SPATIAL LOCALIZATION IN NORMAL AND AMBLYOPIC VISION*

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(Received 6 July 1982; in revised form 28 January 1983)

Abstract—Spatial localization was investigated for each eye of amblyopic observers using a bisection paradigm. The stimuli were comprised of a grating composed of bright lines, and a test line. The test line was either placed above the grating (bisection-no overlap) or within the row of lines comprising the grating (bisection-with overlap) and thresholds for each bisection task were measured as a function of the fundamental spatial frequency of the grating. Vernier thresholds were also measured. For the nonamblyopic eyes at low spatial frequencies, bisection thresholds were a constant fraction ("Weber" fraction) of the space to be bisected, while at high spatial frequencies thresholds were approximately a constant retinal distance (a hyperacuity). However the spatial localization of an amblyopic eye depends upon both the type of amblyopia, and the stimulus configuration. Specifically, for anisometropic amblyopia, spatial localization (bisection-no overlap) and vernier, when scaled to the resolution losses, were normal. However, spatial adjacency (bisection with overlap), while enhancing the spatial localization of nonamblyopic eyes at high spatial frequencies, markedly elevated thresholds in the amblyopic eyes of anisometropic amblyopes. Strabismic amblyopes on the other hand show disturbances in both spatial localization tasks which can not be accounted for on the basis of reduced resolution. Their results are characterized by an absence of a constant Weber fraction at low spatial frequencies and "crowding" effects at high spatial frequencies. For strabismic amblyopes, the optimal localization thresholds were similar to the Snellen threshold, while for anisometropic amblyopes, the optimal localization thresholds were several times better than the Snellen threshold.

INTRODUCTION

The normal human visual system is capable of judging relative distances and dimensions with great accuracy. The early experiments of Fechner (1858) and Volkmann (1858, 1863) showed that the mean errors obtained in bisecting space were approximately a constant fraction of the distance being bisected, unless the interval was small. Bisection or spatial interval discrimination, when the distances concerned are small, represents one of a variety of tasks which result in spatial discriminations which are an order of magnitude better than the eye's resolving capacity, and thus fall under the general rubric of hyperacuity (Westheimer, 1975; Westheimer and McKee, 1977; Westheimer, 1981; Klein and Tyler, 1981). However, it is not yet clear how the visual system achieves such fine discriminations, nor precisely what the relevant cues are for hyperacuity (Westheimer 1981; Watt et al., 1982; Ward et al., 1982).

Amblyopia (from the Greek, amblyos, dull; -opia, vision) is an anomaly of spatial vision which is usually associated with constant strabismus (turned eye), anisometropia (unequal refractive error) or both. The predominant characteristic of amblyopia is reduced acuity for Snellen letters and reduced grating acuity (Gstalder and Green, 1971; Levi and Harwerth, 1977; Hess and Howell, 1977; Hilz et al., 1977; Thomas, 1978; Bradley and Freeman 1981). While grating acuity and Snellen acuity are affected in a similar manner in anisometropic amblyopes, they are decoupled in strabismic amblyopes (Levi and Klein 1982a, 1982b). There is recent evidence suggesting that other spatial capacities of amblyopes may be abnormal, with strabismic and anisometropic amblyopes showing different abnormalities. For example, Bedell and Flom (1981) and Flom et al. (1982) have reported that strabismic but not anisometropic amblyopes show low spatial frequency distortions of positional information. Anisometropic and strabismic amblyopes also differ with respect to fine spatial discrimination (Levi and Klein, 1982a,b). Anisometropic amblyopes, like normals, can resolve vernier offsets in grating stimuli which are about 15% of the bar width corresponding to their cutoff spatial frequency. Thus, when scaled with respect to their grating acuity, anisometropic amblyopes, like normals, showed "hyperacuity" even at high spatial frequencies. Strabismic amblyopes on the other hand showed more severe losses in vernier acuity, and were incapable of making vernier discriminations at high spatial frequencies. In those experiments, the vernier stimuli consisted of two rows of bright lines, with an offset between the upper and

*Supported by a Research Grant from the National Eye Institute Bethesda, MD, R01EY01728, and a Biomedical Research Support Grant (SO7RR0174709).
lower rows. However, similar results are obtained with more localized stimuli such as a single line above, and a grating below (Fig. 1, top).

The abnormalities evident in the vernier acuity of strabismic amblyopes at high spatial frequencies may represent an inability to maintain positional or orientation information at high spatial frequencies specific to strabismic amblyopes. In contrast, discrimination of the relative luminance phase of a sine-wave and its third harmonic (Lawden et al., 1982) or of a rampwave (Pass and Levi, 1982), is reported to be abnormal in both strabismic and anisometropic amblyopes at high spatial frequencies. The poor phase discrimination of strabismic amblyopes is not surprising in light of the markedly abnormal position discrimination which they exhibit on vernier tasks. However, the poor phase discrimination of anisometropic amblyopes is surprising considering their relatively good vernier discrimination. One possible explanation for these discrepant results is that rather different cues may be used in performing these two tasks. In vernier discrimination, the relevant features are separated (usually one above the other), and either relative position or orientation cues (Andrews, 1967; Sullivan et al., 1972; Westheimer, 1981; Ward et al., 1982) may be used. In phase discrimination tasks on the other hand, the relevant features are the positions of variations in the luminance profile of the stimulus, and these are adjacent to the reference. For example, in the first plus third harmonic task of Lawden et al. (1982), in the peaks-subtract phase, the third harmonic sharpens the edges of the reference fundamental, while in the peaks-add phase, the appearance is more triangular. Thus, the performance of anisometropic amblyopes on spatial discrimination tasks may depend upon the nature and location of available cues.

Because spatial localization is such an elemental aspect of the normal visual impression (Westheimer, 1979), we have performed experiments similar to those of Volkman (1858, 1863) in which observers bisected the horizontal distance between two lines. A wide range of distances was tested, to include both the range where normal observers’ discrimination is a constant fraction of the distance to be bisected, and the range in which bisection is a “hyperacuity.”

In order to emphasize different cues for spatial discrimination, the bisecting line was placed either above the space to be bisected (i.e. with no overlap) or adjacent to it (i.e. between the lines defining the space to be bisected, as in Volkmann’s experiments). Vernier discrimination was also measured, and the results were compared to the bisection tasks (specific details of the stimuli are given in the next section). The results showed that the abnormalities in spatial localization with an amblyopic eye depend upon both the type of amblyopia, and the stimulus configuration (i.e. whether the features are adjacent or not). The pattern of results further suggests that amblyopes, like dichromats in the color domain, may be helpful in understanding the components of spatial analysis.

**METHODS**

**Stimuli**

The stimuli consisted of very high contrast bright lines generated on the CRT of a computer (Commodore 2001 BN with green phosphor). Three basic stimulus configurations were used. Examples of each configuration are shown in Fig. 1. Each stimulus consisted of a grating composed of bright lines, and a test line of the same length and luminance as the lines of the grating. With the first configuration (Fig. 1, top), the task was vernier alignment. With the second configuration (Fig. 1, center) the task was bisection (this stimulus configuration will be referred to as “bisection-no overlap”). The third stimulus configuration (Fig. 1, bottom) was similar to the second, a bisection task, except that the test line was now spatially adjacent to the grating. This stimulus will be referred to as “bisection with overlap”. Our rationale in choosing these 3 stimuli was that each contains different features which may be important in spatial localization. The first stimulus (vernier) contains position and orientation cues (Andrews, 1967; Sullivan et al., 1972; Westheimer, 1981; Ward et al., 1982), the second (bisection-no overlap) contains position information without spatial adjacency; while the third stimulus (bisection-with overlap) contains position plus adjacency (luminance) cues to position but no orientation cues. In each case the spatial configuration to be bisected (or aligned) was a grating. In order to minimize possible effects of eccentric fixation (in strabismics), in several control experiments (vernier and bisection-no overlap) the test target was also a grating, and was of sufficient extent to include the fovea and eccentric locus. In these experiments, lines with random offsets were placed between the test field and the edge of the display in order to rule out edge

![Fig. 1. Shows schematically the 3 stimulus configurations used. The fundamental spatial frequency of the grating is the reciprocal of the interline distance.](image-url)
effects. In each of the experiments described, the upper and lower targets were abutting i.e. there was no vertical separation unless otherwise stated.

The results obtained with our stimuli were compared to those obtained with conventional stimuli for bisection (i.e. just two lines). The comparison strongly suggests that spatial localization of amblyopic eyes is not simply determined by the distance between features. For example, under conditions in which an observer viewing with the amblyopic eye can accurately bisect the horizontal distance between two lines, the addition of equally spaced flanking lines may make the task impossible.

**Procedures**

The psychophysical paradigm was a self-paced method of constant stimuli with multiple responses, similar to that previously described by us (Levi and Klein, 1982a). Briefly, 100 to 150 trials were presented in a block. A given block of trials contained 5 or 7 stimuli which were presented in a randomized order. In the alignment (vernier) experiments the test line was either aligned with a line in the lower grating, or was 1, 2 or 3 offset modules to the left or right of alignment. Similarly, in the bisection experiments, the test line either bisected the grating or was 1, 2 or 3 offset modules to the left or right of the half-way position. In order to minimize possible ambiguities resulting from a repetitive pattern, the largest offsets were no larger than one fourth of the duty-cycle. Since the thresholds varied from less than 10 sec (e.g. vernier alignment with a non-amblyopic eye) to several minutes, the magnitude of the offset modules was varied in order to place the stimuli optimally on the psychometric function.

At the start of each trial a fixation mark appeared on the screen for 1 sec, and then was replaced by the test pattern, which was presented for 1.5 sec. In order to avoid undesirable position cues, the position of the fixation target and the test-line which replaced it, was varied slightly from trial to trial in a random fashion. The observer's task was to report whether the test line either bisected the grating or was 1, 2 or 3 offset modules to the left or right of alignment.

Separate threshold estimates were made in which a high confidence confusion parameter was either fixed at zero or was free to vary. The d's obtained with this parameter free to vary represent the observers' ability to detect the presence of an offset even if the observer errs in the discrimination of direction. Unless otherwise noted, all thresholds to be shown were determined with the high confidence confusion parameter allowed to vary. The implications of this parameter will be addressed briefly in the Results section and in the Appendix.

**Observers**

Seven adults, with unilateral amblyopia resulting from anisometropia, strabismus or both were tested. Each was experienced in psychophysical observations. For observers G.M., E.E. and R.M. who were tested most extensively, the data presented represents about 15,000 to 20,000 trials each. The visual characteristics of the observers are presented in Table 1. Each observer had clear media, normal fundi and were appropriately corrected for refractive errors. In order to minimize optical aberrations, or the effects of fluctuations in accommodation observers viewed the display through a 2.8 mm pinhole. The untested eye was occluded via a black patch.

**Results**

Since the pattern of results differs between anisometropic and strabismic observers, for the purpose of clarity we present their results separately.

**ANISOMETROPIC AMBLYOPIA:**

**BISECTION-NO OVERLAP**

The open (nonamblyopic eye) and solid (amblyopic eye) symbols in Fig. 2 show the bisection-no overlap thresholds (in seconds of arc) plotted against the fundamental spatial frequency of the lower grating for anisometropic observer G.M. The circles are for stimuli like those shown in Fig. 1 (center), i.e. a test line and a grating composed of at least 8 lines. Triangles indicate data with the grating replaced by two reference lines. The arrows along the abscissa show the cutoff spatial frequency of each eye. The data for each eye are reasonably well fit by two theoretical lines: one at low spatial frequencies with a slope of -1 showing thresholds which are a constant fraction of the space.
Table 2. Visual characteristics of the observers

<table>
<thead>
<tr>
<th>Observer</th>
<th>Age/Sex</th>
<th>Eye</th>
<th>Refractive status</th>
<th>Acuity</th>
<th>Fixation of amblyopic eye</th>
<th>Binocularly</th>
</tr>
</thead>
<tbody>
<tr>
<td>F.E.</td>
<td>22/F</td>
<td>OD</td>
<td>Plane</td>
<td>20/40</td>
<td>Unsteady central</td>
<td>Congenital esotrope strabismus surgery at age 7. Presently constant 4° right esotrope with 2° hypertropia</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OS</td>
<td>Plane</td>
<td>20/15</td>
<td></td>
<td>6° constant left exotropia</td>
</tr>
<tr>
<td>R.G.</td>
<td>28/M</td>
<td>OD</td>
<td>4.50/1.25/90</td>
<td>20/15</td>
<td>! Temporal E.F.</td>
<td>Consant left exotropia 2°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OS</td>
<td>4.00/1.00/90</td>
<td>20/46</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J.B.</td>
<td>23/F</td>
<td>OD</td>
<td>-5.00/1.75/100</td>
<td>20/22</td>
<td>Unsteady central</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>OS</td>
<td>-4.75/1.00/85</td>
<td>20/30</td>
<td>with nasal drift</td>
<td></td>
</tr>
</tbody>
</table>

Anisometropia

G.M. 20/M OD 2.50/0.25/180 20/15 Unsteady central 10° intermittent exotropia at near 18° exophoria

T.G. 58/M OD 7.00/2.25/180 20/50 Unsteady nasal

Strabismus and Anisometropia

J.V. 26/M OD -0.75/0.25/70 20/20 Unsteady nasal Constant 8° left exotropia

R.M. 21/F OD 18.25/4.25/-0.005 20/680 Unsteady nasal Constant 10° right exotropia with 6° hypertropia

Fig. 2. The open and solid symbols show the position threshold (in seconds of arc) for the nonamblyopic and amblyopic eyes respectively of anisometropic amblyope G.M., as a function of the fundamental spatial frequency of the grating (in c/deg). The arrows on the abscissa show the cutoff spatial frequency for each eye. The circles are for the bisection stimulus shown in Fig. 1 (center). The triangles show thresholds when the lower grating was replaced by just two lines. The data for each eye have been fit with two line segments: at low spatial frequencies, a line with a slope of -1, and at higher spatial frequencies, a line with a slope of 0.

Fig. 3 shows the fundamental spatial frequency of the grating scaled to the observer's cutoff spatial frequency in octaves (1 octave = 0.3 log units). The cutoff spatial frequency was determined using the same stimuli as used for the bisection tasks. The ordinate shows the position threshold expressed as a fraction of the cycle of the grating to be bisected (or aligned). In this scheme, if position thresholds are a constant fraction (akin to Weber's law) of the space to be bisected, the data will fall along a horizontal line. If position thresholds are determined by a fixed retinal distance regardless of the distance to be bisected, thresholds will fall along a line with a slope of 1. If the grating resolution and positional information are affected in a similar manner by the amblyopic process, then the data of the two eyes will be superimposed on the graphs when the coordinates are scaled as in Fig. 3.

The data from Fig. 2 have been scaled as described for the nonamblyopic (open symbols) and amblyopic eyes (solid symbols) and replotted in Fig. 3 along with several experiments in which the test line was replaced by a grating (squares). The results of experiments with the vernier target are also shown (A's and N's).

When scaled in the manner described above, the bisection results for each eye can be described in two phases. For low spatial frequencies (4 octaves or more below the resolution limit) the results for each eye fall close to a horizontal line, showing that for widely spaced stimuli, thresholds for bisection are a constant fraction (for this observer, approximately 1/75) of the space to be bisected. For higher spatial frequencies (up to one octave below the resolution limit) position thresholds increased. The data for both eyes fall along a line with a slope close to 1.0 suggesting that for each eye, the position threshold is a constant retinal
coordinates. Now, the open and solid symbols show the creasing spatial frequency. The line which fits this portion for the two eyes in octaves below the resolution limit). The N's and A's show the of the data is consistent with a eonsianf position threshold spatial frequencies position thresholds increase with in-

Figure 4 shows the position thresholds for each eye of anisometropic amblyope G.M. for the bisection with overlap configuration. The data are plotted in the same normalized format as the previous figure. Open symbols are for the nonamblyopic eye, solid symbols for the amblyopic eye. As in Fig. 3, at low spatial frequencies, up to about 4 octaves below the resolution limit, the results for each eye are more or less consistent with a horizontal line; bisection thresholds are a constant fraction of the distance to be bisected. At higher spatial frequencies, the results for the two eyes diverge. The thresholds of the nonamblyopic eye fall remarkably close to the constant (11.5°) vernier line taken from Fig. 3. The data of the amblyopic eye, however, show a marked departure from a constant retinal distance line. These data are consistent with a line with a much steeper slope (about 2.5), showing that for each factor of 2 increase in spatial frequency, position thresholds increase 5 fold. Thus at

distance. Since the scaled results for the two eyes are more or less superimposed, positional analysis with non-adjacent stimuli appears to be affected similarly to the grating resolution in anisometropic amblyopes. We have previously reported similar conclusions based upon the vernier data of 5 other anisometropic amblyopes (Levi and Klein 1982a,b).

It is of interest to note, however that thresholds for bisection and for vernier alignment are not equivalent under these stimulus conditions. The vernier thresholds for each eye of G.M. are also shown in Fig. 3 by the N's (nonamblyopic eye) and A's (amblyopic eye). Vernier thresholds for each eye, when plotted on these coordinates fall along a line with a slope of approxi-
mately 1, up to one octave below the cutoff spatial frequency, suggesting that for each eye, vernier thresholds are a constant retinal distance, regardless of spatial frequency. For the nonamblyopic eye this constant distance is about 11.5°, for the amblyopic eye it is approximately 35°. The factor of three difference in vernier acuity between the two eyes is about the same as the difference in grating acuity for this observer. Note, however, that for each eye, vernier thresholds are a factor of two lower than bisection thresholds. When the features were separated by a vertical gap of 6–7 thresholds for both bisection and vernier acuity of the nonamblyopic eye of G.M. were approximately 40 seconds. Thus in the abutting condition, vernier stimuli may provide additional cues to position not present in the bisection stimulus. Several investigators (e.g. Andrews, 1967; Sullivan et al., 1972; Ward et al., 1982) have suggested that orientation may be a strong cue.

ANISOMETROPIC AMBLYOPIA:

Figure 4 shows bisection with overlap results for each eye of anisometropic amblyope G.M. for the bisection with no overlap configuration. The data plots are for the nonamblyopic eye, solid symbols for the amblyopic eye. As in Fig. 3, at low spatial frequencies, up to about 4 octaves below the resolution limit, the results for each eye are more or less consistent with a horizontal line; bisection thresholds are a constant fraction of the distance to be bisected. At higher spatial frequencies, thresholds for both bisection and vernier alignment are not equivalent under these stimulus conditions. The vernier thresholds (when specified as a fraction of the cycle) increase with increasing spatial frequency; they are also consistent with a constant vernier threshold, which is about a factor of two lower than the position threshold. Thus, for this anisometropic amblyope, vernier and bisection with no overlap are similar in the two eyes when scaled to the resolving capacity of each eye. 

### Graphs

**Figure 3.** The results of Fig. 2 along with additional bisection data where the test line was replaced by a test grating (shown by the squares) are plotted here on normalized coordinates. Now, the open and solid symbols show the position thresholds (expressed as a fraction of the cycle) for the nonamblyopic and amblyopic eyes respectively, as a function of the spatial frequency of the grating (normalized for the two eyes in octaves below the resolution limit). Note that the data are fit by two lines. For spatial frequencies greater than 4 octaves below the resolution limit, position thresholds are a constant fraction of the space to be bisected (i.e. a “Weber” fraction). For higher spatial frequencies position thresholds increase with increasing spatial frequency. The line which fits this portion of the data is consistent with a constant position threshold (in terms of retinal distance). The N's and A's show the vernier thresholds of the nonamblyopic and amblyopic eyes of the same observer. Since the vernier thresholds (when specified as a fraction of the cycle) increase with increasing spatial frequency, they are also consistent with a constant vernier threshold, which is about a factor of two lower than the position threshold. Thus, for this anisometropic amblyope, vernier and bisection with no overlap are similar in the two eyes when scaled to the resolving capacity of each eye.

**Figure 4.** Shows bisection with overlap results for each eye of observer G.M. (anisometropic amblyope). The symbols and axes are the same as in the previous figure. In the low spatial frequency region, the results for each eye are consistent with a constant “Weber” fraction i.e. bisection with overlap thresholds are a constant fraction of the cycle (1/75). At higher spatial frequencies, bisection with overlap thresholds are adequately described by the constant vernier line of 11.5° for the non-amblyopic eye. However, the results of the amblyopic eye show that the thresholds are not a constant value but increase with increasing spatial frequency, so that 1 octave below the resolution limit, position discrimination is impossible.
high spatial frequencies, adjacency improves position discrimination by about a factor of two in the nonamblyopic eye, but degrades position sensitivity of the amblyopic eye markedly between one and two octaves below the resolution limit. This marked degradation of position sensitivity may be seen more clearly in Fig. 11 for G.M. as well as another anisometropic amblyope, where the results are plotted in seconds of arc rather than the "Weber" fraction.

**STRABISMIC AMBLYOPIA:**

**BISECTION-NO OVERLAP**

The pattern of results for observers with constant strabismus differs from that of the anisometropic amblyopes discussed so far. Position thresholds for bisection-no overlap (scaled as in Figs. 3 and 4) are shown in Fig. 5 by the circles for each eye of observer E.E. (open symbols — nonamblyopic eye; solid symbols — amblyopic eye). The data of the nonamblyopic eye of this mild strabismic amblyope were quite similar to that presented for G.M. (Fig. 3). At low spatial frequencies, position thresholds are a constant fraction (1/90) of the distance to be bisected, while at higher spatial frequencies, the thresholds increase with a slope of unity (compatible with a fixed retinal distance of about 19°). Similar to the data of other non-amblyopic eyes the position thresholds for bisection with no overlap are about a factor of two higher than the vernier thresholds. For the nonamblyopic eye of this observer, the vernier thresholds (N's) are compatible with a fixed retinal distance of about 9° up to about one octave below the resolution limit.

The pattern of results for the amblyopic eye of this strabismic amblyope differ markedly both from the data of the nonamblyopic eyes, and from the results of the amblyopic eye of anisometropic amblyope G.M. (and T.G., shown in Fig. 7). Firstly, there does not appear to be a constant "Weber" fraction for bisection (at least over the 8 octave range of spatial frequencies tested). Rather, the "Weber" fraction for bisection gradually increases with increasing spatial frequency up to about 2 octaves below the resolution limits. However, note that even when scaled with respect to the cutoof spatial frequency, the retinal distances are much larger than those of the fellow eye. At still higher spatial frequencies, bisection thresholds increase sharply so that thresholds could not be measured at spatial frequencies higher than about 1.5 octaves below the cutoff spatial frequency. This "crowding effect" at high spatial frequencies is evident to some degree even in the nonamblyopic eye.

Interestingly, the effect of spatial frequency on the vernier thresholds of this observer are even more dramatic. Thus at 4 octaves below the resolution limit, vernier thresholds (N's) are about 2 percent of the distance between the lines; however between 3 and 2 octaves below the resolution limit vernier thresholds increase dramatically, so that this observer was unable to detect any offset 2 octaves below the resolution limit. We have previously reported similar "crowding effects" for vernier discrimination in 7 other strabismic amblyopes (Levi and Klein, 1982a, b). What is of particular interest here, is the finding that bisection and vernier thresholds are affected in different ways in the same observer. Thus, at low spatial frequencies there appears to be no constant "Weber" fraction for bisection with the amblyopic eye. Two octaves below the resolution limit, the bisection and vernier thresholds of the amblyopic eye appear to be approximately equal but are 4 and 8 times poorer (after scaling to the resolution limit) than the corresponding bisection and vernier thresholds of the fellow eye.

**STRABISMIC AMBLYOPIA:**

**BISECTION WITH OVERLAP**

The effect of spatial adjacency on the bisection thresholds of each eye of E.E. are shown in Fig. 6. The data with her nonamblyopic eye viewing are quite similar to the data of G.M.'s nonamblyopic eye for the same task, in showing a "Weber" fraction of about one part in ninety at low frequencies, and a constant retinal distance, approximately equal to that obtained with vernier alignment (about 9°), at higher spatial frequencies. The results with the amblyopic eye viewing, follow a similar form to that shown by this observer for bisection with no overlap (Fig. 5). As in the preceding figure, the "Weber" fraction, increases as spatial frequency increases. The lines for the non-
overlapped bisection data of Fig. 5 are redrawn in Fig. 6 to facilitate comparison. It is interesting to note that while the results of the bisection with overlap experiments follows the same form, the thresholds tend to be consistently lower. Inspection of the raw data and comparison of thresholds calculated with and without the confusion parameter led to the conclusion that the adjacency cues seem to allow the stimulus with no offset to be distinguished from those stimuli with either rightward or leftward offsets. This enhancement of offset detection, as opposed to offset direction discrimination is further treated in the Appendix.

Other observers

Figures 7 and 8 show the bisection results of 4 other observers with mild to moderate amblyopia. The data in Fig. 7 are for bisection-no overlap. The dashed lines are the geometric mean of the data of the non-amblyopic eyes. The error bars show the total range of the data rather than the standard error. The symbols show the results of the amblyopic eyes. The acuities are shown for each observer. The results are in good agreement with the data shown in Figs 3 and 5. For the anisometropic amblyope T.G. (open symbols) the results are similar to those of G.M. in showing a more or less constant “Weber” fraction at low spatial frequencies and a constant retinal distance at high spatial frequencies. The two strabismic amblyopes, R.G. (solid circles) and even J.B. with minimal acuity loss (solid circles and squares) show little evidence for a constant “Weber” fraction at low spatial frequencies, and a sharp rise in thresholds as spatial frequency increases, similar to the results of observer E.E. (Fig. 5). The half-solid circles show the results for observer J.V. with both constant strabismus (eso-
amblyope E.E. in Fig. 6. Each of the observers shows a departure from the constant retinal distance at high spatial frequencies, and only the anisometropic amblyope shows data consistent with a constant “Weber” fraction up to 4 octaves below the resolution limit.

Figure 9 summarizes the loss of positional information for each observer using a visuogram display (Bodis-Wollner, 1972; Tyler, 1981). The ordinate shows the ratio of scaled position thresholds (i.e. the “Weber” fraction) of the amblyopic to nonamblyopic eyes. This was obtained by taking the difference between the scaled data (log axes) of the amblyopic eye and the template fit to the data of the nonamblyopic eyes. The abscissa is spatial frequency scaled to the observers’ resolution limit. Note that these visuograms show the relative loss in position sensitivity after scaling for the grating resolution losses. The left hand panel are the results for bisection-no overlap; the right panel, bisection with overlap. The circles shown in the visuograms of G.M., E.E. and R.M. show the scaled losses in vernier acuity. Several features of these visuograms are noteworthy. (1) Anisometropic amblyopes show no additional loss of positional information for bisection-no overlap or vernier. Similarly for bisection with overlap, at low spatial frequencies there is no additional loss of position sensitivity; however, at high spatial frequencies both observers show “crowding” effects. (2) Strabismic amblyopes show marked losses in positional sensitivity over a wide range of spatial frequencies for each stimulus configuration. These observers show no constant “Weber” fraction at low spatial frequencies and crowding at high spatial frequencies. (3) Observers with both strabismus and...
amblyopes show results which are consistent with the
results of the observers with strabismus. (4) There
appears to be a gradation of the losses of strabismic
amblyopes which is more or less consistent with their
relative acuity losses. Interestingly, however, extreme
amblyope R.M. with 20/680 acuity shows similar
scaled position losses to J.V. with 20/80 acuity. It
should be noted however that R.M. has a very marked
anisometropia (probably congenital) and shows much
greater losses in grating resolution than J.V.

In order to further clarify the relationship between
the position acuity and Snellen acuity of strabismic
amblyopes we have plotted the **unscaled** position
thresholds (in seconds) for bisection-no overlap against
spatial frequency (normalized to the resolution limit)
for 4 strabismic amblyopes with Snellen acuities
ranging from 20/30 to 20/680. (Fig. 10). Snellen acuities
corresponding to the 75% correct level were determined
for each observer with the E charts designed by
Davidson and Eskridge (1977). These charts maintain a
constant interletter separation and a high degree of
contour interaction. These acuity values are plotted
beside the right most ordinate. For comparison, the
open symbols show the data of the nonamblyopic eye
of observer R.M. with the most marked amblyopia
(20/680) and interestingly, the nonamblyopic eye with the
best bisection acuity. The open circles are for a
test line plus grating. Open triangles are for test line
plus two reference lines, and the open squares are for a
test grating plus reference grating. As in Fig. 2, the
data of the nonamblyopic eye are reasonably well fit
at low spatial frequencies by a line with a slope of —1
(i.e. a constant Weber fraction) and at high spatial
frequencies by a constant retinal distance of about
17.5 sec, approximately 3 times smaller than her Snellen
acuity (i.e. a hyperacuity). The solid symbols are data
from amblyopic eyes of 2 strabismic amblyopes. The
half-solid symbols are from 2 observers with both
strabismus and anisometropia. For each of these
amblyopic eyes, the thresholds are more or less
consistent with a constant retinal distance at low spatial
frequencies, and marked increases in threshold at high
spatial frequencies. There are two points of special
interest here: (1) for observers with more marked losses
of Snellen acuity, the “crowding” occurs at lower
spatial frequencies than those with mild losses (in spite
of the fact that the abscissa is scaled to the observers’
cutoff spatial frequency), and (2) for each amblyope
with strabismus, the lowest position threshold (in
seconds of arc) coincides fairly closely with the
observer's Snellen acuity (shown on the right hand
ordinate); i.e. there is no hyperacuity. These results are
consistent with the notion that strabismic amblyopes
have a specific loss of position information, and that
the same visual mechanisms which limit their Snellen
acuity, limit their position acuity. We have previously
noted this close match between Snellen acuity and
position acuity in other observers using a vernier task
(Levi and Klein, 1982a,b).

The data of the two anisometropic amblyopes for bi-
section with overlap (where they show the greatest
abnormalities) are replotted in Fig. 11, in the same
coordinates as in Fig. 10. The open symbols are from

![Fig. 10. Bisection-no overlap data of 4 amblyopic eyes with
constant strabismus (solid symbols, no anisometropia; half-
solid symbols, both strabismus and anisometropia). The left
ordinate is position threshold (in seconds of arc), the right
ordinate shows the Snellen equivalent. The arrows pointing
toward the right ordinate show each observer’s Snellen
acuity. The abscissa is the fundamental spatial frequency
of the grating, scaled to the observers’ cutoff spatial
frequency. For reference the data of the nonamblyopic eye
of R.M. (the most severe amblyope, and with the acute
fellow eye) is shown. The open circles are for a test line
plus grating; open triangles, for a test line plus two reference
lines and the open squares are for test grating plus reference
grating.]

![Fig. 11. Bisection-with overlap data for two anisometropic
amblyopic eyes are replotted here in the same coordinates as
in Fig. 10. The open symbols are data of the nonamblyopic
eye of G.M. The solid circles and squares are for the
amblyopic eyes of G.M. and T.G. respectively. Their Snellen
acuities are shown along the right hand ordinate. The solid
triangles are data of the amblyopic eye of G.M. obtained
with “classical” stimuli (i.e. 2 reference lines and a test
line). Note that between 1 and 3 octaves from the cutoff
spatial frequency, thresholds with the classical stimuli are
more or less constant, while those with a test line and a
grating show marked “crowding.”]
the nonamblyopic eye of G.M. The line drawn through the low spatial frequency limb of the data has a slope of -1 (a constant "Weber" fraction). For spatial frequencies higher than 5 octaves below the resolution limit, thresholds are consistent with a constant retinal distance of about 11.5 sec, about 4 times lower than his Snellen acuity. The solid circles are the data of the amblyopic eye of the same observer, the solid squares are the data of another anisometropic amblyope (T.G.). For both amblyopic eyes, the low frequency limb of the functions are parallel to, but displaced up from the nonamblyopic eye, consistent with a constant Weber fraction which is elevated in proportion to the loss in grating resolution. The lowest thresholds of the amblyopic eyes of the anisometropic amblyopes (3.5 octaves below the resolution limit), like those of the nonamblyopic eyes, are about 4 times lower than their Snellen acuity, suggesting that in anisometropic amblyopes, as in normals, position discrimination is a hyperacuity. Interestingly however, for spatial frequencies higher than 3.5 octaves below the resolution limit, thresholds increase dramatically for both observers' amblyopic eyes. We attribute this dramatic increase in thresholds at high spatial frequencies to "crowding" effects. This conclusion is based upon a comparison of the thresholds of G.M.'s amblyopic eye when the stimulus was a test line embedded in a grating (shown by the solid circles) to results obtained when only two reference lines were presented (solid triangles). This point will be discussed further in the next section.

"CROWDING EFFECTS" IN SPATIAL LOCALIZATION

"Crowding" or contour interaction is a well known characteristic of amblyopic eyes (Flom et al., 1963; Hess and Jacobs, 1979). In a clinical setting, it is manifest as better acuity with single optotypes than with a line of optotypes and is more pronounced in strabismic than in anisometropic amblyopes (Stuart and Burian, 1962). At several points we have suggested that the absence of a constant vernier or bisection threshold at high spatial frequencies in amblyopes may represent a form of "crowding" (Levi and Klein, 1982a,b and present study). However, an alternative explanation is that position discrimination is simply poor in amblyopic eyes and becomes worse when the space to be judged is decreased. If this were the case, then the results obtained with classical bisection stimuli consisting of just two lines and a test line should be essentially the same as reported here, where the space to be bisected was embedded within a row of lines. Under "uncrowded" conditions, i.e. in the constant "Weber" fraction range, the results are equivalent with gratings and classical targets (see triangles in Figs 2, 3, 4 and 6). However, in amblyopic eyes, where thresholds increase markedly as spatial frequency increases, (i.e. under conditions which we have alluded to as showing crowding) quite different results are obtained with grating stimuli and classical stimuli.

Figure 12(A) shows how bisection thresholds of the amblyopic eye of R.G. depend upon the presence and number of flanking lines on either side of the lines defining the space to be bisected. The data shown here are for bisection of two lines separated by 17.4 min. The test line was either above the space to be bisected (bisection-no overlap, shown by the solid symbols) or was adjacent to the other lines (bisection with overlap, open symbols). The data shows that the addition of just a single pair of flanking lines essentially doubles the threshold for both conditions. Additional flanks further degrade spatial localization, but to a slightly greater extent for the non-adjacent case than for the adjacent stimuli. Figure 12(B) (open circles) shows similar effects for anisometropic amblyope G.M. for bisection with overlap of two lines separated by 16.1 min (about two octaves below his cutoff spatial frequency). It should be pointed out that the high confidence confusion parameter used to determine thresholds (see Methods) provides a conservative estimate of the loss of position information under conditions of "crowding", both in normal and amblyopic eyes. In effect where "crowding" occurs, these thresholds represent the ability to discriminate the blank (i.e. perfect alignment or bisection) from the offsets, even where there is some uncertainty regarding the direction of offset. This point is shown in Fig. 12(B) where detection thresholds (open circles - positive confusion parameter) and discrimination thresholds (solid squares - zero confusion parameter) are shown (see Appendix for details of how these two thresholds were obtained from the same raw data). The data show clearly that the effect of the flanking lines was to elevate the thresholds to a greater extent when confusion was not allowed than when it was.

It is also of interest to note that these "crowding effects" increase with increasing spatial frequency. For example, the solid triangles in Fig. 11 shows that for
the amblyopic eye of G.M., when tested with "classical" stimuli (2 reference lines and a test line), thresholds for bisection with overlap vary little as the interline separation changed from about 30 to 8 min. In this same range, between 3 and 1 octaves below the resolution limit, thresholds increased markedly with the addition of flanking lines (solid circles). In this range, with flanking lines, thresholds increased approximately 5 fold, becoming indeterminate one octave below the resolution limit. Thus, for both strabismic and anisometropic amblyopes, the marked degradation of thresholds at high spatial frequencies appears to be attributable to "crowding".

**DISCUSSION**

The results of the nonamblyopic eyes show that spatial localization is remarkably accurate. At low spatial frequencies, localization is a constant fraction (approximately 1/90) of the distance to be bisected. At high spatial frequencies, the results are consistent with a constant retinal distance which is smaller than the resolving capacity of the eye, and thus may be considered a "hyperacuity" (Westheimer, 1975). The present results also show that the spatial relationship between the lines demarcating the space to be bisected and the test line is important. Thus, when the lines were adjacent (bisection with overlap) the constant retinal distances are about one half of the values obtained with non-overlapping stimuli.

The present results show that amblyopes display marked abnormalities in spatial localization when viewing with their amblyopic eyes; however, the abnormalities depend upon both the type of amblyopia and the stimulus configuration. The pattern of results of anisometropic amblyopes and amblyopes with constant strabismus differ markedly. For the anisometropic observers spatial localization for non-adjacent stimuli, when scaled to the resolution losses, was normal. However, spatial adjacency, while enhancing the spatial localization of the nonamblyopic eyes at high spatial frequencies, markedly elevated thresholds in the amblyopic eye (Figs 4 and 8). The phenomenological reports of the observers may provide some insight into the difficulty experienced by anisometropic amblyopes with adjacent stimuli at high spatial frequencies. They report that with the non amblyopic eye, under equivalently "crowded" conditions, even when the resolution of the individual lines is difficult, the position of the bisecting line can be gauged by the brightness distribution of the pattern. Thus if the bisecting line is offset to the left, there will be an apparent brightening on the left. On the other hand, when it is centered, no such brightening occurs. Thus it appears that there may be cues to position in the luminance profile of nearby adjacent stimuli. When viewing with the amblyopic eye, anisometropic amblyopes seem to be unable to utilize these cues. Similar conclusions have been drawn based upon the inability of anisometropic amblyopes to discriminate the relative phase of compound gratings (Lawden et al., 1982; Pass and Levi, 1982). Interestingly, the retinal periphery displays a similar inability to perform such a task (Klein and Tyler, 1981). On the other hand, bisection-no overlap and vernier thresholds, when scaled to the resolution losses, appear to be more or less normal in anisometropic amblyopes, suggesting that orientation and position information are not markedly disturbed.

The results of strabismic amblyopes show much more disturbed spatial localization. Firstly, at low spatial frequencies, even with classical (uncrowded) stimuli there is no constant "Weber" fraction. It is in this low spatial frequency range that Bedell and Flom (1981) and Flom et al. (1982) have reported that strabismic (but not anisometropic) amblyopes make large constant errors. Our signal detection paradigm with feedback eliminates constant errors; however, it is interesting to note that the acuteness of position information is degraded in this range of spatial frequencies. This finding is especially striking in light of the robustness of the constant "Weber" fraction for position in normal vision. For example, using classical stimuli, the "Weber" fraction remains constant in the periphery of normal observers (Bedell, personal communication) and under scotopic conditions (Johnson and Bedell, 1982). The low spatial frequency results of strabismic amblyopes are consistent with a specific loss of position information and suggest further that for strabismic amblyopes the same mechanisms may be involved both in Snellen acuity and position acuity. At higher spatial frequencies bisection thresholds both with and without overlap are elevated; however, it is interesting to note that the "crowding" for vernier is more marked than that for the bisection experiments so that for E.E. (e.g. Fig. 6) there is a small range of spatial frequencies over which bisection is possible, but vernier is impossible.

The data of observers with amblyopia associated both strabismus and anisometropia seem to show the abnormalities associated with each of these conditions.

In both strabismic and anisometropic amblyopes we have demonstrated "crowding" effects. The "crowding" effects shown here for bisection seem to be directly attributable to abnormal spatial interactions (see Fig. 12). Contour interaction occurs in normal vision both for acuity (Flom et al., 1963) and for hyperacuity (Westheimer and Hauske, 1975), and therefore represents a normal physiological function; however, the extent of such interactions appear to be much greater both in the normal periphery (e.g. Bouma, 1970) and in the central field of the amblyopic eye (Flom et al., 1963; Hess and Jacobs, 1979; Levi et al., 1981).

The abnormalities shown here cannot simply be explained on the basis of eccentric fixation since similar results are obtained when the stimuli are two rows of gratings and are sufficiently extended to include both the fovea and the eccentric locus. Nor are the abnormalities likely to result from abnormal eye movements, since spatial localization does not depend upon a
stationary image (Westheimer and McKee, 1975; Faehle and Poggio, 1981; Morgan and Watt, 1982). Furthermore, in several observers the results were checked with brief exposures, and also by rotating the display through 90 deg. Neither of these manipulations altered the pattern of results. Thus, we conclude that the abnormal patterns of spatial localization represent neural abnormalities in the amblyopic visual systems. Since the pattern of results differs so strongly between the strabismic and anisometropic amblyopes, it seems reasonable to conclude that strabismus and anisometropia exert different influences on the development of spatial localization.

Since strabismus and anisometropia amblyopia can selectively (or at least unequally) affect different aspects of spatial analysis, it seems likely that there exists more than one mechanism (or strategy) for fine localization. Such a conclusion would be difficult to draw on the basis of experiments on normals, since similar threshold values are obtained with a variety of stimulus configurations (Westheimer and McKee, 1975). Thus, amblyopes, like dichromats in the color domain, may provide useful insights into the mechanisms of spatial analysis.

Acknowledgements—We thank Ruth Manny, Earl Smith and Harold Bedell for helpful discussions, and our observers for the many hours of experimental observations.

REFERENCES


APPENDIX

THE CONFUSION PARAMETER

Our observers (both amblyopic and nonamblyopic) sometimes reported that they made "high confidence confusions" where they were highly confident of the presence of an offset but were uncertain (or were certain but wrong) about direction of offset. A similar phenomenon was reported by Krauskopf and Campbell (cited in Krauskopf, 1980) for a vernier task. To illustrate this effect raw data from one run are shown in Table A1. These are the data which produced the thresholds shown in Fig. 12(B) for 3 lines on each side of the test line.

Table A1.

<table>
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</tbody>
</table>

The six flanking lines had a spacing of 16.1 min. The test line was presented at one of 7 equally spaced positions from 4.5 min to ±4.5 min around the bisection point with the overlapped configuration. The observer responded with integers from 3 to +3 depending upon the perceived position of the test line. The columns of the Table indicate the stimulus and the rows indicate the response. Thus, for example, of the 19 times the test line occurred far to the right the observer responded far to the right on 8 occasions and far to the left on 5 occasions. The surprising feature of this data is that of the 96 times the test line was presented away from the symmetry point, the observer called it symmetric only 2 times. That is, the observer rarely missed an offset. Yet the direction of offset was incorrectly judged 30 out of the 96 times. The observer correctly identified the zero offset case 7 out of 33 times implying the middle category was indeed being used.

This type of data can occur whenever there are two or more types of mechanisms or strategies available. For the present data, one strategy which is always present is relative position. In the case of bisection with overlap the strategy of spatial symmetry may also be used. The observer may be able to detect a "brightening" or an asymmetry when the test line is displaced from the bisection point and yet the direction of offset may not be discriminable.

In order to obtain both the detection threshold (recognition of the zero offset stimulus) and the discrimination threshold (recognition of offset direction) a modification of our regular signal detection methodology (Levi and Klein, 1982) was used. The discrimination threshold was obtained in the standard manner as follows. The 7 × 42 independent data points shown in the Table were fit by a 7 parameter maximum likelihood function. Six of the parameters were the criteria levels used by the observer in order to subdivide the responses into seven categories. The seventh parameter was the threshold. The d' values were proportional to the stimulus offset. For the data shown, the discrimination threshold was 6.6 ± 1.4 min. For this data the d' distance between the rightmost stimulus (4.5 min to the right) and the leftmost stimulus (4.5 min to the left) was d' = 1.35. The threshold is obtained by extrapolating to a d' of unity. In order to obtain the detection threshold the data is reprocessed using an extra parameter (the confusion parameter). This parameter gives the probability by which an offset stimulus gets mistaken for a stimulus of the opposite sign. For the data under discussion the confusion parameter had the value 0.23 ± 0.05, and the detection threshold was 2.4 ± 0.3 min. This threshold corresponds to a d' distance between the bisection stimulus and an end stimulus of d' = 1.9.

The precise way in which the confusion parameter enters the calculation is now described. The standard ROC curve is based on a noise distribution

\[ f_n(x) = \phi(x) \]  

where \( \phi(x) = \exp(-x^2/2\sigma^2) / \sqrt{2\pi} \), and a signal distribution

\[ f_s(x) = \phi(x - k/t) \]  

where \( t \) is the threshold (offset in minutes producing a d' of unity) and \( k \) is the stimulus offset in minutes. Thus \( k/t \) is the expected d' for an offset of k min. High confidence confusion data is fit by assuming the signal distribution has the form

\[ f_s(x) = (1 - \sigma)\phi(x - k/t) + \sigma\phi(x + k/t) \]  

where \( \sigma \) is the probability that the stimulus will be judged to be of the wrong sign.

In our experiments the confusion parameters became negligible whenever the Weber fraction was below 0.02. It became large (>0.1) under two circumstances: (a) for bisection with overlap, when the Weber fraction was above 0.03 (most of the strabismic amblyopes fell in this range), (b) for bisection without overlap when the Weber fraction was above 0.25. Although the latter circumstance is to be expected with the repetitive pattern, the former is surprising. Much remains to be done to fully understand the crowding phenomena which allow the amblyopes to detect bisection but not discriminate offset direction.