Monocular Geometry Is Selectively Distorted in the Central Visual Field of Strabismic Amblyopes

Mario Fronius and Ruxandra Sireteanu

Strabismic amblyopia is associated with a distorted perception of visual space. The aim of our study was to investigate the monocular space perception of strabismic observers at several locations in the central and peripheral visual field. We tested nine observers with strabismic and/or anisometropic amblyopia, two strabismic subjects with alternating fixation and two normal control subjects. The task was to align a light stimulus with two vertically arranged reference marks. Testing conditions included three separations of the references along the vertical meridian (10°, 20° and 40°) as well as several presentation sites of the vertical references in the nasal and temporal peripheral visual field (5°, 10° and 20° from fixation). Performance with the amblyopic eye was clearly impaired as compared to the nonamblyopic eye. For alignment along the vertical meridian, all amblyopic eyes showed increased uncertainty in their position judgements. Most of the squinting eyes of amblyopes also displayed a systematic lateral displacement of the test stimulus in relation to the reference marks, in the most extreme case up to almost 7°. Usually, larger errors were found with wider separations of the reference marks. In the peripheral field, the differences between the amblyopic and the nonamblyopic eye diminished or disappeared. Thus, monocular geometry appears to be selectively impaired in the central visual field of the deviated eye of strabismic amblyopes. These spatial distortions might be related to the different states of binocular correspondence in the central vs. peripheral visual field, shown by some strabismic amblyopes. Invest Ophthalmol Vis Sci 30:2034-2044, 1989

Amblyopia has been long considered to be almost exclusively a deficit of visual resolving capacity. However, recent evidence indicates that, in addition to acuity loss, strabismic amblyopes show distorted space perception in their deviated eye1,2 as well as an impaired localization of objects in space.3,4

During our previous work with amblyopes, strabismic subjects frequently reported distortions of geometry in their deviated eye: equal horizontal distances were perceived as unequal; some of several vertically aligned dots were subjectively perceived as shifted from their actual position. This latter observation suggested that subjective localization of objects in space is selectively shifted in some regions of the visual field.

Several other visual functions are known to be affected only in certain parts of the visual field of strabismic amblyopes. Visual acuity and binocular functions are reduced in the central visual field, but not in the periphery.5 Interocular suppression is most pronounced in a corresponding central area of the visual field.6,7 In the accompanying paper,8 we reported that the dichoptic shift of retinal coordinates shown by many strabismics (anomalous retinal correspondence) is frequently less pronounced in the central visual field than in the periphery.

Thus, it is conceivable that monocular geometry is also more distorted in the central visual field than in the periphery. In the present study we investigated, with a vertical alignment task, the dependence of subjective monocular stimulus localization on the locus of presentation of the stimuli in the visual field.

Indeed, some of the strabismic amblyopes we tested showed marked alignment errors in the central field of their deviated eyes. However, when the peripheral field was tested, the judgements of the two eyes became very similar.

We were interested to know whether the monocular distortions experienced by strabismic amblyopes in their deviated eyes are related to the state of retinal correspondence in different parts of the visual field. We proposed that the dichoptically measured selective shift of coordinates in the peripheral visual field of the deviated eye might be carried over in a monocularly perceivable distortion of visual space. If this is true, the monocular geometry in the deviated eye...
should be predictable from the pattern of dichoptic localization. To answer this question, the same subjects were tested in both experiments.

We found that the irregularities of retinal correspondence can explain the monocular distortions in some subjects. Where this was not the case, it is possible that events in the individual clinical history of the subjects (age at squint onset, therapy) influenced the two functions unequally and thus obscured the relationship.

Part of the results of this study were presented in abstract form.9,10

Materials and Methods

Subjects

Nine strabismic and/or anisometropic amblyopes and two strabismic subjects with alternating fixation were tested. With the exception of R.D., all of these subjects also participated in the retinal correspondence experiments. Details about the orthoptic status and the clinical history of all subjects are given in Tables 1 and 2 of the accompanying paper.8 Four of these subjects (F.E., R.M.M., J.R., G.Z.) were available only for the correspondence experiments.

Consent was obtained from all subjects after the nature of the procedures was explained fully.

Apparatus

The apparatus consisted of a semitranslucent screen (luminance 0.3 cd/m²) with two black, vertically arranged reference points (8 or 13 mm diameter) on it. Behind the screen at half distance between the reference points was a horizontal line of 64 light-emitting diodes (LEDs) of high luminance (interdiode distance 7.5 mm) which were controlled via a microcomputer (Z 80). The LEDs could be individually lit by remote control by the subjects. During the experiments only one illuminated LED and the two reference points were visible to the subjects. In the experiments where the nasal or temporal periphery was tested, an additional LED could be switched on as a fixation point at distances of 5°, 10° or 20° from the tested vertical.

Procedure

The subjects were seated in front of the screen at distances of 34, 70 or 142 cm. Correspondingly, the distance of each reference point from the line of LEDs was 20°, 10° or 5°, respectively. The subject’s head was fixed on a chin rest.

On pressing a button, one LED light appeared on the screen. When the vertical meridian (passing through the fovea or the eccentric fixation locus) was tested, the subjects were asked to fixate the light stimulus and move it to the right or left until the stimulus was perceived exactly on the imaginary line connecting the two reference points. This LED position was recorded. The step width from one LED to the next was 1.26°, 0.61° or 0.3°, respectively, for the distances of 34, 70 and 142 cm of the subject from the screen.

When the nasal or temporal periphery was tested, the subjects fixated an LED on the horizontal meridian, 5°, 10° or 20° to the right or to the left of the tested vertical. Again, the subjects were asked to align a light stimulus with the reference points.

The procedure was carried out monocularly with either eye. Fifteen to 30 values were recorded in each condition. At each new start, an LED within ten positions to the right or to the left of the correct one was randomly illuminated.

In an additional experiment, vertical alignment was tested with multiple test stimuli. Test stimuli were presented at different positions between the two vertical references. In one condition, the test stimulus was shown only in the presence of the reference marks; in another condition, black dots were successively added on the screen at the positions where the subject perceived the test stimulus as being aligned with the references until the dots built up a complete line.

Results

Alignment along the Vertical Meridian

Strabismic amblyopes solved this vertical alignment task easily and very accurately with their dominant eye. Five of the nine subjects chose the correct position in 100% of the 20–30 trials in each condition (10°, 20° and 40° separation of the reference points). The others made an occasional wrong judgement, not more than one LED position too far nasally or temporally. Therefore, the nonamblyopic eye is a good control for the amblyopic eye under these experimental conditions.

Adjustment made under the control of the amblyopic eye was clearly less accurate. Two components of the impaired position judgement became evident: uncertainty was always increased (visible as a larger variability of the data); and a systematic error was made by most subjects (manifested as a shift of the mean away from the correct position).

Figures 1 to 4 show the means of the results of four strabismic amblyopes and at the same time illustrate the test situation. The reference points (represented by circles with a diagonal black band) are separated by 40°, 20° and 10°, respectively. Although the experiments were done separately for each eye, the re-
ESOTROPIC AMBLYOPE (B.H.)

- RE (non-amblyopic)
- LE (amblyopic)
- Position of reference points

Fig. 1. Vertical alignment of the nonamblyopic eye (open circles) and the amblyopic eye (filled circles) of an esotropic amblyope (B.H.). The reference marks (circles with diagonal bands) are separated by 40°, 20° or 10°. Each data point is the average of 30 adjustments. Standard deviations were smaller than the symbols.

RESULTS OF THE NONAMBLYOPEIC EYE (OPEN CIRCLES) AND THE AMBLYOPEIC EYE (FILLED CIRCLES) ARE PRESENTED TOGETHER IN EACH FIGURE IN ORDER TO FACILITATE COMPARISON.

The subjects whose results are shown in Figures 1 and 2 are two esotropes (B.H., M.F.) and in Figures 3 and 4 two exotropes (O.L., P.H.). Subjects B.H. and O.L. had large angles of squint (15–20°); M.F. and P.H. had small angles (4–10°).

The means of the alignment judgements of these subjects’ nonamblyopic eyes (open circles) were exactly on the line connecting the reference points, irrespective of their separation. The means of the adjustments with the amblyopic eyes (filled circles) were usually shifted from the correct position. The shift was temporalward for the exotropes and nasalward for the esotropes.

The results of all subjects are shown in Table 1. It gives the means of the systematic errors (positive values for nasalward errors and negative values for temporalward errors) and the uncertainty (expressed as standard deviation) of each eye for all subjects.

Two of the esotropes (B.H. and M.F.) also presented in Figs. 1 and 2) showed a consistent, large nasalward shift of the adjustments of their deviated eyes for all the reference point separations. For subject J.W. this shift was only significant for a 40° separation of the reference marks. Subject U.R. frequently set the stimulus one position too far temporally for all the reference point separations, whereas R.D. did so only when the references were 10° or 20° apart. Subject D.M. did not show a systematic shift in either direction.

Both exotropic amblyopes set the light too far temporally, O.L. in all three conditions, P.H. only when the reference points were separated by 10° and 20° (see also Figs. 3 and 4).

In four subjects (B.H., M.F., U.R., O.L.), the systematic error increased as the separation of the reference points became larger. This is most evident in subject O.L., where the mean shift started at 49 min arc (with 10° separation) and increased to 2°56' (20° separation) and even to 6°43' (40° separation) (see also Fig. 3).

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The two esotropic subjects with alternating fixation and with nearly equal (M.F.o) or equal (L.D.) vision in both eyes showed only occasionally incorrect adjustments towards their nasal field (Table 1).

The tested anisometropic amblyope without strabismus (P.S.) differed in the variability of judgements with the nonamblyopic and the amblyopic eye (see Table 1). The judgements with the nonamblyopic eye were correct in 100% of the trials, irrespective of the separation of the reference stimuli. In the amblyopic eye, there was an increased positional uncertainty and a small bias of the position settings towards the nasal field, especially when the reference stimuli were separated by 20° (Fig. 5). This nasal bias was, however, much less than in most of the strabismic amblyopes.

Vertical Alignment with Multiple Test Stimuli

Our test situation where the three dots are the only visual stimuli is of course quite artificial. We do not know from the results of these experiments whether an isolated shift of the fixated middle dot takes place or if there is a bending along the whole vertical meridian. However, the fact that systematic errors increased markedly with larger separation of the reference points in subjects B.H. and O.L. (see Figs. 1 and 3), suggests that distorted space perception is not confined to the fixation locus. In an additional experiment, we tested a strabismic amblyope who showed clear alignment errors already with 10° separation of the reference marks (M.F., see Fig. 2), presenting the test stimulus at different positions between the two vertical references. The positions where the subject perceived the test stimulus as aligned with the reference points built up to a curved line, rather than a straight vertical line with a shifted center. This was true both when the test stimulus was shown only in the presence of the reference marks and when black dots were successively added on the screen at the tested positions until the line was complete (see Fig. 6). Thus, not only the fixation locus

Table 1. Results of the vertical alignment experiment†

<table>
<thead>
<tr>
<th>Subjects</th>
<th>NE</th>
<th>10°</th>
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<th>20°</th>
<th></th>
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<td></td>
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<tr>
<td>B.H.</td>
<td>0°±0</td>
<td>8°±12*</td>
<td>0°±0</td>
<td>23°±22*</td>
<td>0°±0</td>
<td>1°56'±43°*</td>
<td></td>
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<tr>
<td>M.F.</td>
<td>0°±0</td>
<td>1°53'±35°*</td>
<td>0°±0</td>
<td>2°22'±25°*</td>
<td>0°±0</td>
<td>2°22'±38°*</td>
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<tr>
<td>J.W.</td>
<td>0°±0</td>
<td>5°±22°</td>
<td>0°±0</td>
<td>5°±30°</td>
<td>0°±0</td>
<td>40°±43°*</td>
<td></td>
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<tr>
<td>U.R.</td>
<td>36°±216°</td>
<td>12°±9°*</td>
<td>0°±0</td>
<td>5°±30°</td>
<td>0°±0</td>
<td>40°±43°*</td>
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<tr>
<td>R.D.</td>
<td>36°±360°</td>
<td>1°±7°</td>
<td>1°±7°</td>
<td>27°±32°*</td>
<td>0°±0</td>
<td>2°±37°</td>
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<td>D.M.</td>
<td>36°±540°</td>
<td>13°±13°*</td>
<td>0°±16°</td>
<td>7°±24°</td>
<td>0°±28°</td>
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<tr>
<td>O.L.</td>
<td>0°±0</td>
<td>49°±44°*</td>
<td>0°±0</td>
<td>2°56°±44°*</td>
<td>0°±0</td>
<td>6°43°±50°*</td>
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<td>P.H.</td>
<td>0°±0</td>
<td>29°±45°*</td>
<td>0°±0</td>
<td>28°±46°*</td>
<td>0°±0</td>
<td>5°±59°</td>
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<td>P.S.</td>
<td>0°±0</td>
<td>6°±11°</td>
<td>0°±0</td>
<td>19°±19°*</td>
<td>0°±0</td>
<td>4°±16°</td>
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<td>Alternators</td>
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<td>M.F.o.</td>
<td>36°±180°</td>
<td>12°±8°*</td>
<td>1°±7°</td>
<td>0°±0</td>
<td>5°±19°</td>
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<tr>
<td>L.D.</td>
<td>2°±5°</td>
<td>0°±0</td>
<td>0°±0</td>
<td>10°±26°</td>
<td>5°±19°</td>
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Positive values: nasalward error; negative values: temporalward error. NE: nonamblyopic eye; AE: amblyopic eye.

Asterisks: Differences between the means of right eye and left eye are statistically significant (P < 0.05).

† Mean systematic alignment errors and standard deviations of both eyes of all subjects for 10°, 20° and 40° separation of the vertical reference marks.
ANISOMETROPIC AMBLYOPE (P.S.)

- RE (non-amblyopic)
- LE (amblyopic)
- Position of reference points

DISTANCE FROM REFERENCE LINE (degrees)

Fig. 5. Vertical alignment of an anisometropic amblyope without strabismus (P.S.). Symbols as in Figure 1. N = 20-25.

This shows a shifted subjective direction in space. A larger area of the visual field of the deviated eye seems to be more or less involved in abnormal space perception.

Relationship of Distortions to Visual Acuity and Angle of Strabismus

The uncertainty of the alignment judgements was closely related to the subjects' visual acuity. Standard deviations of adjustments of subjects with lower visual acuity were usually larger than those of subjects with relatively good vision (r = -0.83) (see Fig. 7).

The correlation between the magnitude of the systematic positional error and visual acuity was weak (r = -0.54), but significant (P < 0.001) (see Fig. 8). In this context, we were interested in the amount, not in the direction of the constant error. Therefore, the sign of the systematic errors was not considered in the figure and for the calculation. Large systematic errors occurred mostly in severe amblyopes. However, some subjects with very low vision in the amblyopic eye (e.g., J.W., visual acuity 0.08) showed hardly any systematic error (see Table 1). On the other hand, B.H. set the middle dot up to almost 2° too far nasally despite her relatively good visual acuity in the amblyopic eye (0.6-0.8).

A weak relationship was also found between the size of the constant errors and the uncertainty of position settings (r = 0.54). Although large standard deviations occurred with large constant errors, in the case of relatively correct mean position judgement, standard deviations showed the whole range from 0 to 60 min arc.

There was a significant relationship between the angle of squint and the direction and magnitude of the systematic alignment error (r = 0.67, P < 0.001). A divergent squint was associated with a temporalward alignment shift, a convergent squint more frequently with a nasalward shift. The subjects with the largest squint (O.L., B.H.) were among those who had the clearest alignment errors. However, the relationship was not very close: subjects with a similar squint...
may have different monocular geometry (M.F., R.D.; see Table 1).

**Vertical Alignment in the Peripheral Visual Field**

In order to determine whether the spatial distortions of the amblyopic eyes of strabismics are confined to the central visual field, we retested three strabismic amblyopes with the same task, but with the vertically aligned reference points at 5°, 10° or 20° in the nasal or temporal visual field. The vertical separation of the reference points was again 10°, 20° and 40°, respectively. The three subjects with the clearest systematic alignment errors (B.H., M.F., O.L.) were chosen to participate in this experiment. For comparison, two control subjects with normal vision (R.S., S.B.) were tested.

Some subjects (R.S., S.B., B.H.) had difficulties when the references were presented at 20° in the temporal field, since the blind spot interfered with adjustment around the locus of subjective alignment. It has to be considered that the imaginary line connecting the reference points on our flat screen intersected the horizontal meridian at 20° from fixation. Due to the projection onto the retina of points presented in the peripheral visual field on a flat screen (see ref. 11), the locus of subjective alignment was shifted towards the fovea and into the blind spot. Therefore, these subjects were tested with the references above and below the 16° position in the temporal and nasal field. Thus, the locus of subjective alignment was shifted centralwards from the inner border of the blind spot.

In this situation, the control subjects consistently set the adjustable light too close to the fovea, both when the nasal and when the temporal fields were tested (see Fig. 9 for an example). In subject R.S., the shift was up to 52 min arc at 10° eccentricity and up to 5° at 16° in the nasal and temporal field.

Similar results as in the controls were observed in the nonaffected eye of the strabismic amblyopes.

The results of the esotropic amblyope B.H. are shown in Figure 10, in the upper panel for 10° in the nasal and temporal visual field and in the lower panel the 16° positions. The alignment judgments along the vertical meridian were included in the figures in order to facilitate comparison between alignment in the central and peripheral visual field. At 10° in the nasal field, the judgments of the two eyes were different, but with the results of the amblyopic eye shifted in the opposite direction than along the vertical meridian. At 10° in the temporal field, an alignment error towards the same direction as in the central visual field was still present. The alignment errors persisted at 16° in the temporal visual field. However, at 16° in the nasal field, the results of the right and left eye were equal (see Fig. 10).

In subject M.F., the clear alignment differences be-
ESOTROPIC AMBLYOPE (B.H.)

Fig. 10. Vertical alignment at 10° (upper panel) and 16° (lower panel) in the temporal and nasal visual field of an esotropic amblyope (B.H.). The reference marks are separated by 20° and 32°, respectively. Open symbols: nonamblyopic eye; filled symbols: amblyopic eye. N = 15-30. Standard deviations were smaller than the symbols.

tween the nonamblyopic and the amblyopic eye along the vertical meridian diminished or even disappeared in the peripheral visual field (Fig. 11). At 5° in the temporal field, the mean position chosen with the amblyopic eye was still shifted nasally in comparison with the normal eye (not illustrated). At the other locations, however, the results of the two eyes were approximately equal. At 20° in the temporal field, there was even an inversion in the sense that the adjustments made under the control of the amblyopic eye were shifted temporalwards compared to those of the nonamblyopic eye.

Note, however, that due to eccentric fixation of the amblyopic eye, the retinal positions tested were not exactly identical in the two eyes of subject M.F. The tested positions were at distances of 5°, 10° or 20° from the fixation locus, which is the fovea in the nonamblyopic eye, but a 3.5° nasal retinal locus in the amblyopic eye. Therefore, the tested positions in the nasal field of the squinting eye were 3.5° closer to the fovea than in the nonsquinting eye. In the temporal visual field, the 3.5° of eccentric fixation increased the distance between the reference points and the fovea of the amblyopic eye. Considering that the alignment shift towards the fovea in the nonsquinting eye increases as the distance from the vertical meridian becomes larger, eccentric fixation reduces misjudgments in the nasal field and exaggerates them in the temporal field of the squinting eye. However, this does not change the conclusion that position judgments are more similar in the peripheral than in the central visual field of the two eyes of this strabismic amblyope.

In subject O.L., who showed very marked alignment errors towards the temporal field when tested along the vertical meridian (see Fig. 3), the alignment judgments of the two eyes also became very similar in the peripheral visual field (Fig. 12). There was still a temporalward shift in the left eye at 5° eccentricity and 10° separation of the references (Fig. 12, left upper panel). With 20° separation and 10° eccentricity, the adjustments of the two eyes were nearly equal (right lower panel). The similarity between the judgments of the right and left eye in the peripheral visual field was most impressive when the references were separated by 40°; in that condition this subject had shown an alignment difference of almost 7° between the two eyes along the vertical meridian. Alignment
of the two eyes was equal at 20° in the nasal field. The alignment with the left eye was even shifted slightly nasally as compared to the right eye at 20° in the temporal field (Fig. 12, left lower panel).

In order to control for the influence of reference mark separation vs. eccentricity, we added to the usual testing conditions a condition with the references separated by 20°, but presented at 5° in the nasal and temporal visual field (Fig. 12, right upper panel). At this eccentricity, the alignment errors of the amblyopic eye were clearly larger with 20° than with 10° separation of the reference marks (compare with left upper panel). And, with this reference mark separation, a clear localization error was present at 0° and 5° in the nasal and temporal visual field, but absent at 10° in both hemifields (compare with right lower panel). These results confirmed that, at a given eccentricity, a larger separation of the reference marks produces more distorted alignment judgments than a smaller reference mark separation. In addition, they showed that, with a given reference mark separation, central visual field loci showed more severely distorted monocular geometry than peripheral regions.

Discussion

We found distorted monocular space perception along the vertical meridian of the deviated eyes of most of our strabismic amblyopes. This deficit became evident as inaccuracy (larger variation of position adjustments) and as a systematic lateral displacement of the test stimulus in relation to the vertically arranged reference points. In the nasal and temporal peripheral visual field, the difference between the nonamblyopic and amblyopic eye usually diminished or disappeared.

Evaluation of the Results

To our knowledge, this is the first attempt to compare the relative direction in space of central and peripheral retinal locations in strabismics. In addition, it is the first demonstration that errors of vertical alignment are diminished in the peripheral visual field.

In some subjects, we recorded monocular distortions of a magnitude which has not been reported in strabismic amblyopes up to now. The large errors occurred mostly in subjects with severe amblyopia.
Subjects with a visual acuity better than 0.8 had only minimal constant errors. In subjects with acuities of 0.08-0.1, however, we saw the whole range of distortions, from a few minutes of arc to almost 7°. The correlation of systematic localization errors and visual acuity was weak (see Fig. 8). On the other hand, we found a strong negative correlation between positional uncertainty and visual acuity (see Fig. 7). Reduced visual acuity seems therefore to be linked to imprecision of spatial judgements, but it is not likely to be the cause of systematically wrong alignment. This conclusion is supported by the results of a study in which the acuity of normal eyes was artificially reduced with optical blur while the subjects performed a vertical alignment task. Although spatial uncertainty increased under these conditions, displacement thresholds were less impaired than in squinting eyes with clearly better acuity.

The direction of the alignment errors was related to the direction of squint; however, as pointed out in Results, the amount of visual distortion perceived by the subjects could not be predicted reliably from their angle of squint.

Considering that the control subjects set the test stimulus too close to the fovea when the reference stimuli were presented in the peripheral visual field (see Fig. 9), the question arises of whether the alignment errors along the vertical meridian in strabismic eyes are due to eccentric fixation. This cannot be the case, since we saw constant errors in subjects with central (O.L., B.H.) and eccentric (M.F.) fixation. On the other hand, some subjects with far eccentric fixation (P.H., J.W.) made relatively correct spatial judgements (see Table 1).

Comparison with Previous Studies

Until a few years ago, only sparse and mostly qualitative descriptions existed about distorted monocular vision in the squinting eyes of amblyopes. Recently, however, it became increasingly clear that strabismic amblyopia is accompanied by distorted visual perception. It was shown that amblyopes make large errors in partitioning a horizontal line. Bedell and colleagues also found errors of vertical alignment in strabismics with and without amblyopia. However, they found small alignment errors of up to 32 min arc, whereas in our subjects the largest errors were more than 6°. Differences in set-up and measuring procedure may explain the different results. Bedell and Flom used two reference triangles whose facing apices were vertically separated by only 1.6°. They used a briefly flashed (130 msec) test line whose position relative to the apices of the reference triangles had to be reported by the subjects.

In our experiments, the reference points were vertically separated by 10°, 20° or 40°. The larger separation of the reference points may be the reason why we found larger alignment errors. This supposition is supported by the finding that in several of our subjects (O.L., B.H., M.F., U.R.) the alignment errors became larger as the separation between the reference points increased. In addition, our test stimulus was presented continuously and had to be adjusted on the imaginary line connecting the reference points.

The direction of the systematic error of our subjects depended on the direction of squint: the two exotropic subjects set the adjustable light stimulus consistently too far temporally, while the esotropes more frequently set the stimulus too far nasally. These results are at variance with those of Bedell et al, who saw more frequently a shift in the opposite direction: 17 of 20 esotropes localized the test stimulus too far temporally, two of the three exotropes too far nasally. Although the reason for this discrepancy is not clear, differences in testing procedure may contribute. Beside the already mentioned differences, our subjects were instructed to take up and keep fixation on the adjustable light stimulus and to bring this point into a position where it had the same subjective direction in space as the two reference points. In the procedure used by Bedell and colleagues, the subjects were asked to keep fixation on the illusory line connecting the apices of the reference triangles. The test line was then presented nasally or temporally from fixation. In fact, with the same procedure, Flom et al recently showed in their Figure 4 alignment errors that varied from temporalward to nasalward, depending on target location, for one esotropic amblyope; however, according to the legend of this Figure, "the point of subjective equality of flashed line is decidedly to the left," that is, temporalwards. Further experiments comparing the two procedures are needed to elucidate the origin of these discrepancies.

Our experiment with multiple test stimuli indicates that not only the fixation locus of the deviated eye of amblyopes shows shifted subjective direction in space (see Fig. 6). A larger area of the visual field seems to be more or less involved in abnormal space perception. This finding is in agreement with a recent study in which a two-dimensional map of monocular space values of an esotropic amblyope is presented, which shows marked distortions in some regions of the visual field. The question remains, however, as to what extent strabismic subjects experience geometric distortions in a more complex or in a natural visual environment.

Although we tested more peripheral areas of the visual field and we used a slightly different procedure, we found similar correlations between visual acuity...
and positional uncertainty or systematic alignment errors as Bedell et al. 4

There is a controversy in the literature about the positional accuracy of the nonamblyopic eyes of amblyopes. Levi and Klein 13 reported poorer than normal vernier thresholds in the nonamblyopic eye of strabismic amblyopes. Bedell et al 4 found more errors in the dominant eye of amblyopes as compared to subjects with normal vision in a vertical direction- alization test similar to ours. On the other hand, Freeman and Bradley 14 and Rentschler and Hilz 15 claim that their amblyopic subjects had better positional accuracy in a vernier task with their nonamblyopic eye than their control groups.

The nonamblyopic eyes of our amblyopic subjects were very accurate: frequently 100% of the alignment trials were correct. However, in our set-up the detection of errors was limited by the spacing of the LEDs (see Methods). We could not reliably detect errors of the magnitude of 6 min arc or less, as measured in the studies mentioned above for the normal subjects or the dominant eyes of squinting subjects. Therefore, we did not compare the dominant eyes of squinting subjects and normal controls for alignment in the central field. Rather, the dominant eye of our squinting subjects served as reference for the squinting eye.

Considerations about the Etiology of Localization Errors

Bedell and Flom 3 speculated that reduced visual acuity and abnormal eye movements are not the cause, but a consequence of distortions and uncertainty originating at a central level, possibly “at the visual cortex.”

Levi and coworkers 16 showed increased positional uncertainty in the central field of the deviated eye of strabismic amblyopes, similar to that in the normal peripheral visual field. They concluded that spatial uncertainty in amblyopic eyes, as in the normal periphery, is related to reduced cortical sampling grain. This, however, cannot explain the systematic localization errors experienced by strabismic amblyopes. Beside a coarser sampling grain, there must be a selective change of positional information for elements in the central visual field of these subjects—possibly by misrouted connections.

We wondered whether the monocular distortions might be related to the dichoptically measured shift of space coordinates of strabismic amblyopes, described in the accompanying paper. 8 Early strabismus is often associated with a shift of retinal coordinates of the deviating eye in the sense of a compensation for the angle of squint (anomalous retinal correspondence). Dichoptic localization tests revealed that the state of retinal correspondence was not uniform across the visual field of our squinting subjects. We found an increased tendency for the peripheral visual field to show harmonious anomalous correspondence, as opposed to unharmonious anomalous or normal correspondence in the center. In addition, irregularities in the pattern of correspondence frequently occurred in different parts of the visual field.

The anatomical substrate of anomalous retinal correspondence is unknown. However, it is conceivable that dichoptically measured shifts of space coordinates affect the monocular maps of visual space. We tried to relate the subjective localization of dichoptic stimuli along the vertical meridian with monocular localization in the same region of the visual field, by testing the same subjects in both conditions. These comparisons were not made quantitatively, as the conditions differ in the two situations; for example, subjects reported the amount of misalignment in the dichoptic study and set targets to alignment in the monocular study. Rather, localization differences between the central and the peripheral visual field were qualitatively compared, especially with respect to the direction of mislocalizations.

For some of our subjects, the unequal shift of retinal coordinates seen in the dichoptic localization task may explain the distortions of monocular space perception. An example is illustrated in the results of the two tests of the untreated esotropic subject M.F. In the dichoptic localization test (see Fig. 1 in the accompanying paper 8 ), the stimulus presented to the squinting left eye was perceived as clearly shifted more to the left (towards the temporal field) in the central visual field than in the periphery; this was true also for the vertical meridian passing through the eccentric fixation locus (not illustrated). If the shift of retinal coordinates and monocular space perception were related, this would predict that of three vertically aligned elements, the middle one would be seen as shifted to the left (temporalwards) by the squinting left eye in the monocular experiment. Indeed, as if to compensate for the temporal shift in the central visual field, the middle dot was set too far nasally (see Fig. 2 of this article).

We confirmed by a control experiment that in this subject the relationship holds even when the dichoptic experiment is changed. The stimulus presented to the squinting eye was laterally displaced until the subject perceived the two squares as vertically aligned. In agreement with the reported displacements in the previous experiment (see Fig. 1 in the accompanying paper 8 ), the subject needed a displacement of the square towards the right in order to see the squares as aligned. The needed displacement was larger in the central visual field than in the periphery.
The anisometropic amblyope P.S. showed hardly any monocular alignment errors, as could be predicted from his regular dichoptic localization pattern (Fig. 5 of this article and Fig. 7 in the accompanying paper). In some subjects, the relationship between dichoptic and monoptic adaptations was less clear. O.L. for example showed a pattern of correspondence which is certainly not adapted to his present angle of squint. It is difficult to see differences of perceived shift of the dichoptically presented squares in his correspondence pattern (Fig. 4 in the accompanying paper). However, he showed the clearest monocular systemic evidence pattern (Fig. 4 in the accompanying paper). If one considers the stimuli in the dichoptic experiment that are imaged on a vertical meridian near the fovea of the deviated left eye (about 20° left from fixation), the stimulus in the upper visual field was shifted slightly more rightward than the stimulus on the horizontal meridian and that in the lower visual field. If at all, this would predict a slight rightward (nasalward) compensatory shift of the middle dot in the monocular alignment task. Instead, we saw a leftward (temporalward) shift of up to almost 7°. This subject had a complicated history: a large anisometropia, possibly a convergent strabismus in early childhood and a spontaneous change to a divergent squint at some unknown age; two operations for divergent strabismus at the age of 6 years and another operation at 22 years; a postoperative squint of –15° to –20°. It is conceivable that the clinical history of this subject had unequal impact on different visual functions, and that he acquired his pattern of monocular space perception at a different age than his current pattern of retinal correspondence.

While this research was in progress, Flom and co-workers suggested a relationship between monocular distortions and anomalous retinal correspondence, although in a slightly different sense. They discussed that spatial distortions and uncertainty in strabismus might "represent adaptive changes designed to facilitate some form of binocular vision . . . anomalous retinal correspondence and/or uniquely shaped horopters." However, no attempt was made to confirm the relationship by testing subjects in both binocular and monocular conditions.

Our results suggest a relationship between monocular and dichoptic localization in strabismics. Unfortunately, the known variability of data collected in populations of amblyopes does not allow a more decisive conclusion.

In summary, our experiments add to the knowledge of space perception in strabismus and amblyopia, especially concerning the distribution of distortions across the visual field. Further investigations with more complex visual stimuli are needed to understand how strabismic vision functions in a natural visual environment.

Key words: human amblyopia, strabismus, monocular spatial distortions, peripheral visual field

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