Seattle. This research was supported in part by NEI grant 1 R01 EY 02510 to Ronald G. Boothe, NIH research grants RR 00166 to the Regional Primate Center, NICHD 02274 to the Washington Regional Child Development and Mental Retardation Center, and EY 01730 to the Interdisciplinary Ophthalmic and Vision Research Center of the Department of Ophthalmology. Part of this work was presented at the spring meeting of the Association for Research in Vision and Ophthalmology, Sarasota, Fla., 1980. Submitted for publication July 24, 1980. Reprint requests: Lynne Kiorpes, Infant Primary Laboratory, WJ-10, University of Washington, Seattle, Wash. 98195.

Key words: strabismus, monkeys, animal model

REFERENCES


Monocular spatial distortion in strabismic amblyopia. Harold E. Bedell* and Merton C. Flom.

We examined monocular spatial vision of strabismic amblyopes by measuring errors of relative directionalization (specifying whether or not two targets are in vertical alignment) and partitioning (equating left- and right-field spaces). Abnormally large errors were made when fixation occurred with the amblyopic eye; these errors are not attributable to reduced acuity, unsteady fixation, or eccentric fixation. From the results we infer that monocular space perception of strabismic amblyopic eyes is severely distorted and is characterized by "bending" of vertical lines of direction and by local "compressions" and "expansions" of horizontal spatial values. Such distortions can readily account for many of the oculomotor abnormalities of the amblyopic eye as well as for the strabismic subject's phenomenological description of the difficulties experienced in using this eye—difficulties that are typically much worse than the reduced acuity would predict.

In their classic paper, Wald and Burian11 proposed that the visual deficit of strabismic amblyopic eyes affects form or pattern vision with sparing of light perception and spatial projection. In order to assess form vision, Wald and Burian measured visual acuity for letters presented on a standard clinical chart. Pirenne's subsequent analysis of visual acuity (resolution) as a special type of light difference discrimination raises doubt as to whether such visual acuity measurements adequately evaluate form vision.

A number of observations indicate that the visual deficit in strabismic amblyopia is not adequately specified in terms of acuity (or of grating contrast sensitivity, which has recently been proposed to supplant traditional visual acuity measures but which is also readily subsumed by Pirenne's light-difference discrimination analysis). Measured visual acuity of amblyopic eyes typically shows considerable variability and depends, in part, on whether a full chart, single lines of letters, or isolated symbols are used.4 Hess et al. have presented contrast sensitivity curves for two strabismic amblyopic eyes that are indistinguishable from those for their subjects' preferred eyes. Indeed, grating resolution thresholds reported for strabismic amblyopic eyes are typically much better than expected from the performance of these eyes on letter acuity tests. Clearly, the visual angle subtended by an acuity or grating target may not be the sole variable, or even the most relevant, in determining the visual performance of an amblyopic eye.

About 20 years ago, Pugh6,7 reported that amblyopes perceived distortions when they viewed test letters with the affected eye; their descriptions included abnormal spacing between letters or their parts, fragmenting of letter, and changes in the shapes of letters. Recently, Hess et al.8 reported
Fig. 1. Stimulus configuration used to evaluate relative directionalization; it shows the test line displaced leftward of center of the hourglass-shaped fiducial target. When fixating with the amblyopic eye, many of our strabismic subjects called a test line displaced from center by about this amount "right" and "left" equally often.

Similar descriptions of distortions from amblyopes viewing suprathreshold bar gratings. Quantification of this spatial distortion was probably first accomplished by Schor. He performed partitioning experiments on one strabismic amblyope, the affected eye showing relative underestimations of distances in the temporal field by as much as a factor of 3.

We present here for several strabismic amblyopic eyes measures of (1) spatial distortion, quantified as the relative overestimations and underestimations of spaces in the nasal and temporal fields and (2) aberrated relative directionalization, quantified as the lateral offset of a target for it to be perceived as vertically aligned with two others. In combination, spatial distortion and directionalization errors are probably sufficiently large to account for many of the visual deficits of amblyopic eyes. We therefore propose that the Wald-Burian early concept of impaired form vision be broadened to impaired spatial vision and that measures of spatial errors be used to specify and describe this major visual deficit of strabismic amblyopia.

Methods. We tested monocular relative directionalization and partitioning of space with visual targets presented on the screen of a Commodore PET microcomputer and viewed from a distance of 50 cm. The nonviewing eye was occluded with an opaque patch and padded shut.

To measure monocular relative directionalization, subjects specified the perceived horizontal location of a luminous vertical line (3.4 by 32 min arc) with respect to the vertical axis of an hourglass-shaped fiducial target. This target (Fig. 1) consisted of two luminous isosceles triangles (base 4.6 deg, altitude 2.8 deg) with the altitudes aligned vertically and the facing apices separated by 1.6 deg. The test line was flashed for 130 msec at one of several horizontal locations rightward or leftward of the vertical axis of the fiducial target. To encourage fixation at the center of the target and to ready the subject for the test line presentation, two vertical lines (7 by 32 min arc; one at the tip of each triangle) were flashed for two half-second cycles before flashing of the test line.

For monocular partitioning of space, subjects fixated the central one of three horizontally separated luminous vertical lines (3.4 by 32 min arc). The position of the righthand line was fixed and defined a standard space between it and the central fixation line. For each fixed position of the righthand standard target, the subject adjusted the lefthand line (in 3 min arc steps) to produce a space between it and the fixation line that was perceptually equal to the standard space.

Results

Relative directionalization. The results for our 13 strabismic amblyopes were plotted as the percentage of "right," "left," and "centered" re-

<table>
<thead>
<tr>
<th>Standard space, right of fovea (deg)</th>
<th>Subjectively equivalent space, left of fovea (deg ± 1 S.D.)</th>
<th>Standard space Equivalent space</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.56 ± 0.08</td>
<td>0.59</td>
</tr>
<tr>
<td>1.0</td>
<td>1.33 ± 0.16</td>
<td>0.75</td>
</tr>
<tr>
<td>2.0</td>
<td>3.20 ± 0.28</td>
<td>0.63</td>
</tr>
<tr>
<td>3.0</td>
<td>3.81 ± 0.28</td>
<td>0.79</td>
</tr>
<tr>
<td>4.0</td>
<td>4.86 ± 0.44</td>
<td>0.82</td>
</tr>
<tr>
<td>5.0</td>
<td>5.72 ± 0</td>
<td>0.87</td>
</tr>
<tr>
<td>6.0</td>
<td>6.43 ± 0.04</td>
<td>0.93</td>
</tr>
<tr>
<td>8.0</td>
<td>8.53 ± 0.12</td>
<td>0.94</td>
</tr>
</tbody>
</table>
Fig. 2. Relative directionalization data for two strabismic amblyopic eyes are plotted as the percentages of "right" (triangles), "left" (squares), and "centered" (circles) responses for each of several displacements of a test line from the center of the fiducial target. The locus of subjective alignment is the crossing point of the "right" and "left" response functions. The locus of subjective alignment is about 30 min left of center for the left amblyopic eye of subject R. W. (40° esotropia and 8° hypertropia of the left eye; left eye acuity 20/80 with 2° nasal eccentric fixation) and about 18 min left of center for the left amblyopic eye of subject J. F. (20° esotropia of the left eye; left eye acuity 20/180 with 2° temporal and 0.8° inferior eccentric fixation).

Fig. 3. a, Locus of subjective alignment for the right eye of normal subject G. S. is almost exactly centered. b, When foveally fixating 3 deg left of the fiducial target, G.S.'s locus of subjective alignment is displaced about 15 min leftward, i.e., in the direction of the foveal axis. c, Locus of subjective alignment is close to center for the right eye of subject B. A., despite a congenital jerk nystagmus having an amplitude of about 3 deg and a frequency of about 3 Hz. Visual acuity of B. A.'s right eye is 20/70.

*The normal threshold for detecting misalignment of a test line from a fiducial, which is the typical dependent variable in relative directionalization studies, is on the order of 5 to 20 sec arc. That the locus of subjective alignment for some of our normal subjects was displaced from the fiducial by over 1 min arc is explained by our dependent variable, which is a measure of constant error rather than threshold, as well as by our spatial and temporal stimulus parameters, which are not optimal for relative directionalization judgments.*
Figs. 4a and 4b. Monocular partition settings (± 1 S.D.) of two strabismic amblyopes (T. M. and J. F.) are plotted as the size of the space in the left field (ordinate) that was judged equivalent to a standard space in the right field (abscissa). Shown above is the ratio of the standard to the equivalent space for each standard space matched. The settings for the two amblyopic eyes reveal marked and nonuniform spatial asymmetries; settings for the preferred eyes are much closer to physical matches (indicated by the dashed lines both above and below). Subject T. M. has 15° esotropia of the left eye; its acuity is 20/100 with 3° of nasal eccentric fixation; the clinical data for Subject J. F. are given in the legend to Fig. 2.
duced acuity or to the unsteady, eccentric fixation of amblyopic eyes? In persons with congenital nystagmus, wherein there is reduced acuity and very unstable fixation, we found the locus of subjective alignment to be close to the physical center of the fiducial target (Fig. 3, c). The effect of eccentric fixation was examined by having normal subjects monocularly view the stimulus array eccentrically; under this condition, normal subjects made relative directionalization errors similar in magnitude to some of the amblyopes, but opposite in direction (Fig. 3, b). Although the locus of subjective alignment for eccentrically viewing normal subjects was shifted from the fiducial target toward the foveal axis, for the majority of the amblyopic eyes (eight of the 11 who made errors of 10 min arc or larger) it was shifted away from the foveal axis and lay on the opposite side of the fiducial target.

We conclude that the errors of relative directionalization for strabismic amblyopic eyes are not accounted for by their reduced acuity or their unsteady and eccentric fixation. Indeed, the use of an extrafoveal retinal location for fixation by the amblyopic eye might diminish the magnitude of the measured relative directionalization error—by an amount equal to the oppositely directed error made by a normal eye viewing the stimulus eccentrically.

Partitioning in the horizontal meridian. In our partitioning procedure we always presented the standard space to the right of the fixation mark, and the subject adjusted the lefthand target so that the space between it and the fixation mark was perceived equal to the standard space. We depicted the obtained results with the size of the standard space plotted on the abscissa and the subject’s target setting (or subjectively equivalent space) plotted on the ordinate.

The most common response for the six amblyopic eyes we tested is shown for two subjects in Figs. 4a and 4b. For the largest standard space of 8 deg, both subjects set the lefthand target only about 7 deg from fixation to perceive the two spaces equal. Since both subjects had amblyopia of the left eye, the smaller setting was in the temporal field, indicating a relative overestimation of this space in this field. For the smallest standard space of 0.5 deg, the subjects set the temporal field target between 1 and 2 deg, indicating underestimation of this space. The course of the data points between 8 and 0.5 deg indicates a transition from overestimation to underestimation at about 2 to 3 deg. In this region of transition the flatness of the “curve” suggests that several standard spaces in the nasal field were perceived as a single size (or nearly so), which was therefore matched with a single target setting (or nearly so) in the temporal field.

Can these marked nasal-temporal asymmetries be explained by the fixational unsteadiness and/or imaging of the central target at a nonfoveal locus that occurs with eccentric fixation? Subjects with congenital nystagmus did not exhibit large partitioning errors, indicating that the retinal image motion generated by fixational unsteadiness probably was not responsible for the partitioning errors of amblyopic eyes. With regard to the retinal locus issue, we performed experiments on one of our amblyopes in which the central rod was imaged at or very close to the fovea; with the standard and test spaces on opposite sides of the fovea, marked spatial asymmetries were still evident (Table I).

We have shown marked spatial asymmetries with amblyopic-eye fixation at the eccentric locus and at the fovea. However, we cannot tell whether the distortion of monocular space indicated by these asymmetries is confined to one side of the fixation point or whether it is present on both sides. To clarify this point, we directed two subjects (T. M. and J. F.) to fixate first the rightmost and then the leftmost target and to adjust the position of the lefthand target to define two perceptually equal spaces first within the temporal, then within the nasal field. Abnormally large partitioning errors were made within both half fields, indicating that distortion of space was present on both sides of the eccentric fixation locus and extended to at least the fovea, perhaps somewhat beyond it.

Discussion. Monocular testing of the affected eye of strabismic amblyopes revealed large constant errors in the relative directionalization of vertically arranged targets and marked asymmetries in the partitioning of horizontal spaces. We believe that these spatial errors, occurring in orthogonally separate meridians, represent two manifestations of a single deficit—namely, a severe distortion of monocular perceived space within at least the central field of these amblyopic eyes. The errors made with the amblyopic eye fixating indicate a distortion of perceived space characterized by “bending” of vertical lines, each having a common visual direction, and by local “expansions” and “compressions” of spatial values across the field.

Is such distortion of perceived monocular space an unexpected finding in strabismic amblyopic eyes? When the preferred eye of a strabismic amblyope is occluded as a therapeutic measure, the patient often reports distortion, especially of reading material. An associated complaint is the...
inability to move the amblyopic eye accurately from one word to another. Indeed, the inaccurate eye movements that amblyopes often describe, and which have been verified objectively,8 can readily be appreciated to be a consequence of distorted space perception. Hence, aspects of unsteady fixation, irregular smooth pursuit, and directional overshooting and undershooting of saccades, all of which characterize the oculomotor behavior of strabismic amblyopic eyes,8 become explicable in terms of the aberrated visual error signals that must result when the directionalization of a stimulus in space is subject to marked nonuniform distortion.

This spatial distortion must also have deleterious consequences for visual acuity. Relative "expansion" and "compression" of space as well as "bending" of vertical lines of direction must be expected to distort the features of single optotypes6 and, when presented in an array, to blend neighboring letters together into invalid or unrecognizable percepts.7 As a result of the amblyopic eye's unsteady fixation, these percepts must also be considered to be changing in time.8 Distortion would be expected to have a severe effect on the identification of complex targets, such as optotypes. In contrast, there should be a much less disturbing influence on the detection of repetitive spatial patterns such as gratings, for which the positions of the individual elements (spatial phase) are relatively unimportant. Thus the typical finding that visual acuity for strabismic amblyopic eyes is poorer for letters than for gratings2 is understandable because distortion of monococular space limits performance on the letter task whereas performance on the gratings task is primarily determined by the resolving properties of the visual system. Indeed, the visual complaints of strabismic subjects when viewing with the amblyopic eye are more readily attributable to aberration of monococular space sense than to impairment of the resolving capacity of the visual system.

Hence, unlike Pugh,6 7 we do not view these aberrations of monococular spatial vision as merely an interesting but isolated phenomenon associated with amblyopic vision. Nor do we agree with Pugh that these spatial aberrations represent abnormalities at the level of the retina. The magnitude of the spatial errors as well as their probable amelioration with successful therapy suggest to us, as to Hess et al.,4 that these errors occur centrally and probably at the visual cortex. Whatever their anatomical and physiological substrate, only quantitative analysis of these monococular distortions can reveal the extent to which they account for or underlie the sensory and oculomotor abnormalities of strabismic amblyopic eyes.

From the School of Optometry, University of California, Berkeley. Supported by National Eye Institute Research Grants EY 02125 and EY 03694 (Dr. Flom). Submitted for publication July 8, 1980. Reprint requests: Harold E. Bedell, Ph.D., College of Optometry, University of Houston, Central Campus, Houston, Texas 77004. *Present address: College of Optometry, University of Houston, Houston, Texas.

Key words: strabismus, amblyopia, space perception, partitioning errors, directionalization, acuity, eye movements

REFERENCES

Normal square wave jerks. Yuval O. Herishanu and James A. Sharpe.

Fixation stability of the saccadic system was investigated by infrared reflection oculography in 29 normal subjects, young and elderly. Square wave jerks consisting of spontaneous horizontal saccadic excursions of 0.5° and over, followed some 200 msec later by corrective saccades, were recorded in 24% of subjects. The frequency of square wave jerks in the elderly was significantly higher than in young subjects. The results suggest that square wave jerks more frequent than 9/min in young patients can be considered abnormal.

Square wave jerks (SWJ) are sporadic horizontal conjugate saccades away from the intended po-