Investigations in Binocular Vision

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Forward:

The majority of studies in binocular vision concentrate on the processes underlying depth perception. The experiments described in this technical report are somewhat atypical. Instead of focussing on the problem of how the visual system recovers depth, we investigate some rather unexplored phenomena. In so doing, we have charted a rather eclectic course, one that defies being couched under single heading except to say that all our studies reported on here have to do with binocular vision.

This is not to say that this report is without merit. The data presented here will be of use to the vision researcher and the display engineer. Its use to the psychologist/vision researcher is that it raises theoretical issues and questions the validity of previous research and suggests avenues of future investigations. This report's value to the display engineer is that is provides the specifications within which to design ergonomic visual displays. Fatigue and discomfort are common hurdles confronting display engineers. Knowing the parameters of the biological system for which these displays are designed is invaluable information and will hopefully lead to breakthroughs in display design and user comfort. The parameters of the human binocular visual system we report on are the mechanical properties of the two eyes, the processing of direction by the visual system and the spatial extent of visual space that stimulates the binocular system.

As the reader can see from the abstract to follow, linking these disparate chapters together in a coherent story would compromise the clarity of each of the chapters. Therefore, each of the chapters stands alone with its own introduction and conclusion. This report may read more as a chronicle of the studies conducted while I was a visiting researcher than as a series of experiments focussed on a very specific theme.

Abstract

This technical report contains three chapters describing five experiments conducted while I was an intern researcher in Department 5 from August, 1998 to June, 2000.

Chapter 1 reports on an experiment measuring the extent of the bifixation space. Hering (1868) argued that the bifixation space is smaller for near viewing distances than for far. He also the templeward directed eye lagged behind the nasally directed eye with extreme gaze position. The data reported in this chapter support and expand on Hering's claim that the extent of the bifixation space is a function of viewing distance. We expand on this claim in this report by measuring the full area over which the eyes can move together. Our data conflict with Hering's second claim, however. We found that the templeward directed eye lags behind the nasally directed eye with extreme gaze position.

Chapter 2[1] reports on three experiments investigating the effects of occlusion on slant perception and visual direction. Hakkinen and Nyman (1997 *Perception* **26** 29-38) have shown that perceived slant, associated with Ogle's (1938 *Archives of Ophthalmology* **20** 604-623) geometric effect, is reduced when an occlusion scenario is a possible interpretation for the visual system. We present data from three experiments that confirm and expand on this finding. Our stimuli consisted of four types of stereograms depicting two white central rectangles each flanked by two gray rectangles. The central white rectangles varied in height, thus manipulating the polarity of the T-junction information.

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[1] The chapter that would most appropriately hold this position was not included because it has been published as an article in the journal *Perception*. Please see Grove, Kaneko, and Ono (in press) in the reference section of Chapter 1.

Perceived slant was smallest or not apparent when occlusion information indicated the central rectangles were nearer than the flanking rectangles and greatest when cues to occlusion were incompatible with a nearer central rectangle (experiment 1). Vertical visual direction estimates of the outer corners of the flanking rectangles were less accurate when the rectangles appeared slanted than when a depth step was perceived, indicating that perspective information also plays a role in biasing slant percepts (experiment 2). Visual direction measurements of the outer edges of the flanking rectangles indicate that the visual system displaces a portion of the non-fixated plane to fit all monocular features into a single cyclopean view (Mapp & Ono 1999 *Vision Research* **39** 2381-2386) (experiment 3).

Chapter 3 reports on an experiment measuring the spatial extent over which significant interocular transfer of the motion aftereffect occurs. It has been argued that the angular extent over which the field of view is served by binocular neurons in the visual cortex is limited to the central 40 degrees of the binocular visual field. This argument is based on data collected with static stimuli. Here we extend this investigation to include dynamic stimuli. Interocular transfer of the motion aftereffect was measured at three eccentricities, +/-2.5, 25, and 31 degrees. Substantial interocular transfer, expressed as a percentage of monocular adapt/test MAE duration was observed at all eccentricities tested. The spatial extent of binocular interaction is likely stimulus specific. Specific definitions are in order when making claims about the spatial extent of the effective binocular field.

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Chapter 1:

Mapping the bifixation field using the criterion of single vision.

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1.1 Introduction

This chapter investigates the area over which the eyes move together maintaining single vision. The question we address is what is the angular extent over which one can direct their gaze while the visual axes remain intersected at the desired distance (i.e. on target) and whether the size of this area changes as a function of simulated viewing distance. Secondly, we ask, what is the relative position of the eyes when fusion breaks? Specifically, does the nasally directed eye lag behind or precede the templeward directed eye when fusion breaks.

Vergence is said to be a disjunctive eye movement because the two eyes move in opposite directions. Horizontal vergence eye movements involve both eyes turning inwards towards the nose (as in convergence), or both turn outwards towards the temples (as in divergence). Two other classes vergence eye movements should be mentioned. Vertical vergence eye movements involve one eye moving upwards while the other eye moves downwards. Torsional vergence eye movements involve rotation of the eyes in opposite directions. That is one eye rotates clockwise in its orbit and the other rotates

counterclockwise. Version, on the other hand, is a conjunctive eye movement because the two eyes move in the same direction. Tracking a satellite across a cloudless night sky is an example of horizontal version eye movements. There are also two other classes of version eye movements. Vertical version eye movements involve both eyes moving upwards or downwards. Torsional version eye movements involve both eye rotating clockwise or counterclockwise. It is likely that vertical and torsional vergence eye movements manifested themselves during the experimental trials in this study, they were not measured, however. Our discussion will be limited to horizontal version and vergence eye movements.

Hering (1868/1977) asserted that although we have two eyes, we see as though we have one cyclopean eye. This unified perception of the world rests on the eyes' ability to move together with extreme precision. As Hering stated:

> ...we can think of both eyes as a single imaginary eye which lies midway between the two real eyes. If such an eye had to be innervated to turn to the left, right, above or below, the two real eyes would always be equally innervated, and if such an eye had to be innervated to accommodate for greater nearness or distance, both eyes would be innervated not only for an internal accommodation but also for an external bifixation of both lines of sight for nearness or distance. (p.19)

The term equal innervation reflects Hering's idea that the muscles to the each of the two eyes are equally activated or innervated. He postulates two kinds of innervation: one for conjunctive (version) eye movements, and one for disjunctive eye movements (vergence). In either case, the amount of innervation is equal in both eyes.

Hering describes the lateral movements of the eyes in terms of an additive combination of version and vergence. This description, he asserted accounted for instances where the two eyes do not move equally. Consider an instance where the eyes

receive a version innervation to move from the left to the right in the horizontal plane of regard and a simultaneous vergence innervation to move the eyes inward. In this case the left eye should move to the right because the version and vergence innervations both signal the left eye to move to the right. Moreover, the left eye should move twice as far as it would from either of the signals alone. The right eye, on the other hand, receives version innervation to move the eye to the right but also receives equal vergence innervation to move the eye inward, and should therefore, remain stationary. In support of this model, Hering reports data, collected from himself only, indicating that the maximum horizontal excursion of an eye is larger for far viewing distances than for near. Hering argued that for near fixation, vergence innervation to move the eyes inward, and remain converged at the desired fixation plane, should be greater than when fixation is in the distance, when the visual axes are nearly parallel. Therefore, at near fixation, the left eye should be receiving greater vergence innervation competing against the version innervation thereby restricting the leftward excursion of the left eye.

Hering also reported that the area over which his two eyes could move together was relatively small considering the area over which each eye could move on its own. Hering accounted for the restricted binocular fixation field in much the same way as he explained the difference in motility of a single eye at different fixation distances. That is, the lateral recti cannot be as strongly innervated as the medial recti. Thus, Hering posited that the medial recti play a more active role in moving the eyes, either by stronger innervation or because they are simply stronger muscles, than the lateral recti. As a result, Hering's model predicts that the nasally directed eye will overshoot the temporally directed eye when tracking a near object in the frontoparallel plane.

To summarize Hering's ideas, he thought the eyes moved, in most instances, in concert as though they were one organ. However, the area over which a single eye could move was reduced at near fixation distances due to a conflict between the lateral rectus and the medial rectus. Moreover, the area over which the two eyes could move together is significantly smaller than the total area available to the two eyes separately. Again, this is due, in part, to the conflict between the stronger medial recti relative to the lateral recti muscles. The restriction of the binocular fixation space is most pronounced at near viewing distances when the conflict between the lateral and medial recti is greatest. Moreover, Hering predicts that the stronger medial rectus muscles cause the nasally directed eye to overshoot the templeward directed eye in extreme positions.

Mapp et al. (1986) tested Hering's prediction that the maximum excursion of the left eye to the left and the right eye to the right is smaller when viewing a near target than when viewing a far target. In the first three experiments of a series of four, the authors were unable to replicate Hering's original claim, however. That is, no significant near/far difference was observed in the maximum excursion of a templward directed or nasally directed eye. In the fourth experiment, the authors varied gaze elevation with viewing distance. Under these conditions, all observers showed significant near/far differences in the extreme excursion of the eyes. When gaze elevation was depressed and viewing was near, the excursion of the templeward directed eye was less than when the eye elevation was raised and viewing was far. The authors concluded from this that Hering must have confounded eye elevation with viewing distance.

Mapp and Ono (1986) hypothesized that additivity of version and vergence innervation is restricted to within the bifoveate field. In this experiment, observers

fixated at either 125 cm or 32 cm and were instructed to move their eyes to the left or right along the horizontal plane of regard and to note the point at which the Nonius stimulus became misaligned. Moreover, the observers were to note which way the stimulus broke, thus revealing the relative position of the eyes when they ceased to move as one. Their data show that the angular horizontal extent of the bifoveate field is larger at far viewing distances than for near viewing distances, in accordance with Hering's original claim. However, Mapp and Ono reported that, at the 32 cm viewing distance, the nasally directed eye lagged behind the temporally directed eye when the eyes ceased to move together. This is opposite to Hering's prediction based on his idea that the medial rectus muscles are stronger or more strongly innervated than the lateral rectus muscles.

The reports of Hering (1868/1977), Mapp et al. (1986) and Mapp and Ono (1986) all employed foveal afterimages to monitor eye position. This is a very good method for monitoring eye position because an afterimage does not slip over the retina. Nonius lines are another subjective method to monitor the vergence state of the eyes. One possible advantage of the Nonius method, however, is that occlusion of one eye's image by facial structures, such as the nose and orbit of the eye, can be monitored by the observer. An afterimage is "burned" onto the retina and cannot be occluded. Previous studies have illuminated the restrictions of vergence system, attributable to the conflict between the extraocular muscles. Nevertheless, a true mapping of space that can be bifixated is yet to be determined because occlusion of one eye's view by facial structures have not been taken into account.

1.2 Experiment

The purpose of the following experiment is to measure the extent of the area over which

the eyes can move together and maintain single vision in horizontal plane of regard and

oblique locations, noting the relative position of the eyes when fusion breaks. Moreover,

the use of a distal Nonius stimulus, allows us to measure where the area over which the

two visual axes can be directed in synchrony is limited by facial structures.

1.2.1Method

1.2.1.1 Observers. Four male observers, experienced in psychophysical experiments, the

author and three naïve participants participated.

1.2.1.2 Apparatus and stimuli. Stimuli were generated on a Macintosh power PC and

projected on a polarized rear projection screen, subtending 131 degrees horizontally and

102 degrees vertically at a 57cm viewing distance. Two projectors, one for each eye's

image, were fitted with orthogonally oriented polarizing filters. A complimentary pair of

polarizing filters was placed in front of the observer's eyes. Observers sat with their

heads fixed in a chin and forehead rest 57 cm in front of the display. Their responses

were recorded via a trackball mouse. Stimuli consisted of a binocular dot flanked on

either side by additional binocular lines. Above and below the binocular dot were Nonius

lines, visible to the left and right eyes, respectively. Right and left eye images were

presented at one of three separations on a given trial to simulate one of three viewing

distance/vergence conditions (57 cm (6.5 deg vergence): 28.5 cm (13 deg vergence); 10

cm (36 deg vergence). In the 57 cm condition, the actual distance of the display, the

fixation stimulus and the left and right eye's Nonius lines were positioned at the center of

the screen. To simulate a 28.5 cm viewing distance, the right eye's image was displaced

3.25 cm to the left of center and the left eye's image was displaced 3.25 cm to the right of center. To simulate a 10 cm viewing distance, the displacement was 15.2 cm for each eye's image (see Figure 1.1). Observers could move the stimulus along one of 12 radii (24 radii for observer PG) with a track ball. Radii were at 30 degree intervals (15 degree intervals for observer PG) and can be visualized as spokes on a wagon wheel. On a given trial, observers moved the stimulus away from or towards the center of the display along one of these spokes, as illustrated in Figure 1.2.

1.2.1.3 Procedure. Each trial began with the stimulus centered on the screen. If the right and left eye's images were separated on the screen, observers were to free fuse the stimulus and move it slowly out from the center along a randomly chosen radius. If the right and left eye's images were not separated, the observer simply fixated the binocular dot and moved the stimulus out from the center.

Experimental runs were blocked such that, on a given run, observers moved the fused stimulus outward until the Nonius lines became misaligned such that one of the Nonius lines was collinear with one of the flanking binocular lines. This was equal to a misconvergence of 0.9 degrees. He then pressed the mouse button indicating that location. In alternating experimental runs, the same observer would move the stimulus outward until it was clearly diplopic and then moved the stimulus back towards the center until the Nonius lines were subjectively aligned and indicated the position of the stimulus with a mouse click.
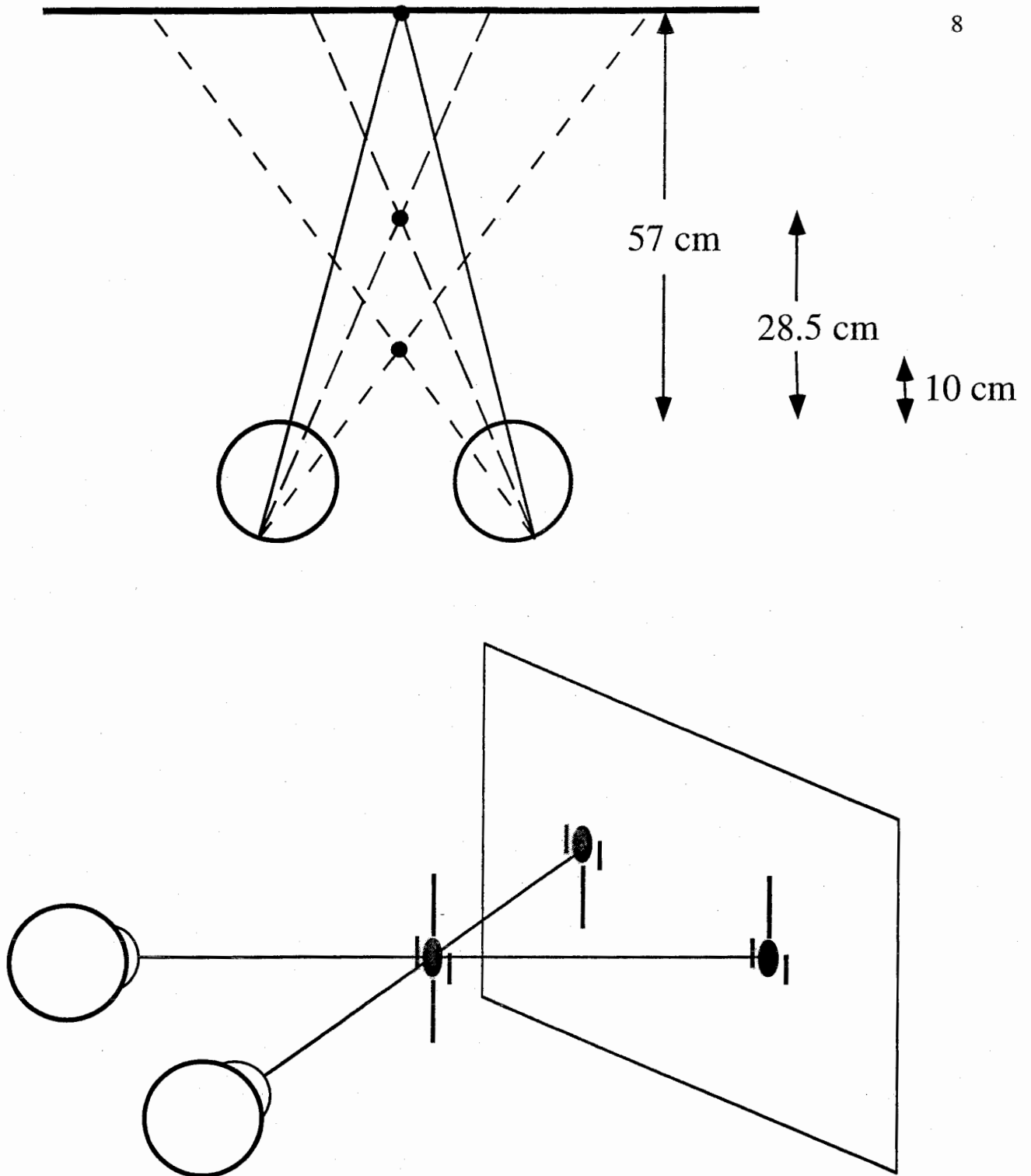
57 cm

28.5 cm

10 cm

Figure 1.1. Illustration of the three different vergence conditions employed in this experiment. Observers "free fused" the fixation stimulus. Top illustration is a top view of the viewing situation. Bottom illustration is an oblique view. See text for details.
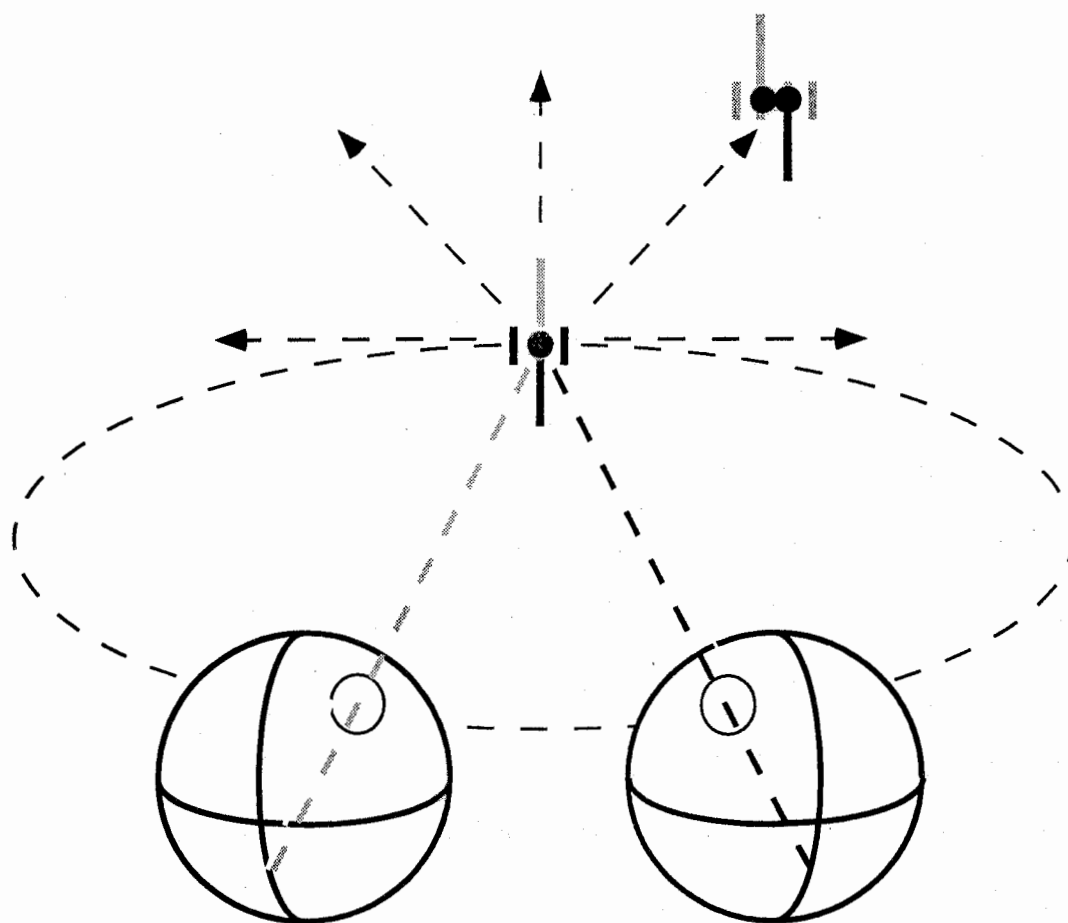
Figure 1.2. Illustration of the task of the observer. After free fusing the stimulus, observers moved it out along one of twelve radii until the Nonius lines were misaligned as illustrated. See text for details.

In all trials observers were instructed to note the relative positions of the Nonius lines when fusion broke. Observers reported whether the right eye's (top) Nonius line appeared (1) to the left or (2) to the right of the left (bottom) Nonius line, or (3) some part of the stimulus was occluded by part of the observer's face or boarder of the display. Observers YF, SN, and NG completed twelve sessions (six in each direction: from single to double; double to single), each containing 36 trials. In a given session, observers viewed each stimulus permutation once (three vergence conditions X 12 radii). Observer PG completed 12 sessions (six in each direction), each containing 72 trials (three vergence conditions X 24 radii).

1.2.2 Results.

Polar axes:

Individual polar plots of the mean settings for twelve observations, six for 'single to double adjustments' and six for 'double to single adjustments', along each "spoke" of the wheel are illustrated in Figure 1.3. Closed squares represent mean adjustments for the 57 cm fixation distance, gray diamonds for the 28.5 cm viewing distance, and the open circles represent the 10 cm viewing distance condition. Open triangles denote the extent of the stimulus display and are presented to indicate where (if ever) the field was limited by the dimensions of the display. This happened most frequently for the 270 degree radii and the two adjacent radii.

Cartesian axes:

Individual Cartesian plots, provided to illustrate both the variability of the data (error bars = +/- <u>SEM</u>) and the radii for which differences in the angular extent of the
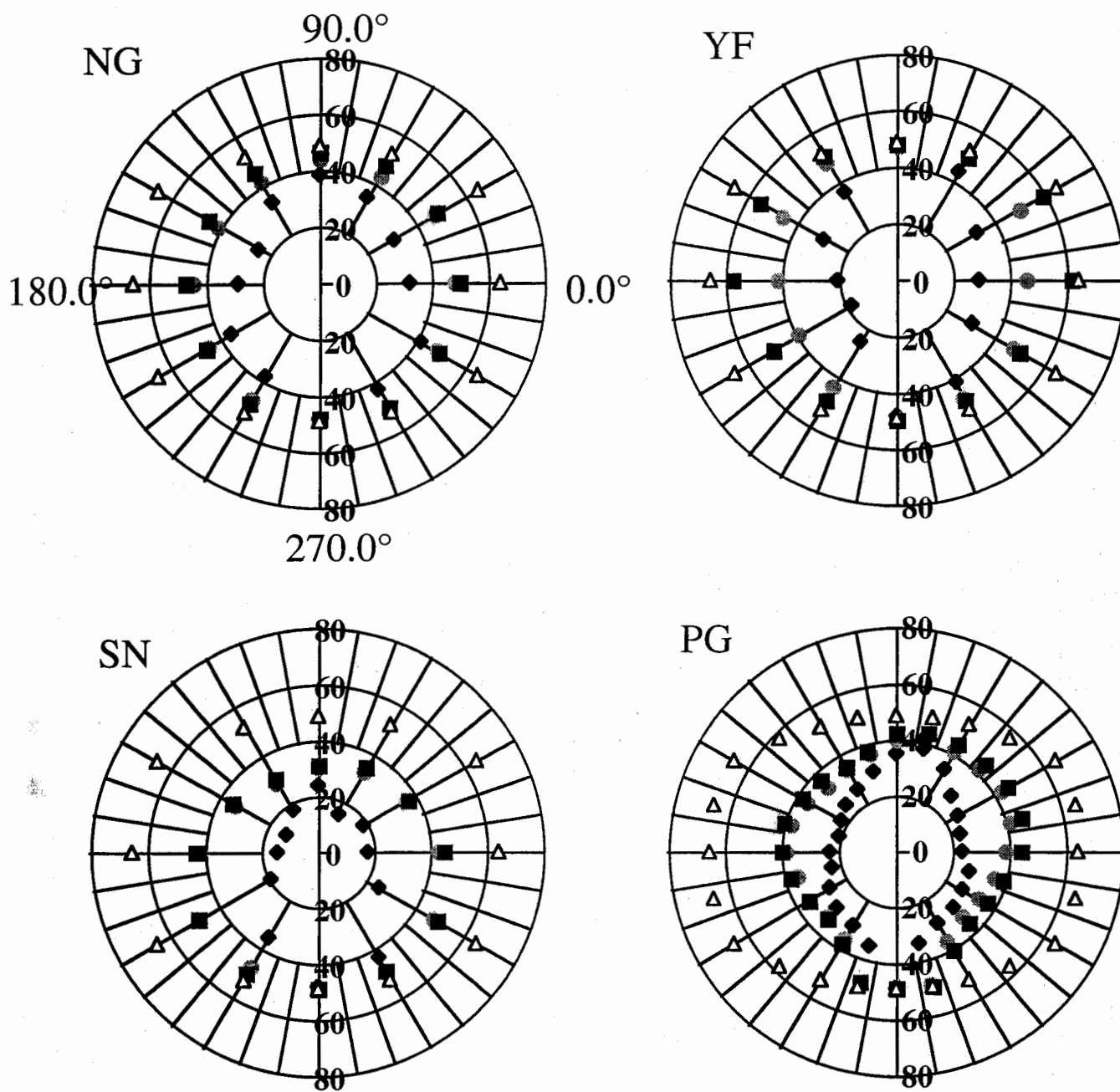
Figure 1.3. Radial plot of mean settings for each observer. Closed squares indicate mean settings at 57 cm viewing distance, gray circles indicate mean settings at simulated 28.5 cm viewing distance; black diamonds indicate mean settings at simulated 10 cm viewing distance.

bifixation field for different simulated viewing distances are at a maximum and minimum, are illustrated in Figure 1.4. It is clear from the graphs that the differences in the extent of the bifoveate field are most pronounced at 0 and 180 degrees, or along the horizontal meridian. This is in agreement with Hering's prediction. It is not surprising that the extent of the bifoveate field converges for the three fixation distances at the 90 degree and 270 degree radii. Conjugates up down movements of the eyes involve little or no conflict between the templeward and nasalward "pulling" muscles.

We computed the mean angular extent of the bifixation field at each simulated viewing distance for each observer and performed a one factor analysis of variance with one repeated measure. This analysis revealed a significant effect for viewing distance, $F(2,6) = 55.87$, $p<0.01$. Tukey (hsd) post-hoc analysis revealed that the mean angular extent of the bifixation field at a simulated viewing distance of 10 cm is significantly smaller than at 28.5, or 57 cm, $p<0.01$. There was no significant difference in angular extent of the bifixation field between the 28.5 and 57 cm viewing distance conditions.

Nonius data:

As we stated above, observers were required to indicate the relative position of the Nonius lines at the point were fusion broke. The percentage of trials which observers reported that the top Nonius line was to the left of the bottom Nonius line along each radius for each viewing distance is illustrated in Figure 1.5. Although observers were given a choice of three responses, top Nonius line to the left, to the right, or some part of the stimulus was occluded, never did they report that the top Nonius line was seen to the right of the bottom Nonius line when fusion broke. Let us consider an example of the Nonius data to understand it clearly. When observer PG reported that the top Nonius line
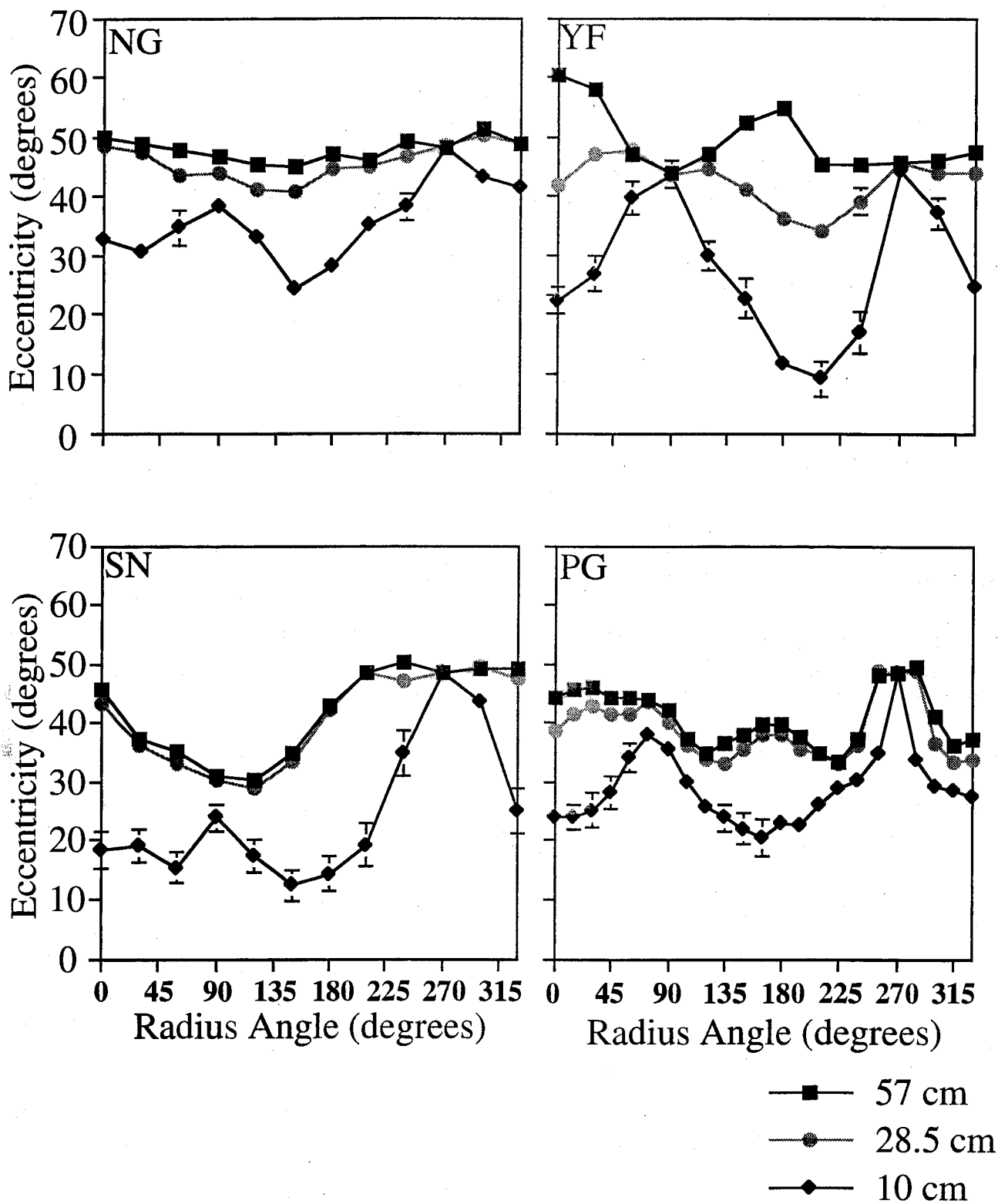
Figure 1.4. Cartesian plot of mean settings for each observer. Symbols are the same as the radial plot in figure 3.
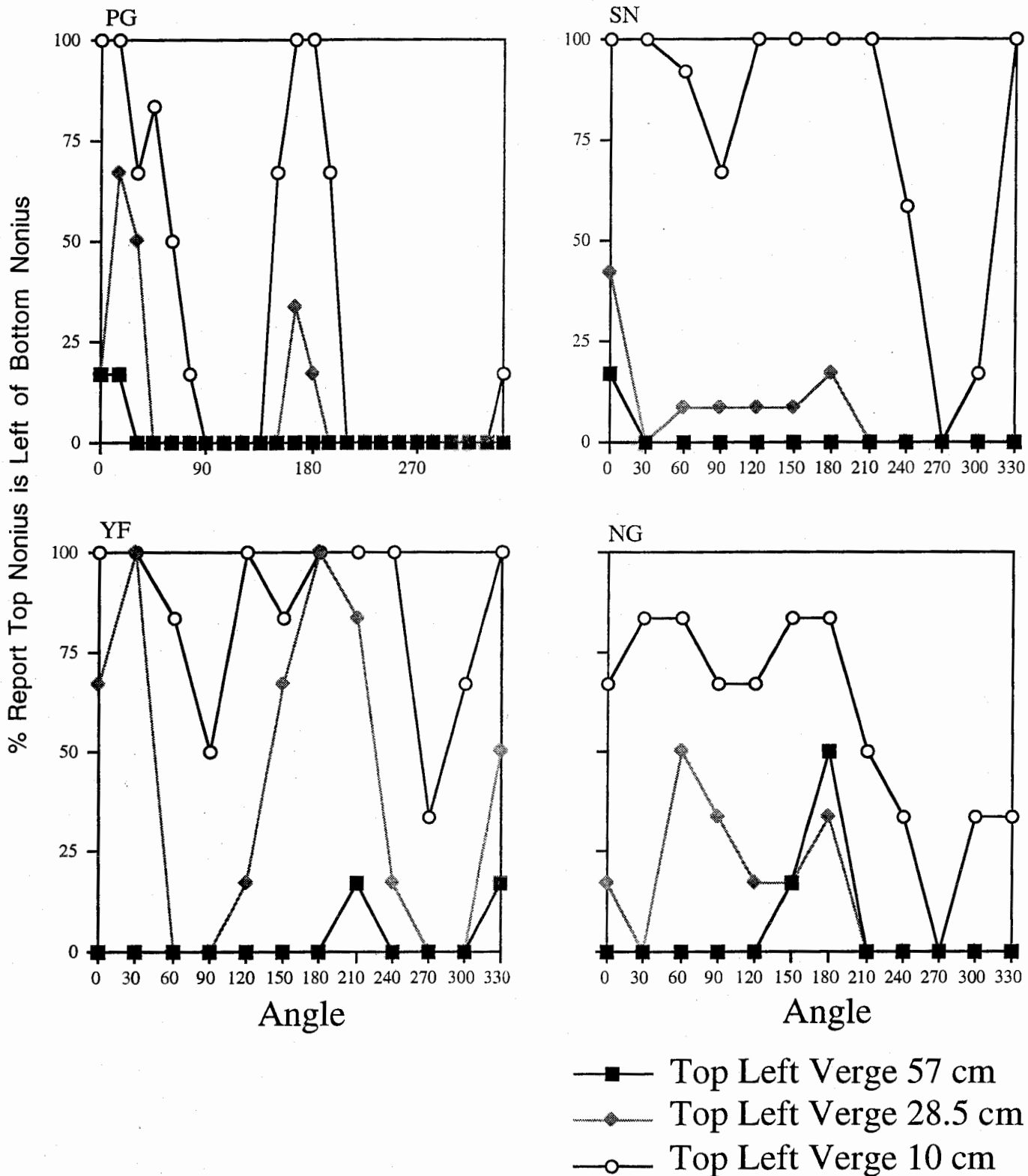
Figure 1.5. Individual data for Nonius responses collected in the experiment. Percent of the trials observers reported that the top Nonius line was to the left of the bottom line when fusion broke. Although observers had a choice of three responses: Top Nonius line left, right, or partially occluded, they never reported that the top line was to the right of the bottom. Therefore the percentage of occlusion responses can be determined by subtracting the percent of "Nonius left" responses from 100%. See text for more details.

was seen to the left of the bottom Nonius line on 50% of the trials measured along the 60 degree radius in the 28.5 cm vergence condition, part of the stimulus was occluded to one eye on the other 50% of the trials. Therefore, observers effectively chose between two responses, "top Nonius to the left" or "partially occluded". The absence of any reports of seeing the top Nonius line to the right of the bottom Nonius line is an important finding in itself because this indicates that the nasally directed eye never preceded the templeward directed eye in extreme binocular gaze positions. This finding is contrary to Hering's prediction, but consistent with Mapp and Ono (1986).

Inspecting the Nonius data more closely reveals another pattern. At the far viewing distance, with few exceptions, observers reported that the Nonius lines remained aligned until the stimulus was occluded to one eye. Trials for which the Nonius stimuli became misaligned before the stimulus was partially occluded to one eye involved a near horizontal movement of the eyes, a radius close to 0 or 180 degrees. Nonius misalignment was reported at the 57 cm viewing distance along the 0 degree radius for observers PG and SN. This is equivalent to an extreme rightward movement of the eyes. Observers YF and NG reported Nonius misalignment for near extreme leftward movements of the eyes (210 degree radius for YF; 180 degree radius for NG). In the near vergence condition, however, the Nonius stimuli became misaligned before the stimulus was partially occluded to one eye in nearly all trials. The restriction of the bifixation field was most pronounced along radii close to 0 and 180 degrees. Observers reported fewer incidences of Nonius misalignment for near vertical eye movements, involving radii close to 90 and 270 degrees were less restricted in the near vergence condition. In fact the limiting factor along the 270 degree radius, was the size of the display. For this

radius, all four observers were able to accurately track the target and maintain subjective

Nonius alignment until it reached the edge of the display. Additionally, all four

observers' data show a dip in the percentage of "top Nonius left" responses near the 90

degree radius in the near vergence condition. For this and adjacent radii (particularly for

observer PG) the stimulus was partially occluded by the observers' eye brows or the top

of the display.

1.2.3 Discussion

Our experiment revealed that the area over which the two eyes can move in

concert is restricted both by viewing distance and the facial structures of the observer.

Specifically we showed that at very short simulated distances (10 cm) the bifixation

space is significantly reduced relative to more moderate viewing distances like 28.5 and

57 cm. We did not observe a significant difference in the angular extent of the bifixation

space between 28.5 and 57 cm however. This is consistent with the report by Mapp and

Ono (1986), who were unable to find a difference in the bifoveate field for viewing

distances of 70 cm and 30 cm. One might imagine a parabolic cone with its apex

somewhere between 10 cm and 30 cm from the observer's face delimiting a cone within

which observers can move their eyes in together and maintain binocular fusion of the

fixated object. This cone might not be perfectly round, however, as the individual's

facial features would place additional limits on the bifixation field.

Mapp and Ono (1986b) report a phenomenon that is related to the issue of a

bifixation field limited by facial features. Ocular parallax, first described by Brewster

(1844), occurs because the optical nodal point of the eye is anterior to the eye's center of

rotation. Mapp and Ono describe a demonstration to illustrate this phenomenon

> While keeping your gaze directed straight ahead, close your left eye and
> slowly move your left index finger from your left ear in the direction
> parallel to your line of sight. Continue to move your finger until you are
> just able to see it. Now, without moving either your hand or your head,
> direct your gaze towards your finger. Your finger probably disappeared.
> If you redirect your gaze forward, your finger will reappear. (p. 1163)

When your gaze is directed straight ahead, the nodal point of your open eye is at its most

anterior location. The light reflected from the tip of your finger passes through the nodal

point and onto the retina. When you direct your gaze towards your finger, however, the

nodal point translates leftward to a point occluded by your nose, preventing an image

from being formed on your retina. Occlusion of one eye's image by the nose certainly

limits the bifixation field and this field should shrink as the fixation plane is brought

closer to the observer.

The discussion thus far has couched the data in terms of its theoretical

significance. That is, our data and Mapp and Ono's (1986) data conflict with Hering's

claims. This is significant because Hering's thoughts on the additivity of version and

vergence are commonly referred to as the law of equal innervation. The recent data has

shown that Hering's assertions have not survived subsequent empirical tests and should

not be referred to as laws. That said, however, Hering's theory should not be discarded;

rather it should serve as a foundation from which to build a more complete understanding

of binocular eye movements (Mapp et al. 1986).

Our data also have practical implications as well. More and more,

human/computer interfaces are employing virtual reality to immerse the user in a virtual

environment. Accompanying these developments are newer 3-D displays. The premise

of a 3-D display is that observers can be immersed in a virtual 3-D environment defined

mostly by binocular disparity. A major problem facing designers of this technology is

the fact that users become fatigued and experience discomfort after a short period of use. The data presented in this chapter serves as another resource for display engineers requiring knowledge of the biological system when setting the parameters (such as display size) of their 3-D systems. Justification for this assertion is outlined in the short literature review below.

Our ability to discriminate the separation in depth between two targets is best when the images of those targets fall on the fovea in each eye. If an observer fixates a point, with symmetrical vergence, for example, their ability to discriminate small depth intervals deteriorates as the target stimuli are moved to eccentric locations away from the fovea. Ogle (1952) showed that as targets with relative disparity were moved away from the fovea along the horizontal meridian, stereoacuity dropped off exponentially. This decrease in stereoacuity would occur if targets were moved out along any meridian (horizontal, vertical, or oblique) and is presumably a function of the increase in receptive field size with eccentricity (Tyler, 1983).

Stereopsis is a three-dimensional sense, however. We can, therefore, consider how removing a target display from the point of fixation along an axis perpendicular to the frontoparallel plane affects our ability to discriminate small depth intervals within the display. Blakemore (1971) systematically investigated this question. He varied the absolute disparity of two slit targets such that they were positioned in front of or behind the fixation point on any given trial. He found that stereo-thresholds increased exponentially as the discrimination targets were positioned further in front of the fixation point (crossed absolute disparity) or behind the fixation point (uncrossed absolute disparity). The angle of convergence was constant in Blakemore's study and the absolute

disparity was introduced by horizontally shifting the stereo half images. This study is relevant to our experiment because absolute disparity is also a function of vergence angle. That is, an equal absolute disparity can be introduced if the stereo half images remain fixed and the observer converges in front or behind the stimulus plane. We assume that an equivalent degradation in stereo-acuity would result from absolute disparities introduced by misconverging on the stimulus plane. We do not know of any study that has confirmed this, however.

Tyler (1983) likens the role of vergence, in three-dimensional space perception, to lateral eye movements in viewing a two dimensional scene. We can perceive the general layout of a two dimensional scene without moving our eyes. We must change our gaze to foveate any details of the scene, however. So too, is the case in three dimensions:

> The stereoscopic situation is analogous to perception of two-dimensional space with a high-acuity fovea controlled by lateral eye movements. It is clear that the general layout of objects in two dimensional space is readily perceived across the 180 degree field with out lateral eye movements...What the eye movements accomplish is detailed perception of a chosen part of the perceived scene. It seems reasonable to suppose that vergence movements serve the same role for the third dimension, bringing regions of interest into the range of best disparity discrimination.
> (p. 283)

Blakemore's (1971) study highlights the adverse effect of absolute disparity, or misconvergence, on stereo-acuity. Clearly, a precise and suitably calibrated vergence system is necessary for optimal stereo performance in a binocular visual system.

Not only will a faulty vergence system degrade disparity discrimination; larger vergence errors result in double vision, or a loss of fusion. For the images falling on the two retinas to be perceptually fused, they must fall on near corresponding points in the two eyes. Considering our two eyes as identical globes with longitudes and latitudes by

analogy to the globe of the earth, points that have the same longitude and latitude in the two eyes are considered to be corresponding points. As you read this page, your eyes converge on the individual letters for brief periods of time. This is done so that the image of each letter falls on the fovea in each eye. The central foveas are a pair of corresponding points, and an object whose image falls on these points is perceptually fused[1]. If an object's image does not fall close to corresponding points in the two eyes, it is perceived as double. This is another reason why humans require a precise vergence system. Our eyes must converge with accuracy between 10 and 20 arc min in order for a small fixated object to appear single. In general, a point image on one eye's retina must fall within 10 to 20 arc min of the corresponding point on the other eye's retina for that object to appear single. This area around the corresponding point is known as Panum's (1858) fusional area and it is smallest for points on the fovea and increases as a function of distance from the fovea on the retina.

1.2.4 Concluding remarks

We have argued that precise vergence control of the eyes relates directly to stereo-acuity and single vision. The relevance of this discussion to display engineers is twofold. First, the dependence of stereo-performance on the vergence control system, is motivation to determine the parameters within which the vergence system works. Secondly, in the studies assessing the constraints of the human vergence system, singleness of vision is used as a dependent variable to find the shortcomings of the vergence system.

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[1] For a complete review of corresponding points, see Tyler (1991), and Howard and Rogers (1995).

The data presented here suggest that a vertically elongated display might be more ergonomically sound. This would be true particularly for head mounted displays and perhaps "heads up" displays, being developed for fighter aircraft. In both situations, movement of the head either contributes nothing to the visibility of the display (in the case of head mounted virtual reality devices), or head movement is restricted, as in the small cockpits of fighter aircraft. In addition, this data compliments our other experiments measuring the inclination of a surface defined by empirical corresponding points (Grove, Kaneko and Ono, In Press). Taken together, these experiments provide useful information about the best distance, shape, and orientation specifications for 3-D displays.

In the introduction we mentioned that horizontal version and vergence eye movements are only two of six classes of eye movements. We did not measure vertical version, vertical vergene, torsional version, or torsional vergence eye movements in this study. We suppose, however, that all such eye movements are involved when directing one's gaze around the full bifixation field and future research measuring these eye movements is necessary to complete our understanding of binocular eye movements.

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Chapter 2:

Perceived slant, perspective and visual direction of

partially occluded surfaces

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2.1 Introduction

This chapter investigates the effect of occlusion information on perceived slant and visual

direction judgments. The question we address is whether occlusion information in the

form of T-junctions can bias the global percept of a stereogram containing ambiguous

disparity information. Secondly, we ask what is the visual direction of features, such as

the outer edges of an occluded rectan, in these stereograms.

Ogle (1938) coined the term "geometric effect" referring to the perception of slant

about a vertical axis when one eye's image is horizontally magnified relative to the other

eye. He used that term because the subjective experience is predicted from the geometry

of the situation. That is, a near left, far right surface will create binocular images that

have larger horizontal extent in the right eye than in the left. We investigated a situation

where the retinal stimulation is equivalent to the geometric effect, yet a depth step is

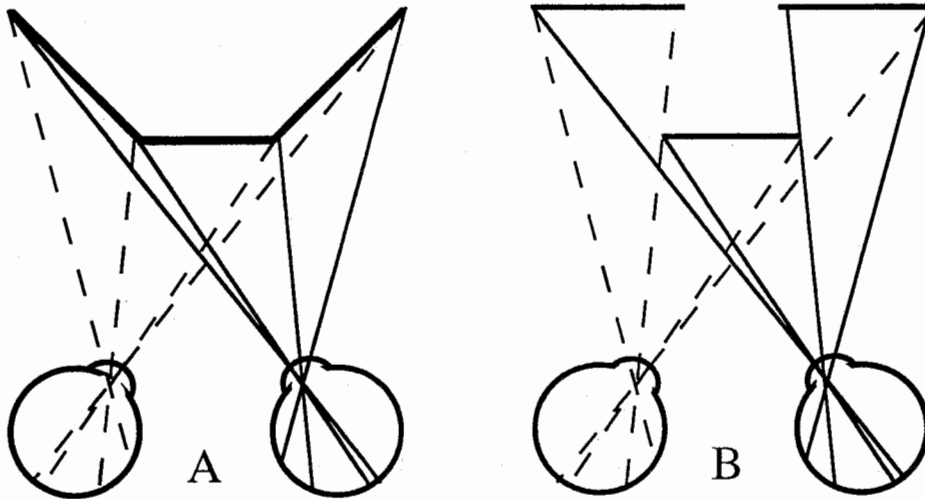perceived instead of a slanted surface. This is illustrated in Figure 2.1.

Figure 2.1. Top view of two surface configurations that generate identical retinal images. In (A) a frontal surface is flanked by two slanting "wings". In (B) a frontal surface is seen closer than two frontal surfaces. Dotted lines indicate left eye's view, solid lines indicate right eye's view. Retinal images are identical in (A) and (B), although observers report seeing (B) most often.

If the flanking surfaces depicted in the figure are featureless, the only difference

between the left and right eye's images of the flanking rectangles is horizontal size.

Moreover, the retinal stimulation in (a), where the global percept is of a frontal surface

flanked by two rectangles slanting with their outer edges away from the observer, is

identical to (b), where two frontal surfaces are perceived in depth-one in front of the

other. This implies that the visual system has at least two possible percepts to choose

from given the disparity information available.

Ohtsuka et al (1996) found that as objects entered a 3-D display from one side,

observers saw those objects slanted about a vertical axis. These authors remedied this

problem by adding a "virtual picture frame" in front of the display, enabling observers to

perceive the intended depth. This clever solution to a practical problem has theoretical

implications as well. When an occlusion interpretation is possible, the visual system,

given retinal stimulation characteristic of the geometric effect, constructs a percept of a

depth step instead of slant. Hakkinen and Nyman (1997) have shown, experimentally,

that perceived slant resulting from Ogle's geometric effect is reduced when that surface

abuts, or nearly abuts, against a zero disparity occluder. In this chapter we present data

from three experiments that confirm and expand on their reports. In section 2, we present

data from stimuli depicting two surfaces that share a common boarder, yet, by

manipulating the T-junction information in the display the percept of a slanted surface

can be biased towards a depth step. T-junctions are cues to interposition such that the top

of the T is interpreted by the perceptual system as belonging to the nearer surface, while

the stem of the T belongs to the occluded surface. T-junctions have been used

extensively in machine vision as a heuristic to reduce the number of possible 3-D

interpretations from 2-D images[2]. For a review, see Winston (1977).

As illustrated above, geometry predicts that the visual system, given identical retinal

stimulation, has at least two percepts to choose from, step or slant. Geometry, combined

with the laws of visual direction also predicts *where* features within this display should be

seen. As outlined in Ono and Mapp (1995), Wells /Hering's laws of visual direction state

that the perceived direction of an object in 3-D space, at the cyclopean eye[3], is the

combination of the visual lines. As originally stated, however, the laws predict diplopia

for objects with retinal disparities of any magnitude. Ono and Mapp argue for a

modification of these laws citing data showing that visual direction at the cyclopean eye

is the mean of the local signs at each eye for small disparities, within Panum's (1858)

fusional range. Recent data has shown that Wells-Hering's laws of visual direction

require a further upgrade (see Mapp & Ono, 1999; Ono et al, 1998). In section 4, we

develop this idea further and compare our psychophysical visual direction data with those

predicted from the existing laws of visual direction.

2.2 Experiment 1

We investigated whether occlusion information, in the form of T-junctions, bias the

global percept of stereograms containing ambiguous disparity information. To do this we

used a stimulus consisting of a vertically oriented white central rectangle occluding two

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[2] T-junctions are a feature of the generic viewpoint assumption. According to this assumption, a small
change in vantage point will not appreciably change the projected image. Therefore, edges and surfaces do
not lie along lines of sight. Also, edges and corners of objects at different distances do not lie along lines of
sight. Thus, in a generic view, all visible edges are represented b y lines, all curved edges by curved lines,
and all visible surfaces by areas. Lines forming T-junctions arise from one object occluding another, with
the top of the T arising from the nearer object.

horizontally oriented gray rectangles. Let us first consider the monocular or pictorial cue available to discern the depth order between the central and flanking rectangular regions. In the case where the central occluder is taller than the flanking gray regions a distinct luminance discontinuity signals an instance of interposition. Supplementing these features are accompanying T-junctions where the horizontal edges of the flanking gray regions terminate at the occluder edge. Therefore, in the stimulus situation just described, a luminance discontinuity, combined with T-junction information, give rich information about the depth order between these two regions.

In order to ascertain whether the global percept of stereograms containing ambiguous disparity information could be biased by occlusion information in the form of T-junctions, we manipulated the occlusion information to create four types of stereograms by changing the height of the central occluder. The first type depicted a pair of central rectangles, each abutting two flanking rectangles, shorter than the central rectangles (T-junction indicating a near central rectangle). The second depicted a pair of central rectangles, each abutting two flanking rectangles equal in height to the central rectangles (Ambiguous T-junction). The third depicted a pair of central rectangles, each abutting two flanking rectangles, taller than the central rectangles (T-junction indicating near flanking rectangles). The fourth depicted no central rectangles and just the four flanking rectangles (No T-junction).

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[3] Although we view the world with two eyes, our perceptual experience and behavior is as if we perceive the world from a single eye mid-way between our eyes. See, for example, Hering, 1879; Church, 1966; Barbeito, 1983; Dengis et al, 1993a; Dengis et al, 1993b)

2.2.1 Method

2.2.1.1 Observers. Seventeen observers from ATR laboratories, reporting normal or corrected to normal binocular vision participated. Six observers were experienced in psychophysical experiments, while the remaining 11 had little or no prior experience in visual psychophysical experiments.

2.2.1.2 Apparatus. Stereo-images were generated on a Macintosh computer and presented on two 40.4 X 30.2 cm colour displays (Model: Sony GDM-F500). The monitors were carefully adjusted such that the two screens faced one another and were aligned and parallel. Observers viewed the screens, via two front silvered mirrors oriented at +/-45 degrees to the median plane of the head, at an optical distance of 65 cm. The computer monitors were cropped with flat black apertures and the entire stereoscope was enclosed with a black curtain.

2.2.1.3 Stimuli. Four types of stereograms, depicted in Figure 2.2, were generated. The first consisted of a taller central white rectangle (subtending 7.4 degrees vertically and 6.4 degrees horizontally) with two flanking gray rectangles, one on each side (6.4 X 4.3 degrees). The second type had the same configuration except the central rectangle was the same height as the flanking rectangles (6.4 X 6.4 degrees). The third type, again had the same configuration except the central rectangle was shorter than the flanking rectangles (5.3 X 6.4 degrees). The fourth type of stereogram contained no central rectangle. Note that the forth type of stereogram is analogous to Ogle's (1938) original stimulus for the geometric effect. All stereograms were presented with 18 min arc disparity, crossed and uncrossed. This is equivalent to a seven- percent horizontal magnification of one eye's image of the flanking rectangles relative to the other.
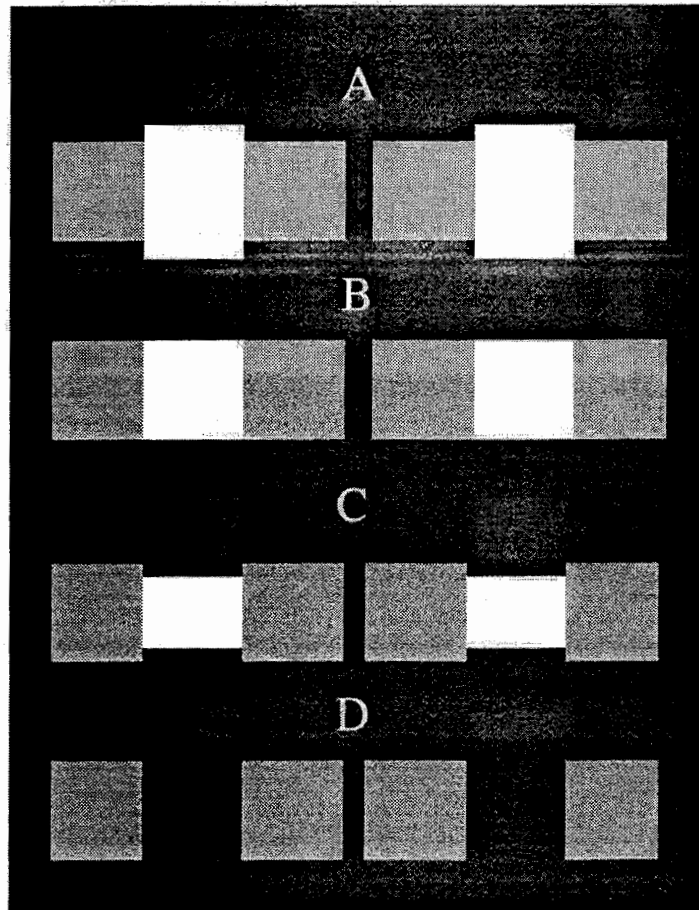
Figure 2.2. Examples of the stereograms used in our experiments. With cross fusion, the T-junction information in (A) indicates that the white rectangle is in front. In (B) the T-junction information is ambiguous. In (C) T-junction information is inconsistent with the white rectangle situated in front, and (D) contains no occlusion information. Observers see a depth step in (A) most often and least often in (D).

By changing the height of the central rectangle, we manipulated the T-junction information. In the stimulus where the central rectangle was taller than the flanking rectangles, as in Figure 2.2a, the T-junction information strongly supported the interpretation that the central rectangle was in front of the flanking rectangles. As the height of the central rectangle was reduced, the T-junction information became inconsistent with an occlusion interpretation, as in Figure 2.2c where the polarity of the T-junction is opposite to 2a.

Each stimulus presentation contained two stereoimages, one above the other, with oppositely signed disparity. This was done to shorten observers' latencies of slant/step perceptions. Allison and Howard (2000) report that when disparity and perspective cues are not in agreement, slant percepts, equivalent to conditions where perspective and disparity cues are in accordance, take approximately 10 seconds to build up. Gillam et al (1988) have shown that the perception of slant is faster in the presence of a reference stimulus or oppositely slanted surface positioned below the test stimulus. In pilot experiments, observers often changed their responses from "step" to "slant" for those stimuli which a slant percept was predicted. We speculate that observers reported that they saw the rectangle as flat before the slant percept had time to build up. The addition of a second identical stimulus, with opposite disparity, was meant to reduce the build up time for the perception of slant so as to reduce spurious responses. This proved to be an adequate solution as all observers reported the percepts to be immediate and stable in subsequent experimental runs.

2.2.1.4 Procedure. Each observer's session began with a preliminary series of trials to familiarize him/her with stereoscopic stimuli, and ensure that they understood what was

meant by "slant" and "frontoparallel". In this series, observers viewed two horizontal rectangles (4.3 X 12.6 degrees), one above the other. Stimuli were presented with disparity of varying magnitudes such that one eye's image was horizontally magnified relative to the other eye's image. If the top rectangle in the right eye's image was magnified relative to the left eye's image, the bottom rectangle was minified relative to the left eye's image. The resulting percept was of two oppositely slanted rectangles. Stereograms without disparity were also presented. These preliminary trials served two purposes. First, to ensure that all observers could see depth in stereoscopic stimuli with disparities in the range of 18 min arc. Second, it established criteria for what would be reported as "slanted" or "flat".

In these training runs, observers were presented with several stimuli of varying magnitudes of disparity between zero and +/-18 min arc. Observers verbally reported their percepts to the experimenter. A preliminary session continued until both the observer and experimenter were confident that the observer had established a stable criterion for zero, positive, and negative slant. A typical training session did not last more than 10 minutes.

In the experiment proper, each observer viewed each of the four stimuli twice, once for each depth order and verbally reported whether they perceived slant or a depth step for both the top and bottom stimuli. A total of 16 responses were taken from each observer (four types of stereograms X two depth orders (crossed and uncrossed) X top and bottom stimuli). Viewing time was unlimited and observers were free to move their gaze around the stimulus.

2.2.2 Results

The mean percentage of times which the group reported seeing the flanking rectangles, whose outer edges had uncrossed disparity, as slanted are plotted as a function of occluder height in Figure 2.3. It is apparent from the figure that as the height of the occluder increased, the percent of reported slant percepts decreased. In the case where the occluder was taller than the flanking rectangles a slant percept was reported only 9% of the responses. When the occluder was the same height as the flanking rectangles, the percentage of reports for slant was nearly equal (53%) to the percentage of reports of a depth step. When the occluder was shorter than the flanking rectangles or absent, the percentage of slant reports was 79.5%. When no occluder was present, 94.1% of the responses indicated a slant percept. The remaining 5.9% in this condition represent the report of one observer who described a black square floating in front of the flanking rectangles such that they appeared as flat and behind the subjective occluder. We explored this phenomenon in more detail in section 3. Although not plotted, all observers reported slant percepts when the outer edges were perceived nearer than the occluder for all types of stereograms. In summary, when occlusion information was rich and supported the interpretation of an occlusion scenario, the majority of observers reported a "depth step" percept when the outer edges of the flanking rectangles were perceived as further than the occluder. When the T-junction information did not support a likely occlusion scenario, observers reported seeing slant in accordance with Ogle's (1938) predictions.

In the preceding part of this experiment, we found that occlusion information can bias the global percept of a stereogram containing ambiguous disparity information.
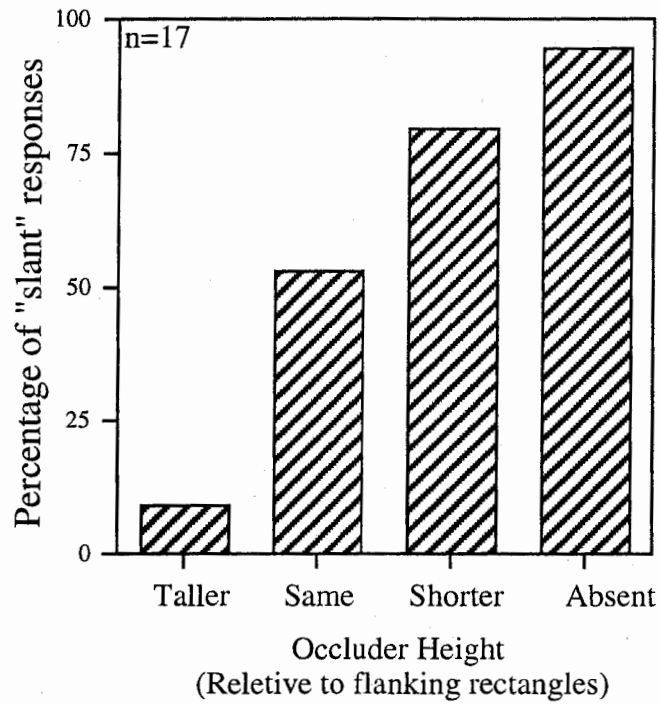
Figure 2.3. Percentage of responses indicating the flanking rectangles were perceived as slanted, consistent with Ogle's prediction, plotted against occluder height. Responses are from 17 observers, each responding twice to each stimulus. See text for details.

Given a choice between "slant" and "step", observers reported seeing a depth step when an occlusion interpretation was possible. On the other hand, we cannot be certain that occlusion information completely eliminated the perception of slant when the outer edges of the flanking rectangles were seen as further than the occluder. Observers' responses were restricted to either "slant" or "depth step" with no provision for intermediate responses. If slant was seen in the stimuli, its magnitude was unknown. Therefore, we next attempted to quantify the extent of bias towards a depth step exerted by occlusion information on the geometric effect by psychophysically measuring perceived slant for each of these stimuli.

Four observers from the first part of experiment 1 viewed stimuli identical to those described above. The only difference was a pair of adjustable test lines, subtending 0.2 X 4.3 degrees, were added above the top image in the stereograms, as depicted in Figure 2.4.

We used a forced choice multiple staircase procedure. Observers were told to imagine the probe lines as though they were fixed like hinges by their inner edges. On a given trial, observers were asked to respond to the following question: "Do the outer edges of the probe lines need to be moved closer or farther from you in order to make the lines parallel to the upper flanking rectangles?" The experiment was self paced and viewing time was unlimited. Observers viewed the stimulus, chose their response, pressed a button on a trackball which extinguished the stimuli. The stimuli were replaced by "+" and "-" symbols. Using the trackball, observers highlighted the "+" to indicate the outer edges of the probe should be moved away from them or the "-" to indicate the outer edges should be moved closer and pressed a button to select their response. The
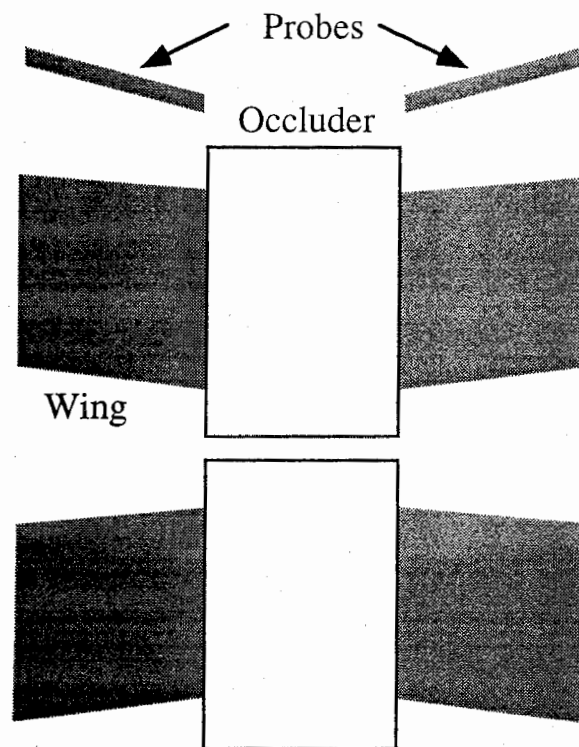
Probes

Occluder

Wing

Figure 2.4. Artistic depiction of the stimulus used for the second part of experiment 1. Perspective is added here to illustrate the possible percepts and was not present, physically, in the stimulus.

first of six staircase reversals was discarded. Two staircases were run for each stimulus (four T-junction conditions X two disparities [crossed and uncrossed]) for a total of 16 staircases. Observers completed four sessions; each containing four randomly interleaved staircases, one for each stimulus type.

Mean slant angles, for each observer, were calculated from a total of 10 reversals over two staircases and are shown in Figure 2.5. The angle of perceived slant is plotted along the *y-axis* and the occluder height is plotted along the *x-axis*. We calculated angle of perceived slant, predicted for the flanking rectangles, using Ogle's (1938) formula. The dashed lines on the graphs indicate the predicted slant from that formula. Positive values indicate the magnitude of perceived slant when the outer edges of the flanking rectangles were seen as nearer than the occluder; negative values represent the magnitude of perceived slant when the outer edges were perceived as farther than the occluder. It is apparent from inspection of the figure that when the outer edge was perceived as nearer than the occluder the magnitude of perceived slant was very close to the predicted value for all four observers across all stimulus types. These results are consistent with observers' reports on the same stimuli in the first part of this experiment. The magnitude of perceived slant when the outer edge was perceived as further than the occluder was in accordance with the predicted value when no occluder was present or when the occluder was shorter than the flanking rectangles for all four observers. For two observers (PG and MS) perceived slant was biased towards a depth step when the outer edges were perceived as farther than the occluder and the occluder was the same height as the flanking rectangles. This was not the case for the other two observers who reported slant for these stimuli that was in accordance with the predicted magnitude. Finally, all four
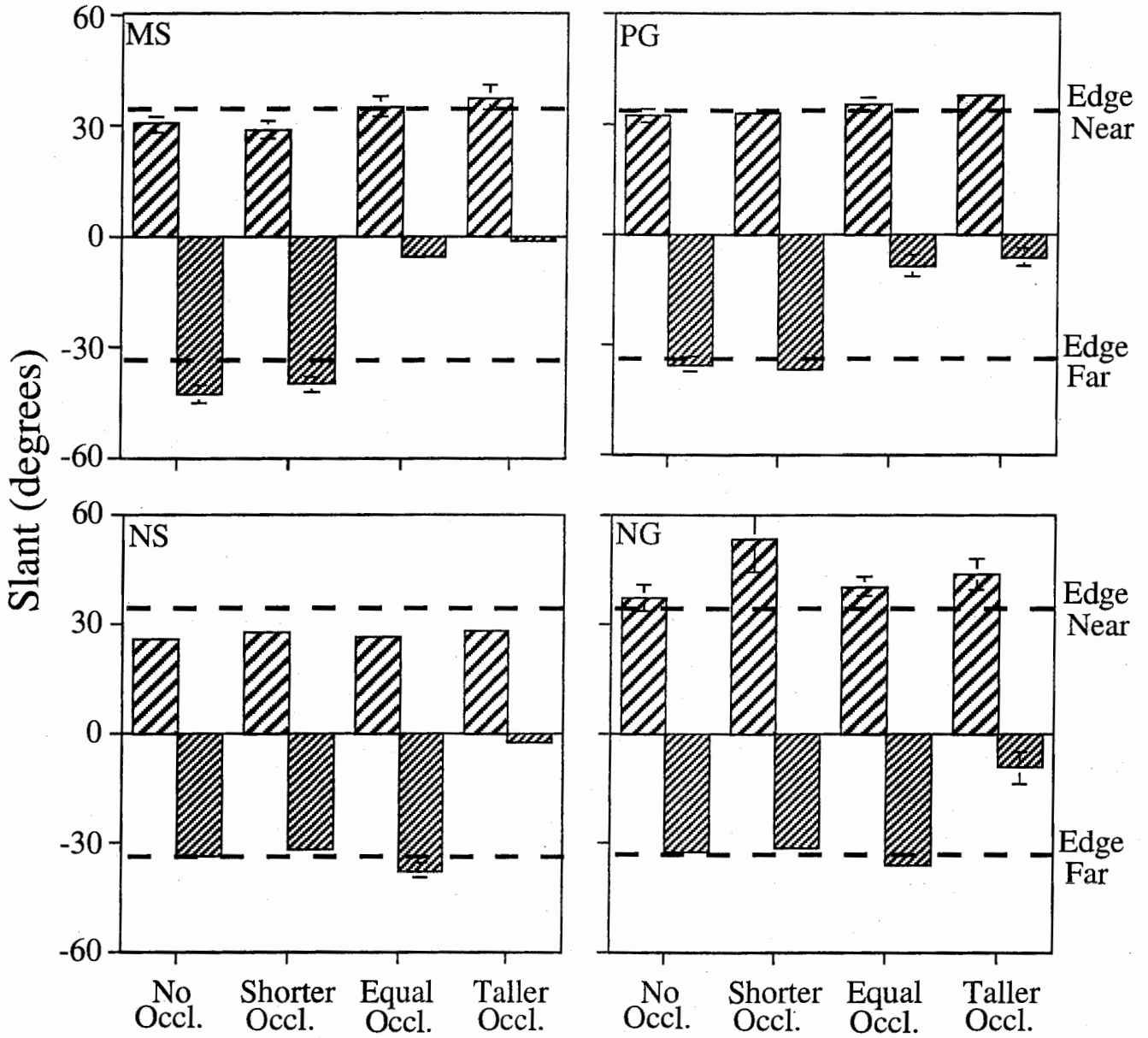
Figure 2.5. Individual mean slant estimates for the four occlusion conditions (No occluder, Shorter occluder, Equal occluder, Taller occluder) and two disparity values. Error bars indicate +/- 1 SEM.

observers slant estimates were biased towards a depth step when the outer edges were perceived as farther away than the occluder and the occluder was taller than the flanking rectangles.

2.3 Experiment 2

Many observers in experiment 1 reported that the flanking rectangles were distorted when they were perceived as slanting towards or away from them. Little or no distortion was observed when the flanking rectangles were part of a global depth step percept. The purpose of this experiment was to explore this distortion systematically. As we will argue in the general discussion, perspective information may combine with the T-junction information present in these stimuli to bias observers percepts towards a depth step.

2.3.1 Method

2.3.1.1 Observers. Four observers from ATR-HIP laboratories participated. All were experienced in psychophysical experiments. All but PG were naïve as to the purpose of the experiment.

2.3.1.2 Apparatus. Same as experiment 1.

2.3.1.3 Stimuli. We used only the stimulus with the central rectangle that was taller than the flanking rectangles. As in experiment 1, disparity was the difference in horizontal extent (7%) of the left and right eye's images of the flanking rectangles. To measure the vertical visual direction of the outer corners of the flanking rectangles, we employed two probes which could move vertically. These probes consisted of two cross hair targets, located adjacent to the outer corners of the flanking rectangles. The cross hairs of the probes subtended 2.5 X 60 min arc and the circle portions subtended 41 min arc. The

probes were randomly positioned at the outer edge of one of the four flanking rectangles
on any given trial.

2.3.1.4 Procedure. Observers sat in a dark room with their chin in a chin rest. Two
computer monitors provided the only ambient light. We used a forced choice method of
constant stimuli in this experiment. Observers viewed the stimuli as they did in the
previous experiment except this time they were instructed to judge whether the vertical
interval between the horizontal lines of the cross hair probes was larger or smaller that
the length of the outer vertical edge of the flanking rectangle. Observers were also
instructed to report whether they perceived the flanking rectangles as slanted or as part of
a depth step. Observers were allowed to move their eyes around the entire stimulus but
were instructed to fixate on one of the cross hair probes when making their visual
direction judgements. A schematic illustration of the stimulus sequence is shown in
Figure 2.6. The cross hair probes were presented with one of eight separations. The
smallest separation between the probes was 9.8 arc min smaller than the length of the
outer vertical edge of the flanking rectangles. The largest separation between the probes
was 9.8 arc min larger than the length of the outer vertical edge of the flanking
rectangles. Observers made five judgements for each of the flanking rectangles and each
probe separation. Data was collapsed across equivalent conditions for a total of 20
responses at each probe eccentricity and disparity value.

Additionally, a zero disparity control condition was employed. In this condition,
the entire stimulus appeared as a flat 2-D image with no detectable distortions. Observers
made vertical visual direction judgements for this stimulus in the same manner as they
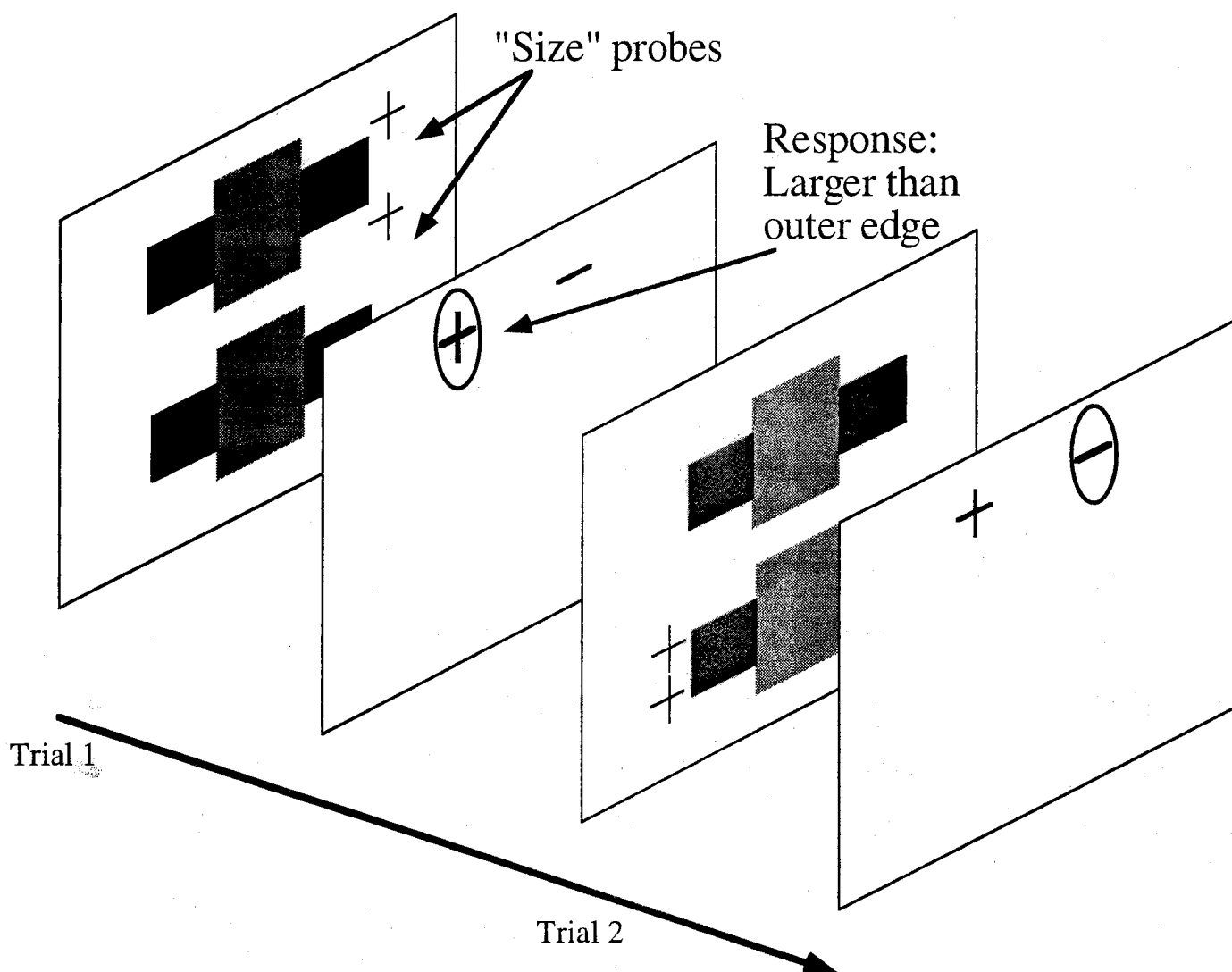
Figure 2.6. Stimulus used in experiment 2 with cross hair probes to measure the vertical extent of the outer vertical edges of the flanking rectangles. See text for details.

did for the test stimuli. All stimuli were interleaved randomly. Observers completed the trials at a self paced rate and took breaks at their own discretion.

2.3.2 Results

Vertical visual direction estimates for each observer are shown in Figure 2.7. The difference in vertical extent between the edge of the flanking rectangles and the interval between the probes, in min arc, is plotted along the *x-axis*. The percentage of "larger than" responses is plotted on the *y-axis*. Positive values indicate that the outer edges of the flanking rectangles were perceived as larger than the objective vertical extent of the stimuli. Negative values indicate that the outer edges were seen as smaller than the objective vertical extent. All four observers' underestimated the vertical extent of the outer edge of the flanking rectangles when they were seen as slanting with the outer edges nearer than the stimulus plane. Observers' errors were markedly reduced, however, when the outer edges of the flanking rectangles were seen as far and a depth step was perceived. As can be seen in the figure, observers' estimates of the vertical size of the far outer edges were nearly equal to the zero disparity estimates. This indicates that virtually no distortion was observed in the depth step percept.

This lack of distortion when a depth step is perceived suggests that other cues are consistent with a frontoparallel occlusion solution, such as linear perspective. With several sources of information present, the visual system takes all of them into account and creates a perceptual solution based on a generic viewpoint, all available information and how it corresponds to past experience (Nakayama and Shimojo, 1992; Koenderink, 1990; Helmholtz, 1910) when viewing these stimuli. This issue is addressed in section 5.
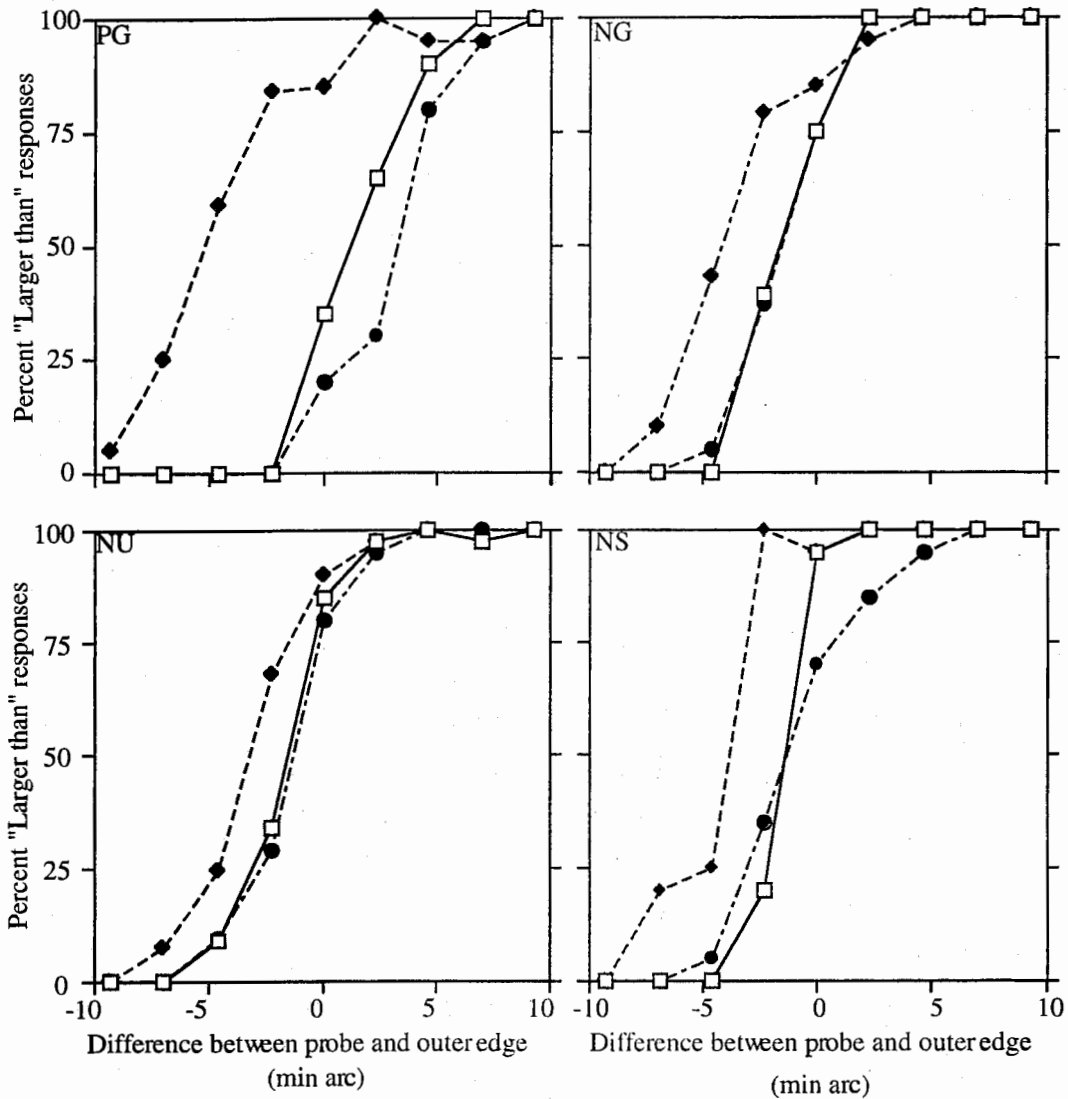
Figure 2.7. Plots showing the percent "Larger than" response for probes with separations within the range of +/- 9.86 arcmin of the objective height of the outer edge of the flanking rectangles, presented with zero, crossed, and uncrossed dispairty.

2.4 Experiment 3

To ascertain the specific location of a point in space, the visual system estimates

its distance and direction from some reference point, such as the cyclopean eye. While

the literature on binocular vision is replete with studies investigating how the visual

system recovers the relative distances of objects from two retinal images (this was the

goal of experiments 1 and 2), comparatively few studies have investigated how the visual

system estimates the relative directions of features. Moreover, these visual direction

studies have largely restricted their scope to a few isolated dots.

Wells-Hering's laws of visual direction have been thought, until recently, to

account for perceived location of discreet objects in space. That is, objects projecting

images onto corresponding points in the two eyes were perceived in their veridical

locations. Ono and Mapp (1995) discuss how veridical locations could be obtained from

the mean of monocular local signs for point stimuli with small disparities. Recently, van

Ee et al. (1999) showed that Wells-Hering's laws predict perceived visual direction of an

eccentrically positioned monocular feature, with an occluder present or not. With

fixation on a near occluder, the portion of a vertical line to the left of fixation, occluded

to the right eye but seen by the left eye, is perceived to be further to the left than the

binocularly visible portions of the same line above and below the occluder. It is not yet

clear what the visual direction judgement of a binocular feature adjacent to the monocular

feature would be, however, for it is not known how the visual system localizes surface

features, such as the edges, when they are perceived in depth. Therefore, we ask how the

displacement of monocularly seen features in the stimuli employed in experiment 1 affect

the visual direction judgements of more eccentric binocular features, such as the outer edges of the flanking rectangles.

Recall from experiment 1, when the outer edges of the flanking rectangles were perceived further than the occluder, the global percept was either slant or a depth step, depending on the polarity of the T-junction information. Let us consider an extreme case where the flanking rectangle is slanted to the point where it is collinear with the cyclopean line sight, as illustrated in Figure 2.8a. Viewing the scene from a single camera/eye positioned midway between the eyes, the flanking rectangle would not be included in perception. It is apparent, however, from Figure 2.8a that the right eye's view contains the flanking rectangle and must be represented in the cyclopean view. To do this the visual system displaces the outer edge of the flanking rectangle (d) and, to a lesser extent, the intermediate areas between its outer and inner edges outward in order to include the surface in perception. Although the magnitude of perceived slant reported in experiment 1 is much less than the limiting case just described, we speculate that the perceptual displacement of the areas on the flanking rectangles continue to be displaced outward when these areas are beyond the plane of fixation.

This situation where the outer edges of the flanking rectangles, perceived as frontoparallel, might be perceptually displaced outward is illustrated in Figure 2.8b. This is very similar to the stimulus used by Ono et al. (1998) and is illustrated in Mapp and Ono (1999). In this case a region on the occluded surface adjacent to the occluder is seen monocularly. According to Wells-Hering's laws the visual direction of this feature is transferred, unaltered, to the cyclopean eye and is therefore displaced outward. As a result, more eccentric features, such as points on the occluded surface (the flanking
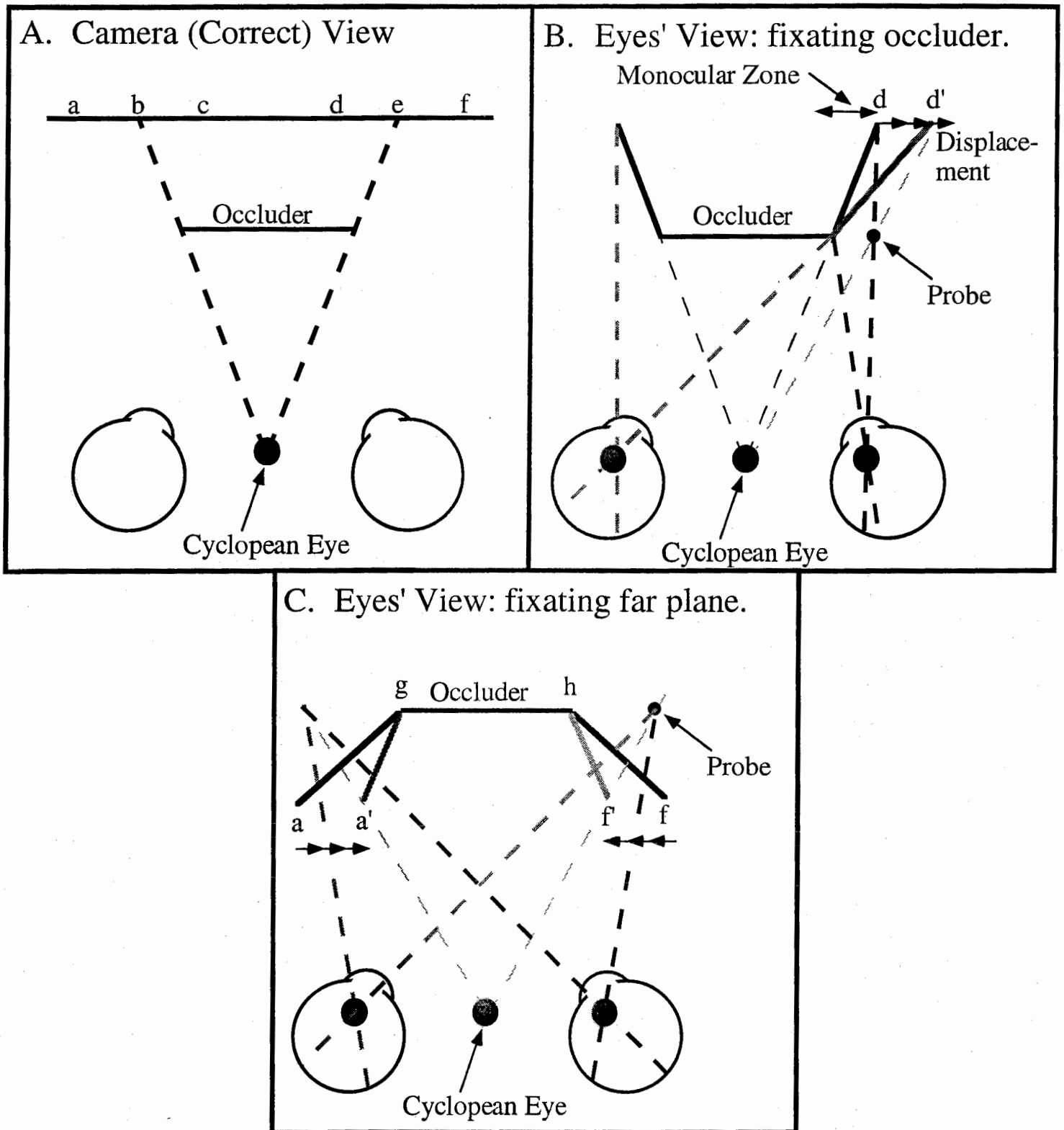
Figure 2.8. Illustration of the putative perceptual displacements executed by the visual system to maximize the number of features included in the cyclopean view. (A) Features seen from a camera view midway between the eyes. (B) Perceptual displacement of features on the backward slanted flanking rectangles when fixation is on the near plane. (C) Perceptual displacements of the outer edges of the near flanking rectangles when fixation is in the plane of the central rectangle. See text for details.

rectangles in our experiments) must also be perceptually displaced outward. Consequently, the outer edge of the flanking rectangle in our stimuli may be perceived in a more eccentric location than predicted from the average of the monocular local signs.

This experiment measured the visual direction of the outer edges of the flanking rectangles in our stimuli to determine how their perceived location is affected by the displacement of monocularly seen features. Ono and Mapp's (1995) analysis, states that the visual direction of the outer edge of the flanking rectangles, being a binocular feature, is equal to the mean of the visual lines at each eye. Another possibility is that the visual system displaces perceived visual space on the non-fixated plane to fit all monocularly visible features into the cyclopean percept (Mapp and Ono, 1999)[4]. As we stated above, it is possible that the visual system's estimates of visual direction of discrete points differ from features belonging to surfaces that occlude one another. Therefore, we employed two stimulus conditions, the test condition where one surface partially occludes another, and a control condition where a binocular rectangle is flanked by isolated binocular lines.

2.4.1 Method

2.4.1.1 Observers. Three observers (NG, SN, PG) from experiment 2.

2.4.1.2 Apparatus. Same as experiment 1.

2.4.1.3 Stimuli. This experiment employed two conditions, test and control, each with unique stimuli. The test condition contained the rectangular stimuli, which were the same as the previous two experiments. The probes used to measure visual direction were

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[4]Mapp and Ono (1999) illustrate that monocularly seen features are displaced away from the occluding edge to be included in perception. In the stimuli employed in this study, monocular features are displaced outward (away from the median plane). If a surface is viewed through, and located a short distance behind, an aperture, monocularly seen features seen by the right eye are displaced to the right and features seen by the left eye are displaced to the left. Necessarily, perceptual space visible through the aperture is

unique to this experiment, however. These probes consisted of two cross hair targets, one located above and below the outer corners of the flanking rectangles. The cross hairs of the probes subtended 2.5 X 60 min arc and the circle portions subtended 41 min arc. An example of what observers saw in this experiment is illustrated in Figure 2.9. The probes were randomly positioned at the outer edge of one of the four flanking rectangles on any given trial. In order to ensure that both the outer edge of the flanking rectangles and the visual direction probes were stereoscopically fused, we reduced the magnitude of disparity to 9 min arc, within Panum's (1858) fusional range (Howard and Rogers, 1995).

The control stimuli consisted of the large central rectangle and four vertical lines (0.32 X 6.4 degrees), each positioned in the same location as the outer edge of the flanking rectangles used in the previous two experiments. These flanking lines were presented such that the top two lines had uncrossed disparity (9 min arc) and the bottom two had crossed disparity, or vice versa on a given trial. To minimize diplopia, the visual direction probes were modified for the control condition such that the cross hairs matched the width of the flanking lines.

2.4.1.4.1 Test Procedure. We used a forced choice method of constant stimuli in this experiment. Observers viewed the stimuli as they did in the previous two experiments except this time they were instructed to judge whether the vertical line of the cross hair probe was located to the left or the right of the outer vertical edge of the flanking rectangle. Observers were also instructed to report whether they perceived the flanking rectangles as slanted or as part of a depth step. Observers were allowed to move their eyes around the entire stimulus but were instructed to fixate on one of the cross hair

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compressed as well as displaced. Compression of perceptual space is outside the scope of this paper,
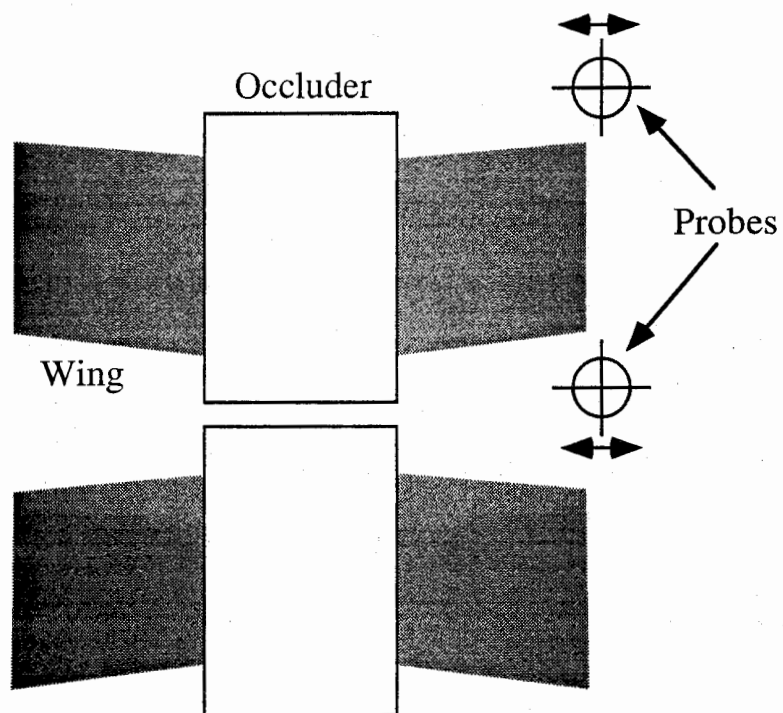
Figure 2.9. Stimulus used to measure visual direction in experiment 3. See text for details.

probes when making their visual direction judgements. Therefore, observers fixated in the plane of the central occluder for all visual direction judgements. The cross hair probe was positioned at one of seven eccentricities. The position closest to the median plane was objectively collinear with the outer edge of the smaller of the two eye's images of the flanking rectangle. The position furthest from the median plane was objectively collinear with the outer edge of the larger of the two eye's images. Observers made five judgements for each of the flanking rectangles and each probe eccentricity. Data was collapsed across equivalent conditions for a total of 20 responses at each probe eccentricity and disparity value.

2.4.1.4.2 Control procedure. This procedure was similar to the test procedure except observers were to judge whether the vertical line of the cross hair probe was to the left or right of the line positioned in the same location as the outer edge of the flanking rectangle. Note that only the lines and the central rectangle were present in the control stimuli, the flanking rectangles were not present. Observers were also instructed to report whether they perceived the flanking lines as closer or farther than the cross hair probe. Again, observers were allowed to move their eyes around the entire stimulus but were instructed to maintain fixation on one of the cross hair probes during visual direction judgements. Probe locations were the same as for the test stimulus. Data was collapsed across equivalent conditions to obtain a total of 20 observations at each probe location for crossed and uncrossed disparity.

2.4.2 Results

We conducted Probit analysis (Finney, 1971) to determine the mean visual direction estimates of the outer edges of the flanking rectangles and the control lines for

each observer. A two factor analysis of variance, with one repeated measure (5 occluder/control conditions X 2 disparities), revealed a significant effect for disparity, $F(1,2)=58.44$, $p<0.05$ on visual direction estimates and a significant interaction between disparity and occluder conditions, $F(4,8)=42.81$, $p<0.01$. Newman Keuls post hoc tests revealed that visual direction estimates of the outer edges of the flanking rectangles were significantly more eccentric than those of the control stimuli when both were perceived to be further, in depth, than the stimulus plane, $p<0.01$. Moreover, visual direction estimates for the outer edges of the flanking rectangles were significantly less eccentric than those of the control stimuli when both were perceived to be closer, in depth, than the stimulus plane, $p<0.01$.

Probe locations, in min arc, are plotted against the percentage of trials observers judged the probe to be further from the median plane than the outer edge of the flanking rectangles (test stimuli) or the flanking vertical lines (control stimuli) in Figure 2.10[5]. The left column of graphs represents data for which the outer edge of the rectangles, or the flanking vertical lines, appeared further in depth than the probe. The right hand column represents data for which the outer edge of the rectangles, or the flanking vertical lines, appeared closer in depth than the probe. The dashed vertical line in each graph intersects the *x-axis* at the predicted visual direction value if perceived visual direction is the mean of the monocular visual lines, or half the angular disparity (4.48 min arc).

For all observers, the probe settings for the control stimuli more closely approximated the visual direction value predicted from the mean of the monocular lines for both crossed and uncrossed disparities. When the outer edges of the flanking

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[5] The raw data proved to be more illustrative than the Probit plots and are, therefore, illustrated here.
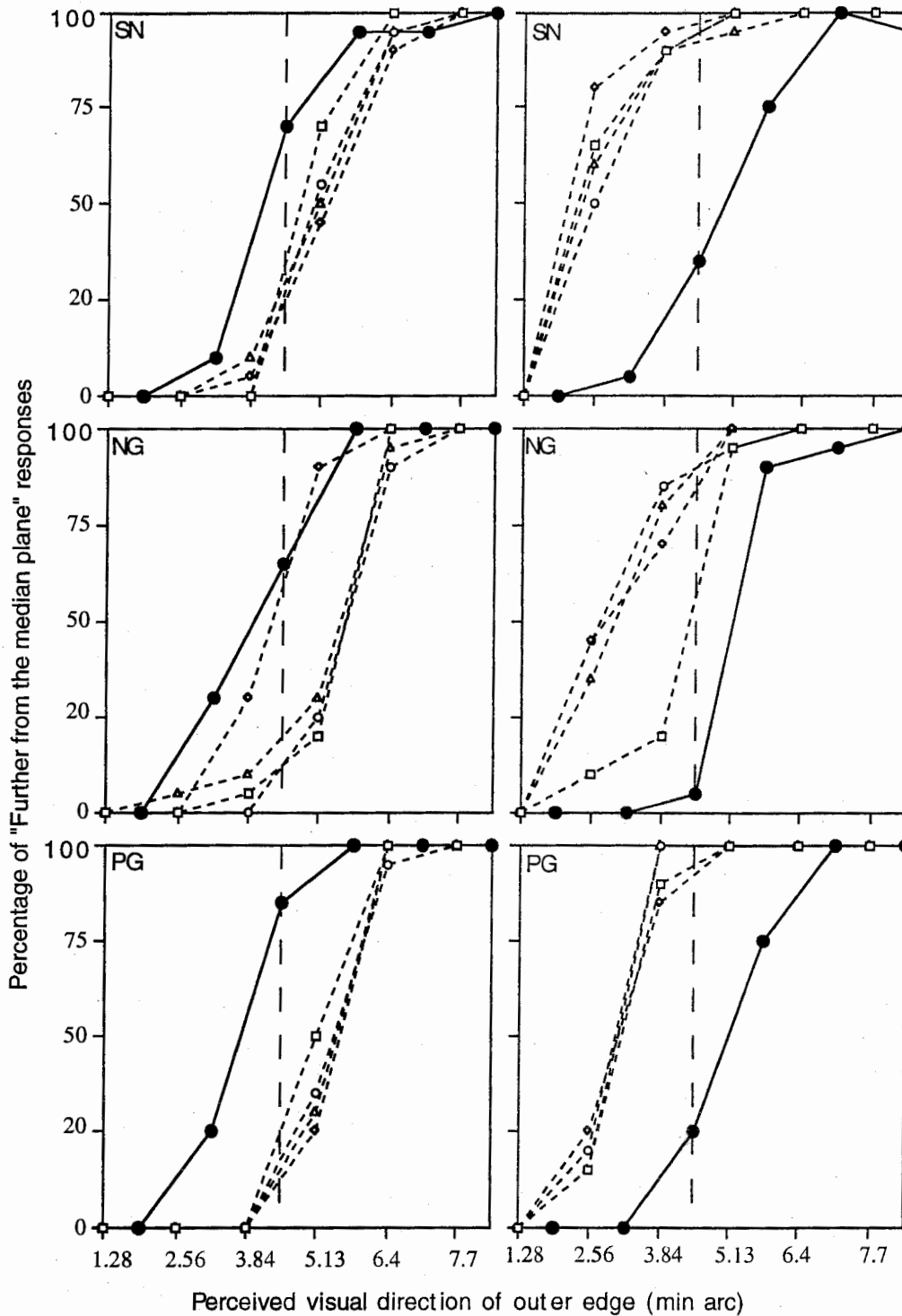
Figure 2.10. Psychometric functions for the three observers in experiment 3. Percentage of responses observers judged the probe to be further from the median plane than the outer edge of the flanking rectangles is plotted along the *y-axis*. Visual direction, in min arc, is plotted along the *x-axis*. Visual direction values are relative to the outer edge of the image of the smaller of the two eye's images of the flanking rectangles. A value of zero would be collinear with the outer edge of the smaller image. Larger values indicate visual directions further from the median plane. The vertical dotted line indicates the mean of monocular visual lines. Visual direction judgements, when the outer edge was perceived as further than the occluder, are shown in the left hand column. Visual direction judgements, when the outer edge was perceived as closer than the occluder, are shown in the right hand column. Open squares indicate judgements for the taller occluder condition; open circles for the same height condition; open triangles for the shorter occluder condition; open diamonds for the no occluder condition; closed circles for the control condition. See text for details.

rectangles were perceived as further than the probe and central rectangle, all observers' visual direction judgements of the outer edges were more eccentric than predicted from the mean of the two visual lines. Moreover, all observers judged these features to be more eccentric than the control stimuli with the same disparity. This is indicated by the shift to the right of the psychometric functions for direction judgements of the edges of the flanking rectangles relative to the predicted value and the control data.

When the outer edges of the rectangles were perceived as closer than the probes and central rectangle, the visual directions of these features were judged to be less eccentric than predicted from the mean of monocular lines for all observers. Moreover, these visual direction judgements were less eccentric than the control stimuli with the same disparity. This is indicated by the shift to the left of the psychometric functions for visual direction judgements of the edges of the flanking rectangles relative to the predicted value and the control data. As we argue below, however, the perceptual displacement of surface features is consistent with our idea that the visual system displaces perceptual space to include all monocularly seen features in perception. The visual directions of isolated features (the control stimuli in this experiment), on the other hand, agree most closely with the predictions of law 3c of Ono and Mapp (1995).

2.5 Discussion

2.5.1 Occlusion and the bias of perceived slant towards a depth step.

The data from experiments 1 and 2 clearly show that occlusion information in the form of T-junctions or the presence of a subjective occluder biases perceived slant towards a depth step in stereograms containing ambiguous disparity information. Together the results of both parts of experiment 1 and those of experiment 2 support the report of

Hakkinen and Nyman (1997) that a possible occlusion interpretation in a stereogram can bias the percept of slant towards a depth step. Hakkinen and Nyman argue that a common boarder or near common boarder is sufficient for the reduction of perceived slant. They report that the magnitude of perceived slant increases incrementally with increasing separation between the flanking rectangle and the occluder. Here we have expanded on this finding and shown that the two objects may continue to share a common boarder, and perceived slant can be biased by changing the polarity of the T-junction information. Moreover, our results show that this bias is an all or none phenomenon. When the T-junction information was interpreted to indicate the central rectangle was in front of the flanking rectangles and the outer edges of the flanking rectangles were perceived behind the stimulus plane, the percepts were biased completely to a depth step. If T-junction information was inconsistent with a near central occluder, the magnitude of perceived slant was in accordance with Ogle's (1938) predictions.

In addition to luminance defined occlusion cues, we have also shown in another experiment that the presence of a subjective occluder can also bias perceived slant towards a depth step. In this stimulus situation, the retinal images of the flanking rectangles were completely consistent with perceived slant of the same magnitude predicted by Ogle (1938), yet the subjective impression of an occluder completely biased the perception of slant to a depth step in four out of five observers. As we mentioned above, monocular features (Lawson and Mount, 1967; Lawson et al., 1974; Nakayama and Shimojo, 1990) and points with uncrossed disparity can enhance the sharpness of a subjective contour (Takeichi et al., 1992). This experiment shows that subjective

contours can themselves bias the percept of disparate images, where simulated slant is perceived as a step.

The bias of perceived slant towards a depth step even in the presence of a subjective occluder suggests that more information may be present that supports a frontal plane solution. In all the stimuli reported here, the perspective information was most consistent with a frontal plane interpretation and represents a better 'generic view' (Nakayama and Shimojo, 1992; Koenderink, 1990) in that the images of frontal plane rectangles would alter less with changes in viewpoint than those of backward slanting rectangles. Likewise, perspective information was consistent with a frontal plane for the flanking rectangles whose outer edges appeared near. However, there was no other visual information to support a percept of a complete gray rectangle floating above the central white occluding rectangle, regardless of its height. The only possible interpretation was that they were slanting forward in depth.

In a related study by Gillam et al. (1999) where two frontal surfaces were perceived as separated in depth when the available disparity information was most consistent with a single slanted surface, the authors posited that the depth described in their experiments may be learned by association. Their stimuli, like ours, were untextured. Under normal conditions the rectangles in their study (and ours) would be covered in texture providing retinal disparity cues to disambiguate the possible step/slant interpretations. Our experience with such objects and the perspective information they contain may bias an observer's interpretation of the stimuli employed here, where disparity is ambiguous, perspective information indicates a frontal surface and there is information present to support a possible occlusion scenario. As Helmholtz (1910/1962)

would argue, the visual system infers a frontal plane/occlusion solution based on its past experience with similar configurations involving textured surfaces.

In experiment 2, we found that observers underestimated the vertical extent of the outer edge when it was perceived as nearer than the stimulus plane. No such error was observed, relative to zero disparity estimates, when the flanking rectangle was perceived behind the occluder and frontoparallel. This perceived shape distortion for the slanted percepts and not for the frontal percepts reflects the conflict between disparity information, indicating a slanted surface, and perspective information, indicating a frontoparallel surface. We conclude, therefore, that perspective information, combined with occlusion cues, contribute to the bias of the global percepts given stimuli with ambiguous disparity information.

2.5.2 Visual direction.

The data from experiment 3 indicate that visual direction estimates of surface features (test stimuli) are different from visual direction estimates of isolated features (control stimuli). Below, we account for these visual direction judgements by applying principles outlined in Mapp and Ono (1999).

Figure 2.8a illustrates what a camera placed at the position of the cyclopean eye would see. A picture taken from this vantage point would include points (a), (b), (e), and (f) only, yet we know, from Leonardo, our experience, and the literature (Erkelens et al., 1996; Ono et al., 1998) that features (c), and (d) are also included in perception. Mapp and Ono (1999) argue that the visual system perceptually displaces features on the far

plane to include monocularly seen features in cyclopean perception[6]. Binocular features located more eccentrically than the monocular zones adjacent to the occluder should be perceived in their veridical locations according to the laws of visual direction. However, to maintain their relative positions with the displaced monocular points in space, these binocular features must also be perceptually displaced outward. Furthermore, a feature to the immediate right of that binocular point will also be perceptually displaced as well as the feature to its immediate right, and so on. This analysis predicts that binocular features, such as the outer edges of the far surface should be perceptually displaced outward when fixation is on the plane of the near surface. The data from experiment 3 are consistent with this analysis, but see footnote 3 as well.

The same principles can be applied to the case were the flanking rectangles appear slanted such that the outer edges are behind the stimulus plane. Assuming that the observer is fixating the right edge of the occluder, in Figure 2.8b, the image of that edge and the slanted flanking rectangle falls on the cyclopean line. Because the edge of the occluder is fixated, it is therefore seen in its veridical location. Additionally, because point (b) is a monocular feature, the angle between the edge of the occluder and (b), in the right eye, is transferred to the cyclopean eye and is perceived as more eccentric than the occluder edge, according to Hering's law (3). This is consistent with the data of experiment 3 which showed that visual direction estimates for the outer edges perceived behind the stimulus plane were more eccentric than either the predicted values or the visual direction estimates for the isolated control stimuli.

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[6] The figure supporting this analysis is published in Mapp and Ono (1999) and is, therefore, not presented here.

Finally, Figure 2.8c illustrates why the outer edges of the flanking rectangles are perceptually displaced inward when the outer edges are perceived as closer to the observer than the occluder and the probes. With fixation on the plane of the occluder, all the features on the flanking rectangles are closer in depth than the fixation plane. Lillakas et al. (1998) showed that edges of an occluder were displaced inward when observers fixated binocular features on the far surface. In experiment 3 the forward slanting rectangle is in front of the fixation plane and, according to our discussion above, features on the near non-fixated plane are displaced inward, from point (f) to (f') on the right side and from (a) to (a') on the left side. Again, this is to include monocularly seen areas on the fixated plane in perception. This perceptual displacement is contingent on the feature (outer edge) belonging to a surface. The control data for an isolated line in depth show that this feature was displaced to a much lesser extent than the outer edge of the flanking rectangle. The perceptual displacement of features seems to be propagated along surfaces to a greater degree than through the empty spaces between objects.

The perceptual inward displacement of the outer edges, with no accompanying change in depth, might be accompanied by an increase in the angle of perceived slant. Only one observer's data in experiment 1, NG, was consistent with this analysis, however. Moreover, the outward displacement of the outer edges, perceived behind the stimulus plane, was not accompanied by a reduction of perceived slant as would be expected from a displacement with no change in depth.

In conclusion, the data from experiment 3 compliment the data and analyses reported by Lillakas et al. (1998), Ono et al. (1998) and Mapp and Ono (1999). That is, when one surface occludes another and the two surfaces are separated by a small depth

interval, the visual system perceptually displaces features on the non-fixated plane to include all features visible to both eyes in it's unified representation of the visual field. The data presented here support these previous reports and generalize them to surfaces in depth, either as part of a global percept containing a depth step or surfaces slanted relative to one another.

2.6 Concluding comments

In recent years there has been a growing tendency to view binocular phenomena more broadly. That is, as a process involving surfaces rather than being concerned with the coding of depth or direction of discreet points. The growing literature on the role of monocular regions in stereopsis and the recent studies expanding on Wells/Hering's laws of visual direction, in the context of surfaces in depth, many of which are cited throughout this paper, is evidence of this. As Gillam et al (1999) point out, these recent developments suggest that 'matching or pairing' might not be the primary process in stereoscopic vision. The data presented in this paper add to this claim. What has traditionally been thought of as a stimulus for the perception of slant has been shown to be susceptible to factors like cues to occlusion. Our data, showing the distortion of perceived shape, underscores the idea that binocular phenomena should be viewed as a process involving surfaces instead of points since a point by point analysis of our stimuli would not predict the percepts reported here. Moreover, we have shown that visual direction estimates are also affected by the configuration of the stimulus. The visual direction of surface features is coded differently than for isolated points. This seems to be true for both frontal surfaces separated in depth or surfaces that slant relative to each other. Indeed, this recent research suggests that point by point considerations in

binocular vision is not only a cumbersome task but may well be irrelevant when considering the complexity of our natural visual environment.

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Chapter 3:

Interocular transfer of the motion aftereffect with

stimuli over 60 degrees in diameter.

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3.1. Introduction

This chapter investigates interocular transfer of the motion aftereffect as a function of stimulus diameter. The question we address is what is the angular extent over which significant interocular transfer of the motion aftereffect can be measured. Our results have implications for previous studies, using static stimuli, which have claimed that the effective binocular field is limited to the central 40 degrees of the visible field.

The human binocular field is approximately 200 degrees wide. Of this 200 degrees, the two eyes can see approximately 120 degrees simultaneously. Previous research has suggested, however, that the actual angular extent of the visual field that is served by binocular cells in the visual cortex is much smaller than 120 degrees. In a binocular rivalry experiment, Fahle (1987) presented observers with orthogonal gratings, one to each eye, and measured the time each eye's grating was seen at different eccentricities. In the central visual field, each eye's image was seen for half of the presentation time. At greater eccentricities, however, one eye's image dominated. At eccentricities greater than +/- 20 degrees one eye's image was seen nearly twice as long as the other eye's image, suggesting a drop off in binocular interaction in the periphery.

Grigsby and Tsou (1994) present data showing that binocular contrast thresholds are lower than monocular contrast thresholds in the central 40 degrees of the visual field. They report that at eccentricities greater than +/-20 degrees from the median plane binocular thresholds were not appreciably lower than monocular thresholds, suggesting that binocular neurons receive little input from the far periphery. Their data for flicker sensitivity show that binocular performance is superior to monocular performance at all eccentricities tested, however.

Based on these reports, one might conclude that the effective binocular field, the angular extent of the visual field supporting binocular interaction, is limited to just 40 degrees. Here we argue that, although this may be true for the stimuli for which these measurements were taken, the spatial extent of binocular interaction is likely stimulus dependent. This is evident in Grigby and Tsou's (1994) report, where the effects of eccentricity were different for static gratings and for flickering stimuli. It is well known that the peripheral retina is more sensitive to motion and other temporally modulated stimuli, like flickering lights, than to static form. For example, a wiggling finger in the extreme visual periphery can be identified, but becomes invisible when it stops moving (Anstis, 1987). Therefore, the restriction of the binocular field to the central 40 degrees may be specific to static stimuli. The question of how far into the periphery binocular interaction exists as measured with dynamic stimuli remains unanswered.

Another useful measure of binocularity is the interocular transfer of aftereffects. Of interest to us is the motion aftereffect (MAE) (see Wade, 1994 for an historical review). The MAE is characterized by apparent motion of a static stimulus that is in the opposite direction of previously inspected motion (Wohlgemuth, 1911). Interocular

transfer is characterized by apparent motion of a monocularly viewed static stimulus that is in the opposite direction of previously inspected motion presented to the contralateral eye. Interocular transfer is a valuable psychophysical tool because it can isolate neural mechanisms that are in some sense exclusively binocular (Blake et al., 1981). Interocular transfer experiments do not exclusively tap binocular neurons, however. It is a general feature of this paradigm that the transferred aftereffect is somewhat diminished in comparison to same eye adapt/test paradigms. To account for this asymmetry, a model has been proposed which contains two classes of visual cells: monocular neurons which can be activated by input from one eye or the other, and binocular neurons which can be activated through either eye. This is represented as a Venn diagram in Figure 3.1. Consider adapting one eye to leftward motion, for example, and rightward motion is perceived when a static stimulus is viewed with the left eye. According to this model, the transferred aftereffect is due to adaptation of the binocular neurons. The fact that the transferred aftereffect is smaller than aftereffects measured in the same eye as was adapted can be understood by referring to Figure 3.1. If the same eye is adapted and tested, the monocular and binocular neurons that were stimulated during adaptation are also involved during the test phase. Therefore, 100% of the neurons involved in the adaptation phase are also involved in the test phase, resulting in a maximal aftereffect. If, however, the unadapted contralateral eye is tested, a smaller aftereffect is predicted because a smaller percentage of the adapted neurons are involved in the test phase. Considering Figure 3.1, the monocular neurons involved during the test phase are not stimulated during adaptation and would still accurately signal zero motion in a stationary test stimulus. The binocular neurons have been adapted, however, and will yield an
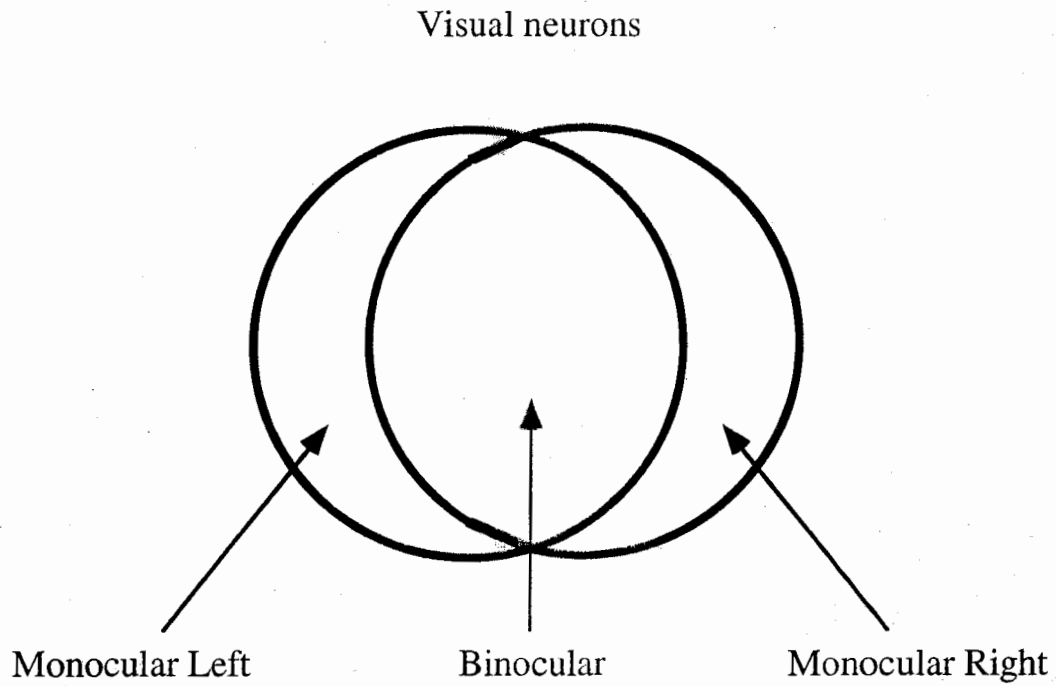
Figure 3.1. Venn diagram depicting two classes of visual neurons: monocular neurons, which can be activated only through one eye or the other, and binocular neurons, which can be activated through either eye.

aftereffect. The resulting MAE magnitude is only a fraction of the same eye adapt/test condition because different populations of neurons are recruited during adaptation and test, respectively.

According to this model, interocular transfer of aftereffects is evidence that at least some neurons sensitive to the stimulus modality (i.e. orientation, color, motion, etc) receive binocular input. This is indicated graphically by the overlap of the two circles in the Venn diagram of Figure 3.1. This assumption has formed the basis of several investigations measuring interocular transfer of aftereffects in normals and groups with known binocular deficits (for example, stereoblind strabismics, amblyopes). Movshon et al. (1972) measured interocular transfer of the tilt aftereffect in normals, strabismic stereoblind, and non-strabismic stereoblind observers. The magnitude of interocular transfer of the tilt aftereffect, as measured by perceived tilt of an objectively vertical test stimulus, was greatest in the normals, followed by the non-strabismic stereoblind, and then the strabismic stereoblind observers, who reported markedly reduced aftereffects relative to the normals.

Wade (1976) measured interocular transfer of the MAE in observers with normal stereopsis and those lacking stereopsis as a result of uncorrected strabismus. He inferred binocular interaction from the presence of measurable interocular transfer of the motion aftereffect and reported reduced interocular transfer in observers with childhood strabismus relative to normals. Wade identified the direction of deviation (eso or exo) in childhood strabismus as a possible factor determining the extent to which binocularity survives in these patients. Mohn and van Hof-van Duin (1983) could also discriminate between participants with normal stereopsis and those with stereo-deficiencies based on

their interocular transfer data (for a more comprehensive review of this literature, see Wade et al., 1993; Wade, 1994).

The above studies measured interocular transfer of aftereffects with the stimuli located in the central visual field. Interocular transfer proved to correlate well with known binocular function of the clinical and normal observers. Of issue in this report is whether binocular function extends into the periphery of the visual field as measured by interocular transfer of the MAE. Therefore, we compared the duration of monocular adapt/test and interocular transfer of the motion aftereffect as a function of stimulus diameter to determine the spatial extent of binocular interaction in the human visual field.

3.2 Experiment

3.2.1 Method

3.2.1.1 Observers.

Three observers participated, the first author and two naïve observers. All had normal binocular vision and were experienced in psychophysical experiments.

3.2.1.2 Apparatus and stimuli.

Stimuli were generated on a Macintosh power PC and projected on a polarized rear projection screen, subtending 100 degrees horizontally and 70 degrees vertically at a 100cm viewing distance. Two projectors, one for each eye's image, were fitted with orthogonally oriented polarizing filters. A complimentary pair of polarizing filters was placed in front of the observer's eyes. Observers sat with their heads fixed in a chin and forehead rest 100 cm in front of the display. Their responses were recorded via a computer keyboard.

Stimuli, illustrated in Figure 3.2, consisted of two 90 degree portions of a circular ring containing a radial luminance defined grating, eight cycles/360 degrees presented at 15% Michelson contrast. These gratings were presented on a uniform gray background with a luminance value equal to the mean luminance of the stimuli. Mean luminances of the right and left eye's images were 14.15 cd/m^2 and 17.41 cd/m^2, respectively. The inner diameter of the ring was 5, 30 or 62 degrees. The number of cycles per 360 degrees of the radial grating did not change with the diameter. Therefore, the stimulus was scaled, approximately linearly, with diameter. The grating was viewed as though through two windows made up of 90 degree portions of a circle. Therefore, the portion of the grating on the right of the display drifted downwards for clockwise rotation while the left portion drifted upwards. The opposite was true for counterclockwise rotation.

The adaptation stimulus rotated either clockwise or counterclockwise at 4 Hz. That is, four complete luminance cycles passed a given point on the circumference of the radial grating per second. The test stimulus was stationary.

3.1.2.3 Procedure.

In each trial, the adaptation stimulus was presented for 1 minute and was immediately followed by a 30 second test phase. The duration of illusory motion, perceived during the test phase, was measured to evaluate the strength of the MAE. Observers maintained their gaze at a central fixation point during adaptation and test phases of each trial. During the test phase, observers examined a static grating and pressed one of two buttons indicating the direction and duration of perceived rotation, the left button for counterclockwise and right for clockwise apparent rotation. Observers were instructed to continuously report the perceived direction by pressing buttons during
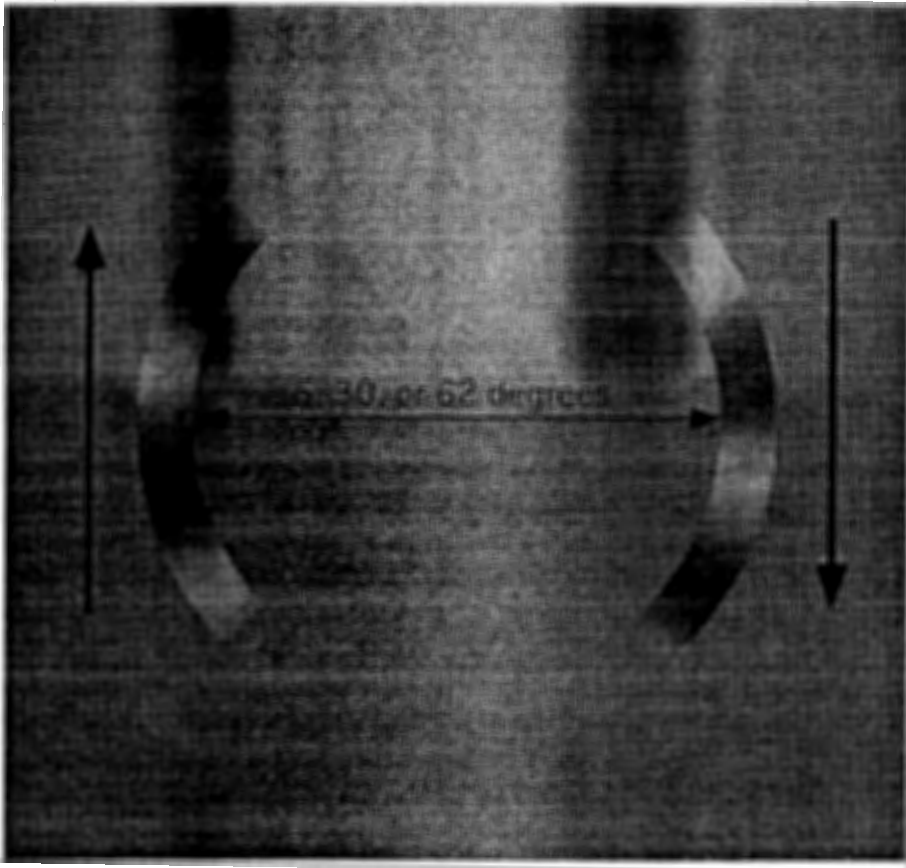
Figure 3.2. Experimental stimuli: Inner diameter was 5, 30, or 62 degrees. See text for details.

the test periods. The buttons were not to be pressed when the observer perceived no motion. The sampling rate of the button press was 66.7 Hz. Observers rested for at least one minute between each trial.

In all trials adaptation was monocular. In the same eye presentation/test condition, both the adaptation and test stimuli were presented to either the left or right eye only. In the interocular transfer condition, the adaptation stimulus was presented to one eye, and the test stimulus was presented to the contralateral eye.

One experimental block consisted of 16 trials: two monocular conditions (left and right eyes) and two interocular transfer conditions (right to left and left to right) X two directions of adaptation motion (clockwise and counterclockwise) X two observations of each condition. These conditions were randomized within each block. A single block was completed for each of the three diameter conditions. Blocks for each of the diameter conditions were carried out in random order across observers. Observers completed three blocks, one for each diameter.

3.2.2 Results.

MAE durations for both monocular and interocular transfer conditions as a function of stimulus diameter are plotted for each observer in Figure 3.3. The data from different eyes in the monocular adapt/test condition, or the eye order in the interocular transfer condition, and the direction of adaptation motion were collapsed. Thus each point presented in the figure represents the mean of 8 observations. Observers reported the longest MAE durations for the monocular adapt/test condition and the smallest diameter of 5 degrees. MAE durations in this condition dropped off at stimulus diameters of 30 and 62 degrees. Longest MAE durations for the interocular transfer
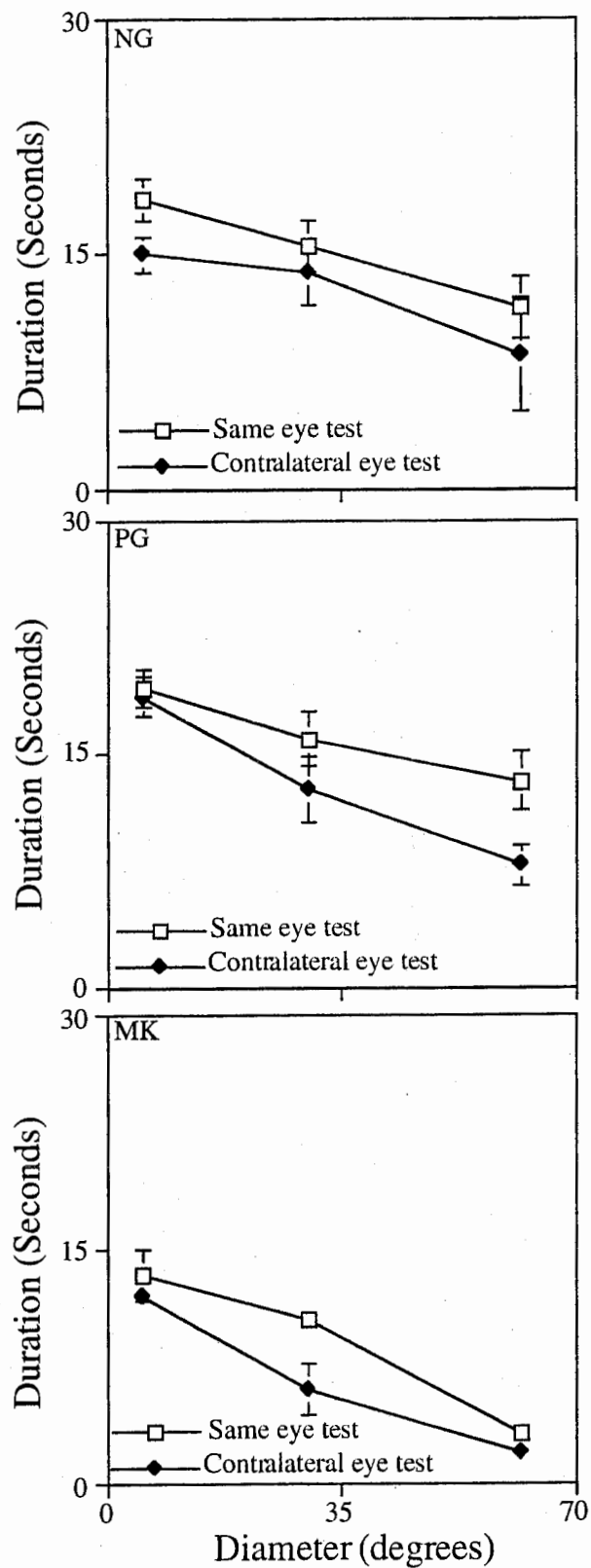
Figure 3.3. Individual data plots, +/- SEM, for the three observers. Each point represents the mean of eight observations. Open squares represent MAE durations for the monocular adap/test condition. Filled diamonds represent MAE durations for the interocular transfer condition.

were also reported for the smallest diameter condition of 5 degrees. MAE durations in this condition diminished at diameters of 30 and 62 degrees.

Interocular transfer MAE durations in the 5 degree diameter condition were over 80% of the monocular adapt/test durations for all three observers (NG=81%, MK=90%, PG=97%). For the diameter of 30 degrees, interocular transfer MAE durations were a smaller percentage of the monocular adapt/test durations (NG=89%, MK=57%, PG=79%) for two of the three observers. For the diameter of 62 degrees, interocular transfer MAE durations were lower still (NG=74%, MK=59%, PG=59%). Despite the diminishing interocular transfer MAE with stimulus diameter, expressed as a percentage of the monocular adapt/test MAE, there was no interaction between transfer conditions and stimulus diameter. Individual analysis revealed a significant effect for transfer (monocular or interocular), for observers MK and NG [MK, $F(1, 7)=14.783$, $p<0.05$; NG, $F(1, 7)=5.962$, $p<0.05$]. A significant effect for diameter was observed in observers PG and MK [PG, $F(2, 14)=14.067$, $p<0.001$; MK, $F(2, 14)=47.9$, $p<0.001$]. Yet there was no significant interaction between stimulus diameter and transfer conditions [PG, $F(2, 14)=1.02$, $p=0.39$; MK, $F(2, 14)=1.03$, $p=0.39$; NG, $F(2, 14)=0.162$, $p=0.85$]. There is certainly a drop off in MAE duration as the diameter of the stimulus increased. This drop off was not significantly different for monocular adapt/test and interocular transfer conditions, however.

3.3 General Discussion

If interocular transfer of the motion aftereffect, defined as a significant proportion monocular adapt/test aftereffects, is taken to indicate the presence of binocular interaction, the data presented here suggest that binocular interaction extends well into

the periphery. While an overall effect of stimulus diameter was observed where MAE durations in both monocular and contralateral test conditions, there was no significant interaction between diameter and transfer conditions. It appears that lager stimulus diameters reduced MAE durations in the same eye and contralateral eye conditions equally. Wohlgemuth (1911) reported the attenuating effect of eccentricity on MAE duration. He reported that the MAE in the far periphery is seen as a compelling but fleeting impression of motion opposite in direction of the adapting motion. Clearly, observers in this study saw the same phenomenon. MAE durations were significantly shorter in the far periphery for two of the three observers. Nevertheless, MAE durations in the interocular condition were a substantial fraction of the monocular MAE at all stimulus diameters tested.

van de Grind et al. (1994) measured MAE durations as a function of retinal velocity and stimulus eccentricity. Their data correspond nicely with our monocular adapt/test data. That is, MAE durations decreased with increasing eccentricity such that at 48 degrees eccentricity, MAE durations were approximately half of those measured in central vision. Our data show a similar trend, though we limited our measurements to a diameter 62 degrees. Moreover, the specific MAE durations reported by observers in this study are compatible with those reported by van de Grind et al. MAE durations measured in the far periphery in van de Grind et al.'s study were as low as three seconds. Caution is necessary in this comparison, however, as they investigated linear motion, while our stimuli depicted rotary motion. Nevertheless, this comparison is meant to illustrate the reasonableness of our data.

In a review of 23 studies on interocular transfer of the MAE, Wade et al. (1993) ascertained the mean interocular MAE magnitude, expressed as a percentage of the monocular MAE. Calculating the mean across several different types of stimuli and methods of measurement, the authors came up with a grand mean of 51%, considerably lower than the accepted value of 60-70%. We plotted interocular transfer durations, expressed as a percentage of the monocular durations and found that all three observers' interocular transfer percentages exceeded Wade et al.'s grand mean at every stimulus diameter tested, as shown in Figure 3.4. Binocular interaction, as indicated by interocular transfer above 51% of monocular MAE, covers a diameter of at least to 62 degrees of the central binocular field.

The maximum stimulus diameter of 62 degrees was chosen because observers' noses began to partially occlude one eye's image. It should be noted, however, that in pilot experiments, robust MAEs were still observed even when part of the stimulus was occluded to the adapting eye. Although binocular interaction, as reported here, seems to manifest itself over 62 degrees of the central binocular field, it may extend even further. We are developing a method to induce and measure MAEs in the extreme periphery independent of occlusion restrictions of facial structures.

The spatial extent of binocular interaction is likely dependent on the method of measurement. Our aim is not to refute the studies reviewed in the introduction, but to extend the definition of binocularity to include binocular interactions in response to moving stimuli. We conclude, therefore, that it is necessary to specifically define the stimulus attributes when making inferences about the spatial extent of binocular interaction.
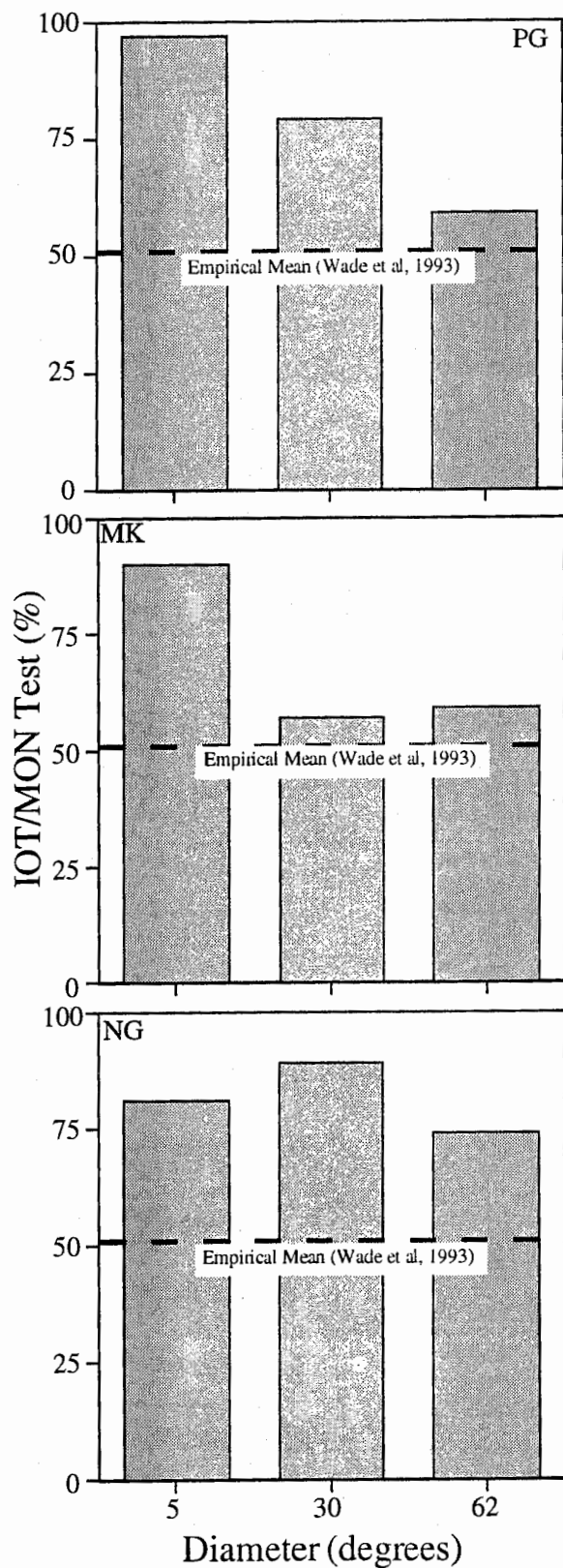
Figure 3.4. MAE interocular transfer, expressed as a percentage of monocular adapt/test MAE durations. Dashed line represents mean MAE durations of 23 studies, expressed as apercentage of monocular adapt/test, reported by Wade et al. (1993).

A3 Appendix: Control Experiment

Prior to the experiment described above, we conducted pilot experiments with each of the

observers to ensure that there was no cross talk between the left and right eye's views

through the polarized filters. Initial tests were run with the first author as the observer

viewing the full circular grating at a diameter of 62 degrees[7]. In order to see whether the

test eye's filter was allowing of the adapt eye's image through, we occluded the

observers' adapt eye and had them view the screen through the test eye's filter during

adaptation. Therefore, during the one-minute adaptation phase the observer was,

subjectively, looking at a blank screen. When the contrast of the grating was very high,

observers could see a faint image of the adapting stimulus through the test eye's filter.

The contrast of the grating was adjusted between trials until the adaptation stimulus could

no longer be seen through the test filter and no MAE was perceived in the static grating

during the test phase.

We next used a counterphase flickering test grating (4 Hz.), regarded by some as a

more sensitive measure of the MAE than a static test (Nishida et al., 1994; Levinson and

Sekuler, 1975). As before, observers "adapted" by viewing a subjectively blank screen

through the test eye's filter for one minute. During the 30-second test phase the observer

viewed the counter phase flickering test grating and pressed one of two buttons indicating

the perceived direction of apparent motion. One button was for clockwise motion, the

other for counterclockwise motion. The buttons were not to be pressed if the observer

could not decide on the motion direction. With no adaptation, observers report seeing

clockwise motion 50% of the time and counterclockwise motion the other 50%. The

contrast of the adaptation grating and test grating were adjusted until no significant bias

was observed in the duration of perceived motion in one direction relative to the other. A

contrast of 15% was settled on using this procedure. This contrast was formally tested

for each of the three observers. Each observer completed 16 adapt/test trials as described

above. Individual dependent measures *t-tests* revealed no significant biases in mean

durations of perceived apparent motion "with" or "against" the adaptation motion. Mean

data for each observer is presented in Table 1.

Observer	Duration "with" (SEM)	Duration "against" (SEM)
NG	10.5 (0.96)	9.9 (1.1)
MK	14.0 (0.55)	14.9 (0.56)
PG	9.0 (0.78)	9.9 (0.85)

Table 3.1. Mean duration (in seconds) of perceived motion with and against adaptation motion. Standard errors are shown in brackets. *t-tests* between "with" and "against" means were not significant for all three observers.

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[7]Cross-talk between left and right eye images is most pronounced with eccentric viewing. Therefore, we tested for cross-talk at the largest eccentricity for which we were measuring interocular transfer of the MAE.

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