Spatial Aberrations and Acuity in Strabismus and Amblyopia

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Spatial uncertainty and distortion were quantified from judgements of the horizontal position of a flashed 0.5 deg vertical line with respect to a flanking reference target in strabismics with and without reduced acuity. Spatial uncertainty was outside the range of 30 normal eyes in all of 23 strabismic amblyopic eyes (visual acuity = 20/40 or worse) and in 20 of 22 squinting eyes with 20/30 or better acuity. Abnormal spatial distortion was found in 16 amblyopic and 10 squinting eyes. In the deviated eyes of the strabismics, the extent of spatial uncertainty and distortion correlated with visual acuity. Spatial aberrations were not accounted for by strabismics' unsteady or eccentric fixation, nor were they mimicked in normal eyes when visual acuity was artificially reduced. The authors suggest that spatial uncertainty and distortion represent the primary abnormalities in strabismics and produce deficits of visual acuity according to their severity. Invest Ophthalmol Vis Sci 26:909-916, 1985

Although functional amblyopia is defined as a reduction of one eye's visual acuity (not attributable to uncorrected refractive error or observable pathology), distinguishing amblyopic from normal eyes using an acuity criterion is problematic. One problem is that measured acuity, particularly for strabismic amblyopic eyes, varies substantially with the type of target used. For example, acuity for gratings is typically much better than for letters and, even for letters, acuity depends significantly upon the relative positions and spacing of optotypes. A second problem is that, regardless of how the acuity is measured, no clear cutoff exists that distinguishes amblyopic from nonamblyopic eyes: while eyes with 20/40 or worse acuity are virtually universally agreed to be amblyopic, disagreement exists among clinicians about whether or not eyes with 20/30 or 20/25 acuity should also be labeled as amblyopic. Qualitatively similar but quantitatively more severe oculomotor and sensory abnormalities occur in strabismic amblyopic eyes, suggesting that these abnormalities exist along a continuum and are at least roughly related to the acuity level.

While perhaps related in severity to the magnitude of acuity loss, oculomotor and sensory abnormalities that occur in strabismic amblyopic eyes are not readily explicable by the reduction of acuity. Motor and sensory abnormalities with similar characteristics are not produced in normal eyes when acuity is reduced artificially by decreasing luminance or introducing optical blur. However, motor deficits such as inaccurate fixation and tracking, sensory difficulties in discriminating suprathreshold targets and controlling visually-guided behaviors, as well as the marked...
Fig. 1. Spatial uncertainty and distortion were quantified from responses of the perceived position of the vertical line with respect to the hourglass-shaped reference target.

dependence of measured acuity on the kind of target used can be explained plausibly by strabismic amblyopes' uncertain and distorted spatial sense, which we previously quantified and proposed to be the primary deficit in these eyes.\textsuperscript{23,24}

If spatial uncertainty and distortions account for oculomotor and sensory abnormalities in strabismic amblyopic eyes, then such spatial abnormalities would be expected also to occur in the deviated eyes of strabismics who, despite normal or nearly normal acuity, exhibit similar oculomotor and sensory abnormalities. Indeed, if spatial uncertainty and distortions occur in the eyes of strabismics with normal acuity, then it is unlikely that reduced acuity accounts for these spatial abnormalities. The reduced acuity in strabismic amblyopic eyes may itself be attributable to spatial uncertainty, spatial distortion, or their combination. The purpose of this study, then, is to quantify spatial uncertainty and distortion in strabismic eyes with normal or nearly normal acuity, and compare the results to measures obtained from normal and strabismic amblyopic eyes. Additionally, the relations between spatial uncertainty, spatial distortion, and acuity were examined in strabismic and normal eyes.

Materials and Methods

Spatial uncertainty and distortion were quantified from observers' judgements of the horizontal location of a briefly flashed luminous vertical line (3.4 by 32 min arc) with respect to the vertical axis of an hourglass-shaped reference target (Fig. 1). The reference target consisted of two luminous isosceles triangles (base, 4.6 deg; altitude, 2.8 deg) with their altitudes aligned vertically and the facing apices separated by 1.6 deg. On each trial, the test line was flashed for 130 msec at one of several horizontal locations rightward or leftward of the reference target's vertical axis. Prior to each presentation of the test line, the observer was cued with a ready signal, either auditory (1-sec tone) or visual (2 half-sec on, half-sec off presentations of targets marking the vertical axis of the reference target). Observers viewed the stimuli (luminance = 43 cd/m\textsuperscript{2}) on the screen of a PET microcomputer (Commodore; West Chester, PA) from a distance of 0.5 m and responded to each presentation of the flashed line by indicating its direction as "right," "left," or "centered" with respect to the axis of the reference target. Testing was monocular, the nonviewing eye being occluded with an opaque patch.

Psychometric functions were fit to the percentages of "right" and "left" responses at the different target positions using probit analysis and a maximum likelihood criterion. Spatial uncertainty was quantified as the line's displacement threshold—the change in the line's horizontal position (in min arc) required to increase the probability of "right" or "left" responses by 1 probit (from 50 to 84%). Spatial distortion was quantified as the constant error in specifying alignment of the line and reference target—the difference (in min arc) between the position of the line where "right" and "left" responses were equally likely (as obtained from the fitted psychometric functions) and physical alignment with the reference target. Experiments with three normal observers and three strabismic observers in which "center" responses were not permitted showed that neither the line displacement threshold nor the constant error of alignment depended upon whether two or three response categories were allowed.

The observers were 22 squinters (16 esotropes and 6 exotropes) with Snellen acuity in the deviated eye of 20/30 or better, 23 strabismic amblyopes (20 esotropes and 3 exotropes with visual acuity of 20/40 or worse in the deviated eye), and 15 normal subjects recruited from the staff and students of the
Results

Pronounced spatial uncertainty and distortion characterized strabismic amblyopic eyes, defined by visual acuity of 20/40 or worse (Figs. 2, 3). In contrast to normal eyes, whose displacement thresholds ranged from 1.2 to 2.5 min arc (median = 1.7), thresholds for the amblyopic eyes ranged from 4 to 47 (median = 12.3) min arc. Constant errors of alignment ranged to 32 min arc in the strabismic amblyopic eyes (median = 11.6 min arc), whereas a constant error exceeding 2 min arc was found in only one normal eye (median = 0.55 min arc). In strabismics' ambyopic eyes, the direction of constant errors of alignment depended upon the direction of deviation. Errors were temporalward (i.e., the line was called "left" and "right" equally often when temporalward of the reference target's physical axis) in 17 of the 20 esotropes and nasalward in two of the three exotropes. Of the normal eyes, approximately equal numbers exhibited temporalward (N = 14) and nasalward (N = 16) constant errors.

Twenty of 22 squinters with 20/30 or better acuity also exhibited abnormal uncertainty in specifying when the line and reference target were spatially aligned (Fig. 2). For the deviated eyes of these squinters with normal or nearly normal acuity, displacement thresholds ranged from 1.6 to 12.3 (median = 5.1) min arc. Spatial distortion was outside the normal range in 10 of these squinters' deviated eyes (Fig. 3), with constant errors ranging from approximately zero...
Fig. 3. Frequency histograms compare constant errors of line-displacement for normal eyes, nondeviated and deviated eyes of strabismics with 20/30 or better acuity, and strabismic amblyopic eyes. Standard errors range from less than 1 min arc to about 5 min arc, and depended largely on the value of the line-displacement threshold. For the nondeviated eyes of the strabismic amblyopes (not shown), constant errors were distributed similarly to those for the nondeviated eyes of squinters with 20/30 or better acuity. Eyes of esotropes and exotropes are represented as in Figure 2.

to 11.1 min arc (median = 2.6 min arc). As in the strabismic amblyopic eyes, constant errors tended to be temporalward in the deviated eyes of esotropes (12 of 16) and nasalward in the deviated eyes of exotropes (4 of 6).

In the nondeviated eye, nine of the 22 squinters with 20/30 or better acuity and 10 of the 23 strabismic amblyopes exhibited abnormal uncertainty (threshold displacement > 2.5 min arc). Constant errors were abnormally large (>3 min arc) in the nondeviated eyes of three of the squinters with normal acuity and three with reduced acuity.

To determine whether spatial uncertainty and distortion were related to visual acuity, we measured visual acuity psychometrically in 23 of our strabismic subjects. Because acuity measured for strabismic amblyopic eyes depends substantially on the spatial arrangement of targets, we used a letter chart with controlled contour interaction.6 For these 23 eyes, visual acuity (expressed as log min arc) correlated highly with spatial uncertainty (r = 0.86) and moderately with spatial distortion (r = 0.52). In Figure 4, it is apparent that one linear function adequately describes the relation between visual acuity and spatial uncertainty in strabismics’ deviated eyes over the entire range of acuities. It is also apparent that normal eyes (stippled area in Fig. 4) are not described by this function. In contrast, the measured values of spatial distortion for squinting and normal eyes partially overlap (Figs. 2, 5).

The higher correlation of visual acuity with spatial uncertainty than with spatial distortion suggests that the former relation is functionally more important. Partial correlations25 revealed that holding the effect of spatial distortion constant had virtually no effect on the correlation between acuity and spatial uncertainty [r(partial) = 0.84], but when spatial uncertainty was controlled, the correlation between acuity and spatial distortion became negative [r(partial) = −0.44]. The straightforward interpretation of these results is that spatial uncertainty is the measure in strabismics that is primarily related to visual acuity. However, this interpretation would be moot if our obtained correlation between spatial uncertainty and distortion (r = 0.78) underestimated the true relation, eg, because of variability in our spatial measures or because we assessed only horizontal and not vertical constant errors. If perfect correlation existed between the spatial uncertainty and distortion of strabismic eyes, then presumably both spatial abnormalities would have a
common basis and of necessity, would be related equivalently with acuity.

Following this line of thought, it is possible that measures of both spatial abnormalities were influenced by the abnormal pattern of fixation in strabismic eyes. Previously, we showed that abnormally large constant errors of alignment (spatial distortions) exhibited by strabismic amblyopic eyes were not attributable to the presence of unsteady monocular fixation: despite severely unsteady fixation, patients with reduced acuity and congenital nystagmus exhibited only slight spatial distortion. As an additional control for the rapid eye movements and eye position errors that occur during unsteady fixation, we repeated spatial measures in 10 strabismic eyes (6 with 20/40 or poorer acuity) with both the line and reference targets briefly flashed (130 msec). Under this condition, eye movements and eye-position errors during fixational unsteadiness should not affect the perceived location of the line and reference target differentially. As shown in Figure 6, magnitudes of spatial uncertainty measured with the entire display flashed were highly correlated \( r = 0.96 \) and were similar to those measured with a continuously visible reference.

To determine whether the nonfoveal fixation that characterizes strabismics' deviated eyes could account for measured spatial abnormalities, we compared spatial uncertainty and distortion in three strabismic amblyopic eyes (visual acuity ranging from 20/40 to 20/240) when the display was presented at the nonfoveal locus of fixation and at the fovea. Foveal viewing was obtained by having subjects fixate a target displaced from the center of the display by an amount equal to the magnitude of eccentric fixation. The results of this control experiment show that foveal viewing does not reduce the magnitude of spatial uncertainty or distortion (Table 1). Further,
That strabismic eyes with normal visual acuity show spatial uncertainty outside the normal range strongly suggests that uncertainty in strabismic amblyopic eyes does not result from reduced acuity. Additional evidence to support this contention was obtained by artificially reducing the acuity of normal eyes with optical blur and by reducing target luminance. Although spatial uncertainty increased when normal eyes were blurred to the equivalent of 20/100 at 0.5 m (on average +4.00 diopters over the distance correction) and when the display luminance was reduced to 0.4 cd/m² (Fig. 4), the resulting uncertainty was substantially less than in strabismic amblyopic eyes with equivalent acuities. Indeed, displacement thresholds in normal eyes when blurred or when target luminance is reduced are, on average, equivalent to or better than the displacement thresholds of squinting eyes with 20/30 and better acuity.

Discussion

Our results confirm that marked spatial uncertainty and distortion occur in the deviated eyes of constant squinters with reduced acuity. Abnormal uncertainty, and in many cases distortion, also characterize spatial judgements made with the deviated eyes of strabismics with nearly normal and normal acuity. Because spatial abnormalities occur in strabismics with normal acuity, but not when acuity is reduced artificially in normal eyes, spatial uncertainty and distortion in strabismic amblyopic eyes can not reasonably be accounted for by the acuity deficit.

If reduced acuity is not the cause of spatial uncertainty and distortion, can we conclude, then, that spatial uncertainty and/or distortion are responsible for the acuity deficits of strabismic amblyopic eyes? Although strong correlation exists between spatial measures and visual acuity in strabismics’ deviated eyes (Figs. 4, 5), this correlation might occur because both a distorted and uncertain spatial sense and reduced acuity result from some other abnormality. We have ruled out two such abnormalities by showing

<table>
<thead>
<tr>
<th>Acuity of amblyopic eye</th>
<th>Eccentric locus</th>
<th>Fovea</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Threshold (min arc)</td>
<td>Constant error</td>
</tr>
<tr>
<td>20/40</td>
<td>8.7 ± 0.9</td>
<td>0.9 ± 0.9</td>
</tr>
<tr>
<td>20/100</td>
<td>36.7 ± 3.9</td>
<td>17.1 ± 3.3</td>
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<tr>
<td>20/240</td>
<td>10.3 ± 2.2</td>
<td>15.0 ± 2.3</td>
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Thresholds and constant errors of displacement at the eccentric fixation locus.

fovea of strabismic amblyopic eyes

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that neither unsteady nor eccentric fixation can account for measured spatial abnormalities in our strabismics. Further, mislocalizations and uncertainty about where letters or fragments of letters are with respect to other letters and/or letter-fragments provides a plausible basis for the impaired visual acuity of strabismic amblyopic eyes and for why acuity varies substantially according to the configuration and spacing of targets. Our correlational data indicate that spatial uncertainty is related more importantly to the impaired identification of letters by strabismic amblyopic eyes; however, our data also indicate that spatial uncertainty and distortion are themselves related strongly. While we are hesitant to speculate on mechanisms that might underlie these obtained correlations, we note that uncertainty and distortion of spatial judgements, along with reduced visual acuity, occur together in normal peripheral vision, which is cited frequently as an analog for the central vision of amblyopic eyes.

We suggest, therefore, that although reduced acuity is used clinically to define strabismic amblyopia, spatial uncertainty and/or distortions are likely to produce the acuity deficit. We further suggest that spatial uncertainty and distortions act in conjunction to produce most or all of the additional motor and sensory abnormalities characteristic of strabismic amblyopic eyes.

If spatial uncertainty and distortion are the primary deficits in strabismic amblyopic eyes, then one might be justified in labelling all constantly deviated eyes as "amblyopic." The justification for doing so is our finding that strabisms' deviated eyes exhibit a continuum of spatial uncertainty (related to their acuity), distinct from the range found in normal eyes. Further, many of our subjects showed abnormal uncertainty and/or distortions in making spatial judgements with the nondeviated eye,

<table>
<thead>
<tr>
<th>Subject</th>
<th>Log minimum angle of resolution (min arc)</th>
<th>Log displacement threshold (min arc)</th>
<th>Fixational eccentricity (min arc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.24</td>
<td>0.46</td>
<td>23</td>
</tr>
<tr>
<td>2</td>
<td>-0.10</td>
<td>0.55</td>
<td>44</td>
</tr>
<tr>
<td>3</td>
<td>-0.07</td>
<td>0.58</td>
<td>70</td>
</tr>
<tr>
<td>4</td>
<td>-0.06</td>
<td>0.54</td>
<td>25</td>
</tr>
<tr>
<td>5</td>
<td>-0.02</td>
<td>0.74</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>0.12</td>
<td>0.63</td>
<td>11</td>
</tr>
<tr>
<td>7</td>
<td>0.16</td>
<td>0.74</td>
<td>19</td>
</tr>
<tr>
<td>8</td>
<td>0.16</td>
<td>0.79</td>
<td>36</td>
</tr>
</tbody>
</table>

both eyes of strabismics. We suggest that measures of spatial uncertainty and/or distortion might be used profitably to examine the development of strabismic amblyopia and to evaluate the effects on each eye of therapeutic interventions.

Key words: strabismus, amblyopia, spatial sense, visual acuity

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References


