DETECTION AND DISCRIMINATION OF THE DIRECTION OF MOTION IN CENTRAL AND PERIPHERAL VISION OF NORMAL AND AMBLYOPIC OBSERVERS

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Abstract—This paper describes the "motion" properties of the amblyopic fovea and compares them to the normal periphery. Specifically, thresholds for detection of the displacement of a grating pattern, and for discrimination of displacement direction were measured. The main findings of these experiments were: (1) in the central vision of both normal and amblyopic observers, unreferenced displacements are detected with an accuracy equal to the observer's grating acuity; (2) in the normal periphery, unreferenced motion thresholds fall off at a slower rate than does grating acuity; (3) in amblyopic eyes, displacement thresholds are most elevated centrally; (4) the addition of an abutting reference improves detection of motion for the normal fovea and in anisometropic amblyopes, but elevates motion thresholds in both the normal periphery and in the fovea of amblyopes with strabismus. The adequacy of the normal periphery as a model for the central vision of amblyopes is discussed.

INTRODUCTION

Amblyopia is an anomaly of the spatial sense of the eye (Wald and Burian, 1944). In addition to the losses in acuity and contrast sensitivity which characterize functional amblyopia (Gestalter and Green, 1971; Levi and Harwerth, 1977; Hess and Howell, 1977), amblyopes are especially handicapped in the performance of tasks requiring fine spatial discriminations. For example, strabismic amblyopes show losses in vernier acuity which are disproportionately greater than their losses in grating acuity (Levi and Klein, 1982a, b). In addition, both strabismic and anisometropic amblyopes show marked losses in spatial phase discrimination of high spatial frequencies (Lawden et al., 1982; Pass and Levi, 1982; Levi and Klein, 1983). The incapacity of amblyopes to make fine spatial discriminations resembles in many respects the poor spatial capabilities of the normal periphery (see Braddick, 1982 for a recent review).

One elemental aspect of the spatial sense of the eye is the detection and discrimination of the direction of object displacement (Westheimer, 1979). Little is known about the amblyopic eye's perception of displacement, although prismatically induced displacement has been used clinically to assess the dimensions of an amblyopic eye's functional scotoma (Irvine, 1966). There are several reasons which suggest that displacement perception may be especially impaired in amblyopic eyes. For example, distortions of the spatial sense, might impair the perception of displacements while having little influence upon the detection of gratings. In addition, the unsteady and asymmetric eye movements exhibited by strabismic amblyopes upon attempted steady fixation might be expected to mask the displacement of a target (von Noorden and Burian, 1958; Schor and Flom, 1975; Ciuffreda et al., 1979, 1980). On the other hand, the performance of an amblyopic eye has often been linked to that of the normal periphery. With regard to motion, the normal periphery has been reported to be rather good at displacement detection (Exner, 1875, 1885; Aubert, 1886; Basler, 1906; Biederman-Thorson et al., 1971; Leibowitz et al., 1972; Tyler and Torres, 1972). What is not clear in normal vision, is how displacement acuity covaries with other peripheral acuities. For example, Leibowitz, et al. (1972) have argued that the fall-off of displacement thresholds for unreferenced motion is slower than the fall-off of visual acuity. On the other hand, McKee and Nakayama (1984) have shown that relative motion acuity declines more rapidly than grating acuity in the periphery. Thus, in the present study we measured displacement thresholds, both unreferenced and referenced, in the central visual field of each eye of amblyopic observers, and compared the results to those obtained in the periphery of normal observers.

EXPERIMENT 1: UNREFERENCED MOTION IN THE CENTRAL FIELD OF NORMAL AND AMBLYOPIC OBSERVERS

Methods

Apparatus and stimuli. In order to ensure that the stimulus whose displacement was to be detected, was

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presented to the fovea (even in observers with eccentric fixation), a grating consisting of bright lines was used. The grating stimulus consisted of at least 16 lines and the stimulus field was at least 3 times the distance between the fovea and the eccentric locus. The stimuli were presented on the monitor of a computer (Commodore 2001) which also tallied the observers' responses and provided feedback following each trial. A fixation line oriented orthogonally to the lines of the grating was provided to aid in accommodation and fixation between trials. At the start of each trial, the fixation line was replaced by the grating which “blinking” (i.e. turned off for 16 msec and then reappeared) once, 500 msec prior to its abrupt displacement to its new position, where it remained for 750 msec. The interline separation of the gratings could be varied, thus enabling us to measure displacement thresholds as a function of the fundamental spatial frequency (i.e. the reciprocal of the interline spacing) of the grating. The 8:1 duty cycle used at high spatial frequencies provides very high contrast of the fundamental spatial frequencies (approx 195%). Edge cues were eliminated by giving the lines at the ends of the grating random displacements at the same moment the grating moved. Unwanted position cues were minimized by (1) performing the experiments with the room lights extinguished, and (2) having the initial phase of the grating random.

In most of the experiments to be reported, the lines comprising the grating were vertical and the direction of the displacement was horizontal, however, in a number of experiments, the stimulus was optically rotated by a dove prism to measure thresholds for the vertical displacement of a grating composed of horizontal lines. In addition, thresholds for displacement of a single line were also measured. For the non-amblyopic eyes, the viewing distance was generally 2.5 m, providing a stimulus field approximately 4° wide by 0.2° high. For the amblyopic eyes, the viewing distance was shortened to “scale” the stimulus field size in proportion to their loss of grating acuity, and to ensure both the fovea and eccentric locus were included in the stimulus field.

Procedures. The psychophysical paradigm was a self-paced method of constant stimuli, with multiple responses (described in detail by Levi and Klein, 1982b and 1983). A block of 125 to 250 trials contained either 5 or 7 stimuli i.e. the grating was displaced 0, 1, 2 or 3 distance modules to the left or right. The order of stimulus presentation was random. The observer responded by giving numbers from −2 to +2 (five stimuli) or −3 to +3 (seven stimuli) to indicate both the direction and the magnitude of the displacement. This “rating scale” methodology requires the observer to adopt a number (4 or 6) of different criteria. The magnitude of the distance modules was varied from observer to observer, to place the stimuli optimally on the psychometric function. The largest displacement never exceeded a quarter of the duty cycle (i.e. a 90° phase shift). Following each trial, feedback as to the magnitude and direction of the displacement was provided. The spatial frequency of the grating was varied between blocks of trials. Prior to data collection, each observer was provided with several hundred practice trials, and 10–20 practice trials were also provided at the start of each new block in order to minimize practice effects. All testing was monocular with the nontested eye occluded via a black patch.

Data analysis. In order to obtain a criterion-free measure of the threshold for correct discrimination of the direction of displacement (discrimination threshold), $d'$ values for each stimulus were determined using a maximum likelihood fit to the rating scale data (Dorfman and Alf, 1969) and interpolation to a $d'$ of 1.0 was used as a measure of the discrimination threshold (i.e. similar to probit analysis with rating scale data). Thresholds for detection of displacements (detection thresholds) were obtained from the same data by calculating the $d$'s between the zero displacement stimulus, and the other stimuli, allowing errors in the judgement of direction of displacement. A detailed description of how detection and discrimination thresholds may be obtained simultaneously using this paradigm is published elsewhere (Levi and Klein, 1983, Appendix 1).

Grating acuity. In order to provide a baseline for comparison, we also measured the grating acuity of each observer using a 3 alternative forced choice task. The stimulus consisted of 3 horizontal luminance strips. Two of the 3 strips contained a square-wave vertical grating (fundamental contrast of 120%), while the third was matched in brightness, but was homogeneous. After each 750 msec presentation the observer's task was to indicate which of the three strips was homogeneous. The fundamental spatial frequency was varied between blocks of trials to generate a psychometric function relating probability of correct response to spatial frequency. Interpolation to 64% correct, equivalent to $d' = 1.0$ for a 3 alternative forced choice (Hacker and Ratcliff, 1979) provided an estimate of each observer's grating acuity.

Observers. Eleven adults served as observers. Nine had unilateral amblyopia resulting from anisometropia, strabismus or both. Two of the authors served as normal controls. The pertinent visual characteristics of the observers are presented in Table 1. Each observer had clear media, normal fundi, and was appropriately corrected for refractive errors.

Results

Displacement acuity vs grating acuity. Figure 1 shows the relation between grating acuity (i.e. the high spatial frequency cut-off) and displacement detection thresholds, obtained with gratings that were a factor of three to four times larger than the cutoff spatial frequency for the normal controls (squares), preferred eyes (circles) and amblyopic eyes of observ-
Table I. Visual characteristics of the observers

<table>
<thead>
<tr>
<th>Observer</th>
<th>Age</th>
<th>Sex</th>
<th>Eye</th>
<th>Refractive status</th>
<th>Snellen* grating acuity (min)</th>
<th>Fixation of amblyopic eye</th>
<th>Binocularly</th>
</tr>
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<tbody>
<tr>
<td>E.E.</td>
<td>22</td>
<td>F</td>
<td>OD</td>
<td>Plano</td>
<td>20/40</td>
<td>1.46</td>
<td>Unsteady central</td>
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<td>Plano</td>
<td>20/15</td>
<td>0.95</td>
<td></td>
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<td>R.G.</td>
<td>28</td>
<td>M</td>
<td>OD</td>
<td>-4.50 -1.25 x 90</td>
<td>20/15</td>
<td>0.76</td>
<td>Unsteady central 12 temporal</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>OS</td>
<td>-4.00 -1.00 x 90</td>
<td>20/46</td>
<td>1.45</td>
<td></td>
</tr>
<tr>
<td>J.B.</td>
<td>23</td>
<td>F</td>
<td>OD</td>
<td>+4.50 - 0.75 x 100</td>
<td>20/22</td>
<td>0.88</td>
<td>Unsteady central 2 temporal</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>OS</td>
<td>+4.75 -1.0 x 85</td>
<td>20/30</td>
<td>1.1</td>
<td></td>
</tr>
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<td>M.C.</td>
<td>29</td>
<td>F</td>
<td>OD</td>
<td>+3.0 - 0.75 x 10</td>
<td>20/50</td>
<td>2.18</td>
<td>Unsteady central 5 intermittent right esotropia</td>
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<tr>
<td>J.M.</td>
<td>30</td>
<td>M</td>
<td>OD</td>
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<td>20/15</td>
<td>0.97</td>
<td>Unsteady central 10 intermittent exotropia at near</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<td>20/60</td>
<td>1.9</td>
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<td>35</td>
<td>M</td>
<td>OD</td>
<td>-7.0 - 2.25 x 180</td>
<td>20/20</td>
<td>1.8</td>
<td>Unsteady central 18 intermittent exotropia</td>
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<tr>
<td></td>
<td></td>
<td></td>
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<td>-4.50 -1.50 x 145</td>
<td>20/20</td>
<td>1.0</td>
<td>temporal</td>
</tr>
<tr>
<td>J.V.</td>
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<td>M</td>
<td>OD</td>
<td>+0.75 -0.25 x 00</td>
<td>20/20</td>
<td>0.92</td>
<td>Unsteady central 1 temporal 8 intermittent esotropia</td>
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<tr>
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<td>OD</td>
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<td>20/600</td>
<td>5.7</td>
<td>Unsteady central 10 intermittent exotropia 10 intermittent exotropia</td>
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<td></td>
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<td>A.S.</td>
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<td>4.0</td>
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<td></td>
<td></td>
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<td>M</td>
<td>OD</td>
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<td></td>
<td></td>
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<td>Plano -0.50 x 45</td>
<td>20/15</td>
<td>0.65</td>
<td>Normal</td>
</tr>
<tr>
<td>D.L.</td>
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<td>M</td>
<td>OD</td>
<td>-0.75</td>
<td>20/15</td>
<td>0.65</td>
<td>Normal</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>OS</td>
<td>-0.75</td>
<td>20/15</td>
<td>0.65</td>
<td></td>
</tr>
</tbody>
</table>

*Acuity obtained using charts designed by Davidson and Eskridge, which contain a constant, high degree of contour interaction.
+A difference in refractive error of 1.5 D or more was classified as anisometropia. Constant strabismus was classified on the basis of unilateral cover testing.

Fig. 1. This figure shows the relationship between grating acuity (the high spatial frequency cutoff) and displacement detection thresholds obtained with gratings a factor of three to four times below the cutoff spatial frequency for the normal (control) observers (squares), preferred eyes of amblyopes (circles) and amblyopic eyes of observers with strabismus (S), anisometropia (A) and both (B).
ers with strabismus (S's), anisometropia (A's), and both (B's). There are several points of note in this figure. Firstly, for the normal observers and the preferred eyes of the amblyopic observers both displacement thresholds and grating detection thresholds tend to be between 40 and 60 sec. These thresholds are quite similar to those reported for displacement of bright (100 cd m^-2) spots in a uniform dark field by Legge and Campbell (1981). Interestingly, while the control and preferred eyes have similar displacement detection thresholds, some, but not all of the preferred eyes have somewhat poorer grating acuity than the control eyes do. Similar conclusions have been previously reported by Kandel et al. (1980). For the amblyopic eyes, grating acuity and displacement detection thresholds are also similar. The solid line in Fig. 2, has a slope of 1. Thus if the amblyopic process affected resolution and displacement detection thresholds in the same way, the data, when plotted on log-log coordinates would conform to this line. In fact the data fit quite well. The best fit line to the data has a slope of 0.90 ± 0.07 (r = 0.94), suggesting that displacement detection thresholds are affected similarly to grating acuity thresholds. Furthermore, there is no clear difference between the results of observers with strabismus, anisometropia, or both. In contrast, strabismic but not anisometropic amblyopes showed a strong decoupling between grating acuity and both Snellen and vernier acuity (Levi and Klein 1982a, b). In the present study, the decoupling between the Snellen and grating acuity of strabismic amblyopes is also evident, with Snellen acuity being significantly poorer than grating acuity (see Table 1); however, what is of special interest here is that the displacement thresholds are much closer to the grating acuity thresholds than to the Snellen acuity thresholds. For example the amblyopic eye of J.V. shows both grating and displacement thresholds of close to 1.3' but has Snellen acuity of 4.0' (20/80). Even more dramatically, R.M. shows a displacement threshold of 4.0', grating acuity threshold of almost 6', and Snellen acuity of 34' (20/680).

Detection and discrimination of the direction of displacement as a function of fundamental spatial frequency. Figure 2 shows displacement thresholds for detection (left panel) and discrimination (right panel) as a function of the fundamental spatial frequency of the grating (i.e., interline separation in degrees) for a normal observer and several amblyopes. The data are plotted in terms of the threshold angular distance (in minutes) through which the stimulus had to be displaced. As has previously been reported by Westheimer (1978), the results are consistent with the notion that the observer detects (left column) or discriminates (right column) a fixed minimum change in position regardless of the interline separation (or even the number of lines). For the normal observer (top row), it is only at spatial frequencies within one octave of the resolution limit (indicated by the arrow), that the discrimination thresholds are slightly elevated when compared to detection thresholds. At the highest spatial frequencies, the ratio of discrimination to detection thresholds approaches 1.5.

Figure 2 also shows the results of four observers with amblyopia. The graphs show detection (left column) and discrimination (right column) thresholds of each eye (in minutes of arc) plotted as a function of the fundamental spatial frequency of the grating (in c/deg). For three of these observers, thresholds were measured for both horizontal (circles) and vertical (triangles) displacements. There are several points of interest here: (1) for each observer, over most of the range of spatial frequencies tested, detection and discrimination thresholds of the amblyopic eye were elevated more or less in proportion to their grating acuity (shown by the arrows). (2) There is little difference in the thresholds obtained for vertical and horizontal displacements for either eye. This suggests that the deficits in displacement thresholds reported here are not likely the result of the horizontal nystagmus common in amblyopic eyes upon attempted steady fixation (Schor and Flom, 1975; Ciuffreda, 1979, 1980). (3) Over much of the range of spatial frequencies, the amblyopic eyes' detection thresholds were about 20% better than their discrimination thresholds. Furthermore, like normals, the discrimination to detection ratio increases at high spatial frequencies. (4) Perhaps the most surprising finding here is that the displacement thresholds of both strabismic and anisometropic amblyopes are scaled roughly in proportion to their grating acuities over most of the spatial frequency range. In contrast, the fine positional cues required for vernier discrimination seem to be severely affected in strabismic amblyopes, so that their thresholds for these tasks are elevated to a greater extent than their grating acuity, particularly at high spatial frequencies (Levi and Klein, 1982a, b; 1983).

EXPERIMENT II: UNREFERENCED MOTION IN THE PERIPHERY OF NORMAL AND AMBLYOPIC OBSERVERS

Methods

The stimuli and methods were essentially the same as those described in Experiment I, with two basic modifications. (1) In order to provide stimuli to the periphery that were as salient as the foveal stimuli, the height and width of the lines, the field size and the fundamental spatial frequency of the grating were "scaled" in proportion to the acuity values typical of each retinal locus (Weymouth, 1958; Westheimer, 1979). This was accomplished simply by keeping the physical stimulus the same at all eccentricities and varying the viewing distance. The appropriate test distances were specified by 
\[ d = d_f (1 + \theta/2.5) \]
where \( \theta \) is the eccentricity in degrees and \( d_f \) is the distance.
Fig. 2. Displacement thresholds for detection (left panel) and discrimination (right panel) as a function of the fundamental spatial frequency of the grating. Thresholds are expressed in terms of the angular distance (in minutes) through which the grating was displaced. The top row is for a normal observer (D.L.). The 4 lower rows are for amblyopic observers. The open symbols are the preferred eyes; solid symbols, the amblyopic eyes. For E.E., J.V., and J.M. thresholds are shown for horizontal displacements (circles) and vertical displacements (triangles). For R.M. thresholds are shown for horizontal displacements only. The arrows show the cut-off spatial frequency for each eye.
Fig. 3. The unreferenced displacement thresholds for the preferred eye of R.M. and for normal observer P.A. are plotted with a linear ordinate. Each open symbol shows the geometric mean of several threshold estimates for detection of the displacement of a single line (diamonds), or a grating with a fundamental spatial frequency 1/3 (circles for R.M. and squares for P.A.) or 2/3 (triangles) of the cut-off spatial frequency, scaled as described in the text. The corresponding solid symbols are for discrimination of the direction of the displacement of the same stimuli. Note here that the foveal thresholds for detection and discrimination of each stimulus have been normalized to a value of 1. The 2 lines limiting the shaded area show the steepest and shallowest slopes of the best fit lines to the individual data for each stimulus. The range of X intercepts was from -5.6 to -14. For comparison the fall-off of grating acuity and vernier acuity in the periphery are shown. It is clear that thresholds for detection and discrimination of displacements fall off more gently in the periphery.

Results

Detection and discrimination of unreferenced displacements in the periphery. Figure 3 shows the decline of motion sensitivity in the normal periphery. Results for detection (open symbols) and discrimination (solid symbols) are shown for normal observer P.A. (squares) and for the preferred eye of R.M. (all other symbols). For both observers the stimuli were "scaled" as described above, and had a fundamental spatial frequency equal to 1/3 of the cut-off frequency (approx 15 c/deg foveally). For R.M., data were also obtained with single lines (diamonds), and with gratings having a higher foveal spatial frequency (29.1 c/deg, shown by the triangles). The results are plotted with a linear ordinate since many spatial thresholds, including displacement thresholds are nearly linear functions of retinal eccentricity (Weymouth, 1958; Genter et al., 1981). To facilitate comparisons between conditions, the foveal thresholds for detection and for discrimination of each stimulus have been normalized to 1. Thus all of the lines fit to the data pass through the ordinate at 1. The absolute Y intercepts and X intercepts are provided in Table 2. The X intercept is a convenient way of approximating the rise in thresholds in the periphery, since it shows directly how far in the periphery

used for foveal viewing*. Thus, at \( \theta = 2.5^\circ \) the height, width and field size were doubled and the spatial frequency halved, with respect to the foveal values by halving the test distance. At \( \theta = 20^\circ \), the height, width and field size were increased nine fold, and the fundamental spatial frequency was 1/9 of the foveal value. This scaling factor is similar to the cortical magnification function of Sakitt and Barlow (1982) (except that they would use 3 where we used 2.5). (2) A horizontal fixation line (similar in color and brightness to the stimulus) was presented continuously. The displacement stimulus, consisting of vertical lines, was presented foveally, and at 2.5°, 5°, 10°, 15°, 20° meridian. All other methodological details are similar to those described in Experiment 1.

Since the periphery is highly susceptible to the effects of practice (Saugstad and Lie, 1964; Johnson and Leibowitz, 1974; McKee and Westheimer 1978; Fendick and Westheimer, 1983) observers were given extensive practice (>6000 trials) prior to the final data collection. Two observers, P.A. (normal) and R.M. (amblyopic) were tested extensively.

*For the normal periphery experiments, \( d_p \), the foveal viewing distance, was 4.5 to 6 M, depending upon the observer and condition.
foveal thresholds will double. The two lines bounding the shaded area in Fig. 3 show the two most extreme lines fit to the data. The steeper of the two has an $X$ intercept of $-5.6$ (obtained for detection of displacement for P.A.) and the flatter has an $X$ intercept, not shown on the graph, of $-13.9$ (fit to the detection data of R.M. shown in Fig. 4). These results are comparable to the data of Leibowitz et al. (1972). For reference, we have plotted the best fit lines to the grating acuity and vernier acuity data of Westheimer (1979, 1982). On these normalized linear coordinates, it is clear that the detection and discrimination of displacements shows less fall-off with eccentricity than do either grating acuity, or vernier acuity. In contrast to the displacement data, grating acuity has an $X$-intercept of about $-2.5$. This $X$-intercept value for acuity holds true for both the horizontal and vertical retinal meridia (Fendick and Westheimer, 1983) and is in agreement with a large body of data (e.g. McKee and Nakayama, 1984). Thus, we conclude that displacement sensitivity falls off less rapidly in the normal periphery than does grating acuity. It is of peripheral interest to note that Snellen acuity shows a fall-off which is closer to vernier, than to grating acuity or motion. This point may be seen in Table 2 in which the slopes, $Y$ intercept and $X$ intercept of the Snellen data of Weymouth (1958) and Westheimer (1967) are summarized. This is of particular interest since it suggests that the normal periphery, like the fovea of strabismic amblyopes shows a similarity between vernier and Snellen acuity, and a decoupling of these two acuities from grating acuity (Levi and Klein, 1982a, b).

**Displacement thresholds in the periphery of amblyopic observers.** Figure 4 shows data for each eye of severely amblyopic observer R.M. The stimulus for each eye had a fundamental spatial frequency equal to 1/3 of the foveal cutoff spatial frequency, and was scaled as described above. Since a logarithmic scaling is a reasonable approximation to an equal discriminability scale (Westheimer, 1979), the data of R.M.'s two eyes are plotted on a logarithmic ordinate. The data of R.M.'s nonamblyopic eye (open symbols) are similar to those of P.A. (and the geometric means of the individual runs are shown in Fig. 3). Figure 4 also shows detection (solid circles) and discrimination (solid triangles) thresholds of the amblyopic eye of R.M. For this observer, with severe amblyopia associated with both constant strabismus and anisometropia, there is little change in threshold across the central 30°. More importantly, the amblyopic deficit, while greatest centrally, is still present at 30°.

We have performed similar (though less extensive) measures on 3 other amblyopic observers. Their results, as well as R.M.'s are summarized in Fig. 5. This figure shows the amblyopic loss (i.e. the ratio of amblyopic eye/nonamblyopic eye thresholds for detection and discrimination) as a function of eccentricity. The data suggest that the peripheral extent of amblyopia (the eccentricity at which the amblyopes' two eyes become similar) may be related to the degree of central loss rather than simply to the type of amblyopia. Similar observations have been made regarding the loss of contrast sensitivity in amblyopic eyes (Katz et al., 1984).

**EXPERIMENT III: RELATIVE MOTION**

The displacement thresholds reported thus far are for motion detection with no nearby reference, and
The amblyopic loss (i.e. the ratio of the thresholds of nonamblyopic/amblyopic eyes) of 4 observers at different eccentricities. The extent of the amblyopic loss in the periphery is related to the degree of foveal loss. at least centrally, are surprisingly close to the observers’ resolution limit. On the other hand, several investigators have reported displacement thresholds for relative motion, which are considerably better than the resolving capacity of the eye (e.g. Basler, 1906; Tyler and Torres, 1972; Westheimer, 1978; Nakayama and Tyler, 1981; McKee and Nakayama, 1984).

Methods

In order to compare relative displacement thresholds with our absolute thresholds, we added a second grating composed of stationary lines (of the same spatial frequency as the displacement stimulus) at various distance above the stimulus. In order to remove vernier cues, the pair of gratings appeared with the relative phase of upper and lower gratings random. Thus, the final position (phase) of the stimulus relative to the reference grating did not provide a useful cue to the displacement. As a control, the experiments were repeated with the upper and lower gratings initially aligned, so that the final relative positions of the grating pair did provide a vernier cue to the displacement.

In each case the grating was a factor of 3 coarser than the resolution limit. The peripheral and amblyopic stimuli were scaled as described previously.

Results

The results of these experiments are shown in Fig. 6 for normal fovea (D.L., top left), normal periphery at 2.5° (P.A., bottom left) and for two amblyopes, J.M. (anisometropic, top right) and J.V. (strabismic and anisometropic, bottom right). Thresholds for detection of relative motion with no vernier cues are shown by the circles; relative motion with vernier cues is shown by the triangles. The solid squares show the displacement detection thresholds with no reference lines.

For normal foveal viewing, the presence of a reference near the test grating i.e. 2 min to about 30 min, resulted in relative motion thresholds of approx 18 sec (a factor of about 2.5 times better than with no reference), independent of vernier cues being present. The presence of the additional vernier cue only helped for the case in which the two rows of gratings were abutting. For this condition, the vernier cue lowered thresholds by an additional factor of about 2.5. This finding may seem somewhat surprising since classical vernier acuity (with 2 lines) is not degraded by a small gap between the features. However, at high spatial frequencies, the presence of a small gap degrades vernier acuity drastically (Levi et al., 1983).

The normal near periphery (2.5°) shows a somewhat different pattern of results. When the reference grating is close to the test, it “masks” the displacement. Displacement thresholds improve once the test and reference gratings are separate, becoming slightly better than the unreferenced motion at a separation of 20 min. Similar results were obtained at 5° and 10° with the thresholds being higher, and the optimal separations larger as eccentricity increased. It is of interest to note that the fall-off of relative motion in the periphery is considerably steeper than that of unreferenced motion suggesting that the normal fovea is highly specialized for relative motion (McKee and Nakayama, 1984; also see Table 2).

The results of two amblyopic eyes are shown in the right column. Both observers have similar anisometropia and Snellen acuity, however J.V. (lower right) also has constant strabismus. The pattern of results for J.M. (anisometropia) were similar to those obtained for the normal fovea, while the pattern of results of J.V. (strabismus and anisometropia) were similar to the normal periphery.

For J.M., the presence of a reference grating provides a smaller improvement in displacement de-
Detection than for the normal observer; however, the basic pattern of results is similar, and the vernier cue provides almost a 2.5 fold improvement in displacement detection when the reference and test lines were abutting. The results of J.V. are quite surprising. Firstly, like the periphery, when the test and reference lines were abutting, displacement detection was “masked”. For the abutting condition, the vernier cue provided no benefit. This finding is in agreement with our previous report that the high spatial frequency vernier acuity of amblyopes with constant strabismus is markedly disturbed (Levi and Klein, 1982a,b). The present results suggest that the normal periphery may also show very degraded vernier acuity for high spatial frequency, abutting stimuli. Secondly, the displacement thresholds of J.V. improve as the test and reference lines are separated. Interestingly, the reference grating (both with and without vernier cues), once separated from the test grating, improves displacement thresholds for this observer by about a factor of two. What is of special interest here is that the absolute values of the referenced displacement thresholds of J.V.’s amlyopic fovea are similar to those obtained at 2.5° in the normal periphery; whereas J.V.’s unreferenced displacement threshold is about 60% higher than that of the normal periphery. Thus, it is tempting to speculate that when there is a reference, the central field of the amlyopic eye performs similarly to the normal periphery, but in the absence of a reference the amlyopic eye is “noisier” and therefore requires somewhat larger displacements.

Discussion

The main findings of this study show that: (1) in the central visual field, unreferenced displacements are detected with an accuracy equal to the observer’s grating acuity. This finding is consistent with previous studies in normal observers (Legge and Campbell, 1981; Leibowitz et al., 1972); however the present data show this to be the case also for amlyopic observers with a wide range of acuity deficits. This finding holds over a wide range of spatial frequencies and suggests that distortions of spatial perception such as those reported by Bedell and Flom (1981) have little differential effect upon detection and discrimination of displacements.

Distortions of motion perception might be expected in strabismic amblyopes due to their nystagmus. The asymmetric eye movements (fast velocity in one direction, and slow velocity in the opposite direction) could result in elevated thresholds for one direction of motion. To examine the possibility that such an asymmetry was present, the raw data for the amlyopic eye of strabismic amblyope E.E. are plotted in Fig. 7. The proportion of “rightward” responses are plotted for each of the 6 criteria for a run with 7 stimuli and 7 responses. Criterion 1 represents the greatest confidence of leftward motion. Criterion 6 represents the greatest confidence of rightward motion. There were no systematic asymmetries in detecting (or discriminating) leftward vs rightward motion for the 3 displacement magnitudes shown in Fig. 7. The d’s between stimuli were 0.5 ± 0.16, 1.34 ± 0.18, and 1.28 ± 0.21 for rightward motion, and 0.6 ± 0.17, 1.11 ± 0.17 and 1.1 ± 0.18 for leftward motion.

(2) With extensive practice, the normal periphery performs remarkably well both in detecting displacements, and discriminating their direction. The decline in detection and discrimination of unreferenced displacements with eccentricity is about 3 times less than the fall-off of grating acuity. It is interesting to note that relative (referenced) motion acuity shows a much sharper fall-off in the periphery (McKee and Nakayama, 1984 and Table 2). This finding seems to reflect the very high degree of specialization of the fovea for relative motion which is a hyperacuity. Similarly, foveal specialization for vernier acuity results in a steep decline of vernier acuity with eccentricity (Westheimer, 1981). Taken together, these results suggest that there is not a single cortical magnification factor. Grating acuity has a X intercept of −2.5 deg. Referenced displacement, vernier acuity and (surprisingly) Snellen acuity have an X intercept of about −1 deg (Table 2 and Fig. 3). The low intercept for Snellen and vernier acuities is reminiscent of our earlier findings (Levi and Klein, 1982, 1983) of greater similarity between the Snellen and vernier acuities of amblyopes, than between their Snellen and grating acuities. The finding that different acuities have different X intercepts raises the intriguing possibility that different acuities may be processed in different cortical regions or that cortical and retinal factors impose different limitations on different tasks.

(3) Throughout the data analyses, separate thresholds were calculated for detection of an offset, and discrimination of the direction of the offset. It was

![Fig. 7. Psychometric functions plotted from rating scale data for the amlyopic eye of observer E.E. The figure plots the proportion of "right" calls for each of 7 stimuli, for each criterion (1 being least certain, 6 being most certain of rightward displacement). The stimuli was a grating with a fundamental spatial frequency of 4.6 c/deg. Five blocks of 125 trials each (total n = 625) were combined. The standard errors shown were obtained from binomial statistics.](image-url)
anticipated that at relatively high spatial frequencies peripheral vision and amblyopic vision might show a greater loss of direction selectivity (discrimination) as compared to simple displacement detection which could be signaled by a nondirection selective flicker mechanism. Our data showed that indeed detection was a bit better than discrimination in amblyopic vision and at high spatial frequencies in normal vision. The surprising feature of our results is that the discrimination to detection ratio did not change as a function of eccentricity. After much practice, the periphery was found to have the same direction selectivity as the fovea (i.e. discrimination has the same X intercepts in Table 2 as did detection).

(4) In amblyopic eyes, displacement thresholds are most elevated centrally. The peripheral extent of the amblyopic deficit seems to depend on the degree of central loss.

How can the elevated displacement thresholds of the amblyopic eye be explained? Eccentric and/or unsteady fixation are not likely to have influenced these results since the grating always extended over both the eccentric locus (where present) and the fovea. In fact, any effect of eccentric fixation might be ascertained by comparing the results obtained with a single line, to that obtained with gratings (Fig. 2). Moreover, similar results were obtained for horizontal displacements of vertical gratings and vertical displacements of horizontal gratings, suggesting that the horizontal fixation nystagmus characteristic of amblyopes, was not an important factor.

Nor are the results reasonably explained on the basis of defocus. In Fig. 8 the displacement detection thresholds of the control, preferred and amblyopic eyes as a function of grating acuity have been replotted from Fig. 1. Added here are the results obtained with the right eye of normal observer P.A. viewing through varying amounts of defocus (from 2.0 to 9.0 D) shown by the D's. It is clear that moderate (2-3 D) defocus has little influence on the detection of displacements, but exerts a considerable effect on acuity (Johnson and Leibowitz, 1974; Westheimer, 1979).

It has frequently been suggested that the central field of the amblyopic eye is similar to normal peripheral retina. The amblyopic fovea is qualitatively similar to the normal periphery in a number of ways including, for example, spatial summation (Miller, 1954; Flynn, 1967; Levi et al., 1981); contrast sensitivity (Katz et al., 1984); suprathreshold contrast perception (Hess and Bradley, 1980; Loshin and Levi, 1983); phase discrimination (Lawden et al., 1982; Pass and Levi, 1982) as well as the effect of position uncertainty (Wardlaw and Cohn, 1983; Cohn, personal communication). See also Braddick (1982) for a recent review of this viewpoint.

Figure 8 allows a direct comparison of the amblyopic fovea with the normal periphery. The Ps on this figure are P.A.'s displacement detection thresholds obtained at various eccentricities. These data are plotted against the grating acuity values of corresponding eccentricities obtained from the data of
Westheimer (1979). For both the normal periphery and the ambylopic fovea, the two acuity measures covary. However, the peripheral displacement thresholds tend to be lower (by 40-60%) than those of ambylopic eyes with similar grating acuity. Thus, for unreferenced displacements, the ambylopic eyes seem to share the property of normal central vision (i.e., approximately equal thresholds for displacement and resolution) rather than the interesting property of normal peripheral vision where detection of displacement is better than spatial resolution.

The experiments with added reference gratings showed that the normal fovea is highly specialized for relative motion and for vernier acuity. Under these conditions, the periphery showed strong "crowding" when the reference lines were close, and an inability to use vernier cues at high spatial frequencies. In these respects, strabismic (but not anisometropic) ambylopes are similar to the periphery. Thus, in terms of the spatial sense, the periphery may provide a reasonable model for strabismic ambylopa. Studying the normal periphery may provide important insights into the nature of strabismic ambylopa and help clarify differences in performance between strabismic and anisometropic ambylopes (Hess et al., 1980; Hess and Bradley, 1980; Levi and Klein, 1982a, b, 1983).

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