eye. I used the clearest case to establish the geometry and fundamental detectability of ocular occlusion.

The issue of generality is in part a matter of thresholds. All types and sources of information are subject to thresholds, conditions under which they become no longer detectable. I have shown that there certainly are conditions extending beyond near space where ocular occlusion is detectable and functionally effective. Parametric studies of thresholds with variations in contrast amplitudes remain to be done to determine the rates at which effective distances collapse as luminance levels decrease. In related studies, Hadani, Gur, Meiri, and Fender (1980) showed that differential displacements in random dot displays can be detected in conditions comparable to flows generated by the smallest involuntary saccadic eye movements. They related these results to a general model of optical flow generated by eye movement (Hadani, Ishai, & Gur, 1980) and suggested that monocular depth perception should result from such saccadic movements. Eriksson (1970) demonstrated that ocular parallax was sufficient to allow judgments of ordinal depth relations between two nonoverlapping surfaces at distances of 2 m to 4 m from the observer. Eriksson used viewing conditions that were less ambiguous than my own, with observers that were aware of the nature of the experiment.

Although the phenomena certainly must be subject to conditions where it would not be detectable, it is unlikely that the detection and use of ocular occlusion should be rare. One reason is that one's nose is always present. This is important not only because of ocular occlusion *by* the nose, but also, even more proximally, because of ocular occlusion *of* the nose! Opaque portions of the eye itself occlude the nose as the direction of gaze is moved temporally. To see this, wiggle the tip of your left index finger just in front of the tip of your nose as you look nasalward using your right eye with the left eye closed. (The motion of the finger tip would be easier to detect in the periphery.) Next sweep your gaze in the temporal direction away from the nose. The nose and your finger should go out of view. This is occlusion; surfaces become progressively hidden as the eye rotates.

Ocular occlusion also should not be rare because the surfaces of one's hands and arms are almost always in view, lying at distances, relative to the surfaces which they occlude, that will yield ocular occlusion. For instance, as I hold a version of this article before me, I can see portions of the brand-name label on a box of floppies come into view and go out of view behind my hand as I move my eye. However, explicit awareness of the specific local form of the transformation with contrasts of varying amplitude is not the concern of real interest and should not be used to intuit the importance and generality of the phenomena. Our own naive observers used ocular occlusion to detect separation of surfaces in the surround despite lack of awareness of ocular occlusion as such. Furthermore, the various forms of the local transformation commonly populate the global array at widely distributed locations. Thus, with movement of the eye in cluttered surrounds, accretion and deletion of optical structure will occur simultaneously at loci all across the retina. As I look about me, objects within the range explicitly studied in Bingham (1993) include not only my nose and hands, but also the frames of my glasses, a cup, a desk lamp, a computer monitor, a disk drive, a basket of pencils, and a clipboard stand. As I actively look around, optical structure is being accreted and deleted at all of the various edges but I cannot consciously observe these widely distributed occurrences even with the greatest of concentration. These transformations specify separation of surfaces in depth, nevertheless. As I hold my head still while viewing the scene monocularly, the spatially distributed character of the scene distinctly persists.

As I attend to specific locations, I can spot accretion/deletion at some but not others (i.e., not without foveating them and moving my head—it is there). Whether I can detect ocular occlusion at all these latter locations remains to be determined. That I can detect it at many is evident. There is little doubt that ocular occlusion must be common to visual experience.

Nevertheless, for the observations and arguments that follow, the common detection and use of ocular occlusion is not required. We only need to know that ocular occlusion can be detected in any single circumstance and that has indeed been demonstrated. The sensory apparatus has been shown to be capable of detecting and using the information in optical flows produced by mere eye movement.

THE EFFECT OF EYE MOVEMENTS ON OPTICAL FLOW

Gibson (1961) formulated the notion of the optic array using a single abstract property of the eye, namely, the point of observation. By definition, the optic array is independent of other properties of eyes. 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 (Gibson, 1950, 1955, 1958, 1979/1986; Koenderink, 1986; Lee, 1980; Nakayama & Loomis, 1974; Warren, 1976). 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 (1979/1986) 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; Regan & 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). In these accounts, eye movement has been distinguished from all other movements of the observer. They argue that, unlike other movement, eye movements cause no alteration in the distances to various surfaces in the surround and therefore, produce no parallax or progressive occlusion. 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 in the eye are coincident; they are not. The center of rotation is located near the center of the eye (Bennett & Rabbetts, 1989; Fry & Hill, 1962; Le Grand & El Hage, 1980; Park & Park, 1933; Verrijp, 1930) whereas, as we have shown, the point of observation is located in the entrance pupil at the front of the eye at a distance of 11 mm from the center of rotation.

In their seminal article on optical flow, Nakayama and Loomis (1974) 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. However, Nakayama and Loomis assumed, reasonably enough, that the effects would be small and could be ignored in an analysis providing a good first approximation. Subsequent optical-flow work has treated this factor as if it were nonexistent. The problem is that the resulting account lends support to the notion that vision begins with and is fundamentally based on the two-dimensional optical pattern projected to a single unmoving point of observation. Necessarily, this would be the situation that would result whenever an observer is placed in a biteboard or any device that prevented head movement. Because visual perception is not prevented by preventing head movement, the rigid optical pattern projected to a single unmoving point of observation must be, by implication from the assumptions, the fundamental basis for perception of surrounding surfaces. Optical flow generated by head movement or locomotion would provide accessory information over and above the fundamental sources in static pattern. Although retinal flow corresponding to optical flow is admitted to be useful grist for the visual mill, the components generated by eye movements remain as interference only to be filtered by the sensory apparatus. The retinal flow of pattern generated by eye movement is portrayed in this account as a useless impairment to vision that is uninformative about the structure of the surround and about the observer's relation to those surroundings. Only with the momentary cessation of eye movement is useful structure in either flowing or static pattern supposed to made (optimally) available.

Eye movements in this approach are distinguished absolutely from all other types of human movement as generating no useful information about the structure of the surround or the observer's relation to it. The assumption conditions the conception of the sensory apparatus and what it does. Eye movement and its result become a difficult problem for the visual apparatus, a factor to be identified and sorted out. Given the existence of ocular occlusion, however, the likelihood that the problem could be solved in a consistent and reliable fashion grows vanishingly small. This is especially true when it is realized that the types of transformation entailed by ocular occlusion are common as well in optical flows produced by head movement. The preferable alternative is to reconsider what the sensory apparatus must be designed to do.

In viewing the literature on acuity, for instance, I noted (Bingham, 1993) that extremely brief tactistoscopic exposures ($\approx$ 200 ms) are used in measures of static acuity like resolution and detection acuity to avoid "Troxler's effect," the rapid fading and disappearance of a constantly illuminated peripheral field (Kerr, 1971). This effect in the periphery is consistent with the more general and well known fading of stabilized retinal images (Riggs, Ratliff, Cornsweet, & Cornsweet, 1953). These pervasive problems with immediate loss of sensitivity in stasis indicate rather strongly that the corresponding sensory apparatus is designed to respond in the face of transformations. In ocular occlusion, as an occluding edge passes a locus on the retina, a given element of optical structure appears and subsequently follows the edge as the eye movement sweeps them both along. That is, as the edge translates across the retina with eye movement, it takes progressively accreted optical elements with it. The result is a brief exposure of a retinal locus to newly appearing optical contrasts. In general, when the point of observation translates even without eye movement, there is no reason to expect the optical edge at which optical elements are accreted to remain unmoving at a single locus on the retina. The sweeping across the retina of such an edge is the rule rather than the exception. For instance, as I fixate the corner of my desk while leaning forward in my chair so as to translate my head towards the corner, the occluding edges of my computer monitor sweep into the periphery of my vision as the occluded texture on the wall behind the monitor comes into view at the leading edge and goes out of view at the trailing edge. The patterns of flow encountered in ocular occlusion are common to flows generated by postural adjustments or locomotion. Thus, both resolution and detection acuity measured via tachistoscopic exposures are likely to reflect performance levels of a sensory system designed to handle accretion of structure in optical flows, including those generated by eye movement as well as various forms of head movement.

The treatment of optical flow by the sensory apparatus has been largely conceived as a matter of optical velocities and displacements on a given locus on the retina as might occur, for instance, when one looks past the edge of the window on a speeding train. However, this circumstance must be relatively rare. As soon as one looks through and moves directly toward or away from any point on the window other than the edge, the optical edge corresponding to the window's edge proceeds to translate across the retina as optical pattern continues to be accreted at that edge. The predominant treatment of optical flow must be in terms of differential velocities and differential displacements that are relevant when a pattern of optical flow is swept across the retina as the pattern evolves. Psychophysical studies have shown that sensitivity to differential velocities (Nakayama, 1985) and differential displacements (Hadani, Gur, Meiri, & Fender, 1980; Nakayama, 1985), in particular, is great. Finally, the eye is always in motion due to eye movements every 200 ms or so (depending on amplitude), due to constant postural sway, and due to intentional movements of the head and body in goal-directed activity. Given this fact, treatment of sweeping optical flow must be a principal function of the sensory apparatus.

The point is that the type of optical flows generated by eye movements are characteristic of those confronted in general by the sensory apparatus. They are not particularly odd or special. Our understanding of how this apparatus is organized and functions is better marshaled in view of these characteristic conditions. I next argue that doing so may also help to resolve some of the paradoxes in our understanding of depth perception.

WHY IS VISUAL EXPERIENCE NEVER STRICTLY TWO-DIMENSIONAL?

Gibson (1966, 1979/1986) described perceptual information in terms of invariants defined over particular transformations. For instance, in the flow generated by linear translation of the point of observation in rigid surrounds, an invariant of the flow is a radial pattern of out- or in-flow, including a node at the center of the radial pattern. This invariant is made obvious by and exists only because of a particular transformation in optical structure, that is, the continuous change in positions of optical elements in the array. Likewise, as shown by the Kaplan displays (Kaplan, 1969; Schiff & Mills, 1990), the optical edge along which optical structure is accreted or deleted in occlusion is an invariant that arises and only exists by virtue of the corresponding transformations, namely, the coming and going of optical structure. Both of these invariants, as perceptual information, are specific to aspects of the observer's relation to surfaces in the surround. The radial outflow specifies translation relative to the surround, and the node specifies the locus of heading. Accretion and deletion also specify translation of the observer relative to occluding and occluded surfaces as well as the relative separation of those surfaces.

Oddly, Gibson (1979/1986) also described the effect of eye movements in terms of invariance over transformation despite his implication that eye movements would not translate the point of observation. According to his account, an optical pattern itself would be preserved over a rigid translation of the optical pattern generated by a change in the orientation of the eye with respect to the array. The invariant (viz., the rigid optical pattern itself or a set of adjacent and nested visual solid angles), as perceptual information, would specify a relation between the retina and the optic array. This analysis implied that eye movements, performed without head movements, would yield specification of array structure and orientation. This was odd because Gibson never suggested that observers should perceive the structure of the optic array as such. Rather, he argued that observers perceive the layout of surrounding surfaces by virtue of the structure of the array or specific changes in that structure.

Also, Gibson emphasized the inherently perspectival nature of perception, that is, that perception is always *of* something *from* some point of view. The point of view is that occupied by the observer. Thus, perception of the surround would always be accompanied by perception of the self, at least implicitly. In vision, this is explicit because surfaces of the observer appear in the field of view, including the observer's nose and portions of the orbit of the eye. These are seen at the same time as surfaces in the surround. In making these observations, Gibson stressed that perception entails a relation between perceiver and perceived. The problem in perceiving the optic array as such would be in determining the whereabouts of the array so that the nature of the relation between perceiver and perceived might be described.

For instance, imagine a monocular observer whose head has been fixed unmoving, but whose eye is free to move. Imagine the observer confronting an array that includes structure (i.e., it is not a Ganzfeld), but that includes no static, monocular "cues for depth." The array would contain contrasts at edges, but no regular gradients of texture or illumination. According to this analysis, with eye movement, only a static optical pattern should rigidly translate across the retina enabling the observer to perceive the array pattern itself along with the changes in orientation of the eye with respect to that pattern. If the optic array itself is perceived in this situation, where is it perceived to be? Hypothetically, its orientation or direction would be specified, but what of its location? Where is it?

It is here that the classical problem of depth perception is encountered. By assumption, the array contains no information for depth. Theoretically, the optic array itself is two dimensional. It has often been suggested that without "cues for depth," the "visual world" should appear flat. But where would it appear to be? When I pose this puzzle to my students, they suggest that it should correspond to a plane, perpendicular to the visual direction and lying at a distance of about 40 cm from the observer. This, however, places the array in depth at a distance separating the array from the observer.One problem is that the array contains structure projected from surfaces of the observer (i.e., the nose and orbits of the eye) so that a paradoxical topological disruption would be required to place the nose at 40 cm from the point of observation. Also, the array is not flat but inherently spherical. If the projection surface is curved, what would be perceived to happen at the borders of the visual field? Does the array appear to end or is the observer perceived to be encapsulated by a spherical surface? With a radius of 40 cm, the observer's body would be cut by the array at about the navel. Finally, what specifies the distance to this surface? At 40 cm, it should be reachable although the arms might be outside or beyond the surface, so they might be expected to contact the array from the backside of the surface. All of this, of course, is paradoxical and untenable.

"Mechanisms for depth perception" have been hypothesized in perceptual theories throughout the history of the study of perception. Constructive mechanisms have been thought to be instantiated in the brain. Lesion or ablation of brain tissue often has been employed to reveal the role of such mechanisms by way of introspective reports or measures of performance in the hypothetical absence of a given mechanism. Curiously, however, this approach has never been applied in an uncompromising way to depth mechanisms. True absence of depth mechanisms should leave one to perceive the backside of one's eyeballs, a situation as horrifying in prospect as anything ever devised by Poe or Kafka. We can be thankful that this never happens. But why is this so? If two-dimensional images are the foundation of perception and those images lie on the back of our eyes, why do we never perceive such images as on the back of our eyes?

A hint perhaps lies in the fact that not only does this never happen, but the result is inconceivable. One might attempt to reject the naive conception of young students as fraught with paradox and yet maintain that depth and distance would simply become nonspecific, unconstrained, or indeterminate in such a situation. But, the array and its structure would remain, if not perceived on the back of the eyeballs, out there, separate from the back of the eye. *Separate* in this context is a spatial notion and entails distance, albeit unspecified, from the point of observation. As intuited by Kant, visual perception without "depth" or distance from the point of observation is impossible. The question is what provides a foundation for perception in which such depth is inherent?

Gibson's hypothesis was that invariance over transformation is the foundation of perception (Gibson, 1979/1986; see also Lee, 1980; and Shaw & Pittenger, 1978, among others). This hypothesis is supported by the successful detection and use of ocular occlusion and by the observation that the retinal flows entailed by ocular occlusion are not different from retinal flows commonly generated by head movement and locomotion. The fact that optical flow generated by the translation of the point of observation is generated and used at the most proximal and microscopic level of human movement in vision, namely eye movement, suggests that the detection of such patterns of optical flow is truly fundamental to the functioning of the sensory apparatus in the eye. If such properties of optical flow as the progressive accretion or deletion of optical texture at a boundary are the fundamental kinds of properties detected by the visual apparatus, then depth becomes an intrinsic aspect of visual information (subject to degrees of specification in respect to level of scaling) rather than being an extrinsic property to be somehow imposed on visual information. The paradoxes entailed by the notion of depthless visual perception can be avoided.

A NOTE ON "EFFERENCE COPY"

Finally, the existence of optical flows from ocular occlusion makes the use of efferent copies somewhat problematic. Some theories of oculomotor behavior have hypothesized that copies of efferent commands to the ocular muscles are compared to "afferent retinal signals" to distinguish components of the afferent signal generated by eye movement from those generated by other sources of movement (Mittelstaedt, 1990; Wertheim, 1990). The problem is that the afferent retinal signal generated by eye movement alone is not stereotypical, but is contingent on the layout of surfaces in the observer's surround. The amplitude of the differential flow on the retina is a function of the happenstantial distances of surfaces in the surround. I give an example to illustrate the nature of the problem: Closing your left eye, place your left index finger so that it is just occluded by your nose as you look directly past your nose with your right eye. Oscillate your finger to and away from your nose so that the finger remains just occluded throughout the movement. Now, look straight ahead with your right eye and the moving finger comes into view. Move the eye back and forth and the finger comes into view along different portions of its trajectory. This situation does not prevent perception. Establishing useful comparison between efferent copies and the afferent retinal signal in situations like this entails strong requirements for the filtering of any afferent retinal signal that might be used.

SUMMARY

Bingham (1993) showed that there are conditions where ocular occlusion is detectable and functionally effective beyond near space. The point of observation translates with eye movement generating flow in the optic array. Therefore, eye movements cannot be distinguished from locomotory or postural movements of an observer in terms of effects (rotational vs. translatory) on optical flow. Studies of optical flow using the assumption that eye movements only generate rotational flows provide approximate analyses accurate for flow projected from surfaces at large distances from the observer. Unfortunately, such analyses conform to a conception of the role of the visual apparatus that is fraught with paradox.

Gibson (1966, 1979/1986) hypothesized that the essential principal in describing perceptual information is invariance over transformation. When describing an eye as scanning the optical pattern projected to a single point of observation, Gibson (1979/1986) described the adjacent order of the rigid optical pattern as an invariant revealed over (rigid) translation across the retina. But what would be specified by this invariant? It would have to be the optic array itself. This analysis is troubling and I am happy to be able to reject it. At the same time, we perhaps have some insight as to why the visual field never looks truly flat. If optical flows including motion parallax are generated by mere eye movements, then perhaps optical flow and the detection of invariance over transformation truly is the foundation of visual perception. To the extent that the dimensionality of the perceived surroundings is intrinsic to the particular character of detected invariants and transformations, then the persistent notion that depth is fundamentally extrinsic to vision and visual information is incorrect.

Finally, ocular occlusion makes the use of efferent copies problematic. If copies of efferent commands to the ocular muscles are to be compared to afferent retinal signals to distinguish those components of the afferent signal generated by eye movement, how is a useful comparison to be established if the afferent retinal signal generated by eye movement is contingent on the layout of surfaces in the observer's surround? Some sort of averaging process should be required and if so, the psychophysics need to be investigated.

Ocular occlusion is relatively simple in its geometry, but its effects are subtle and, ultimately, impossible to intuit directly. Its measurement requires great care and precision reflecting an intense sensitivity of the perceptual apparatus that has long been recognized. Although ocular occlusion is itself geometrically straightforward, its repercussions are rather far-reaching. Gibson provided us with a host of valuable insights and many of them were contained in his analysis of occlusion. Discovering that the phenomena of occlusion exists at the level of eye movements suggests that those insights may indeed provide the appropriate basis for an understanding of perception.

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