Different Patterns of Retinal Correspondence in the Central and Peripheral Visual Field of Strabismics

Ruxandra Sireteanu and Maria Fronius

We tested the state of retinal correspondence at different positions in the visual field of ten observers with strabismic and/or anisometropic amblyopia, four strabismic subjects with alternating fixation and three normal controls. Correspondence was evaluated by the subjective displacement of dichoptic stimuli; to estimate the displacement, we used red-green filters, Bagolini striated glasses, polarizing filters and a phase-difference haploscope. Strabismic observers (amblyopes and alternators) frequently showed variations in the angle of anomaly (ie, the amount of shift of space coordinates in the squinting eye) between different regions of the visual field. Correspondence tended to be closer to normal in the central field and more anomalous in the periphery. These findings cannot be explained by the progressive loss of localization sensitivity with increasing eccentricity. We suggest that the different patterns of retinal correspondence in the central and peripheral visual field of some strabismic observers might be due to a mechanism of selective stabilization of binocular connections in the peripheral visual field, where the larger corresponding areas overcome a limited misalignment of the eyes. In the central visual field, normal correspondence is preserved, and diplopia has to be prevented by interocular suppression. Invest Ophthalmol Vis Sci 30:2023-2033, 1989

Normal binocular vision includes fusion of the retinal images of the two eyes in a single visual percept. Fusion is disrupted when the visual axes are not properly aligned or when the retinal images are of unequal optical quality due to differences of refractive power of the two eyes.

If a misalignment of the visual axes occurs in early childhood, the visual system has two ways to adapt to the situation and avoid diplopia.

One known possibility is the elimination of one image from further processing at some stage of the visual pathway by interocular suppression. Chronic suppression of a squinting eye may be associated with a complex of impaired visual functions (reduced visual acuity, loss of binocularity), known as strabismic amblyopia.

However, not all parts of the visual field of the amblyopic eye are equally affected. The loss of visual acuity is confined to the central visual field, coinciding with a region of pronounced interocular suppression. In the peripheral visual field, interocular suppression may be absent, and visual acuity and binocular functions are frequently spared.

In some strabismic subjects, interocular suppression may alternate between the two eyes. These squinters are able to use either eye for fixation. Both eyes retain good visual acuity. As in amblyopes, binocularity is impaired in the central visual field of strabismic alternators, but may be normal in the periphery.

Another way to avoid diplopia is a shift of the space coordinates of the squinting eye in the sense of a compensation for the angle of squint (anomalous retinal correspondence, ARC). In strabismic amblyopes, the fovea of the nonsquinting eye always holds the "straight-ahead" direction, whereas in strabismic alternators this depends on which eye is used for fixation. The compensatory shift of space coordinates in the deviated eye can be complete (harmonious anomalous retinal correspondence, HARC) or partial (unharmonious anomalous retinal correspondence, UHARC). In some strabismic observers, no such compensation occurs (normal retinal correspondence, NRC).

The question arises as to whether the shift of retinal coordinates of the squinting eye uniformly affects the whole visual field. In analogy to the previously found selective impairment of visual acuity and binocularity, and the deeper interocular suppression in the central visual field, correspondence might be different in the central and peripheral field. Observations made by some of our subjects in the earlier suppress-
sion tests suggested that this might be the case. Different angles of anomaly in different regions of the visual field of squinters have been described before, but frequently the studies were unsystematic and the conclusions contradictory.

We investigated systematically the state of correspondence in a large area of the visual field with a number of dichoptic localization tasks. The tested subjects were strabismic amblyopes, strabismic alternators and anisometropic amblyopes. Frequently we found clear variations of the subjective angle of squint in different regions of the visual field of strabismics, but not of anisometropes. There was a tendency for correspondence to be closer to normal in the central field and more anomalous in the periphery. These findings might be explained by the postnatal refinement of acuity, in conjunction with the differences in spatial grain known to exist between the central and peripheral visual field of adult observers.

Portions of these results have been presented in abstract form.

Materials and Methods

Subjects

The experiments were performed on ten amblyopic subjects and four strabismic subjects with alternating fixation, aged 13–32 years (see Table 1). The amblyopic subjects can be classified as follows: seven strabismic amblyopes (four esotropes, two exotropes, one subject with exotropia for far and esotropia for near fixation) and three anisometropic amblyopes without strabismus. Three of the strabismic ambyopes also had a considerable anisometropia (O.L., J.W., D.M.), and two others had a mild refraction difference between the two eyes (B.H., M.F.). Three subjects were untreated (U.R., D.M., M.F.), two received occlusion therapy (P.H., B.H.) and two underwent surgical treatment at different ages (J.W., O.L.; see Table 1).

All subjects with alternating fixation were esotropic and had a certain amount of anisometropia. One of them was untreated (L.D.), one had an occlusion therapy (F.E.), the other two had undergone surgery (M.Fo., G.Z.).

It was difficult to classify some of the subjects (eg, M.Fo., F.E.) as amblyopes or alternators. They had a slight acuity difference between the eyes and a fixation preference for one eye, but fixation could be held with either eye.

As controls we tested three subjects (R.S., J.H., K.W.) with good vision in both eyes, good stereopsis and no severe refractive errors or differences of refraction between the two eyes.

Subjects M.F. and R.S. are the authors. Informed consent was obtained from all the subjects.

For the orthoptic examination of the subjects, the following methods were used: Snellen optotypes (letters and figures) at a distance of 6 m for visual acuity; Hirschberg corneal light reflection test and prism and cover test for the measurement of the angle of strabismus (at 6 m and 30 cm); Cüppers visuscope test for the determination of the fixation pattern; Titmus, Randot, TNO and Lang tests for stereoscopic vision. The refractive status of the subjects was determined objectively with the aid of a Rodenstock refractometer and subjectively with trial lenses at a distance of 6 m. Usually, the subjects were asked to wear optimal correction during the experiments. Subjects J.W., F.E., G.Z. and J.R. had contact lens correction. In some amblyopic subjects, where the optical correction did not improve the visual acuity significantly (M.F., D.M., P.S.), correction was omitted in order to avoid magnifying or minifying effects of (anisometropic) correction.

The results of these orthoptic examinations are shown in Table 1. As the stereoacuity values of the different stereotests are not always in agreement, we give the range of values found with several tests. The classification “stereoblind” in Table 1 is derived from these clinical stereotests. When tested with an apparatus for the evaluation of perception of motion-in-depth as described in Sireteanu et al., some of the clinically “stereoblind” subjects (J.W., M.F., B.H., F.E.) showed functional binocularity in the peripheral visual field.

Several orthoptic tests were used for the evaluation of retinal correspondence: Bagolini striated glasses for far and near vision; dark and light red filters together with the Maddox cross, without and with prisms correcting the angle of strabismus; and the bifoveal correspondence test of Cüppers. As has been reported previously, the results of the different tests may vary considerably (for a review see ref. 16). Table 2 summarizes the type of correspondence measured in our subjects.

Apparatus

A red square and a green square were projected on a white screen (luminance 1.8 cd/m²). The stimuli were arranged vertically with a distance of 2° between their centers; the length of their edges was 1°.

Twenty-two fixation marks were placed along the horizontal, vertical and diagonal meridians at distances of 5°, 10°, 20° and 30° from the center of the screen. These marks also served as fusion stimuli.

In additional experiments, we tested dichoptic localization in different parts of the visual field by using
<table>
<thead>
<tr>
<th>Subject</th>
<th>Eye</th>
<th>Refraction</th>
<th>Visus c.c.</th>
<th>Fixation</th>
<th>Strabismus</th>
<th>Stereo</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>O.L.</td>
<td>RE</td>
<td>+1.0 = −1.0/0°</td>
<td>1.0–1.25</td>
<td>foveolar</td>
<td>far −15°</td>
<td>stereoblind</td>
<td>Possibly consecutive exotropia. Occlusion therapy at 6 years. Surgery at 6 years (x2) and 22 years. Possibly consecutive exotropia. Occlusion therapy at 5–7 years.</td>
</tr>
<tr>
<td></td>
<td>LE*</td>
<td>+4.25 = −1.5/12°</td>
<td>0.08</td>
<td>0–0.5° nasal, unstable</td>
<td>near −20°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P.H.</td>
<td>RE</td>
<td>+4.75</td>
<td>1.0–1.25</td>
<td>foveolar</td>
<td>far −10°</td>
<td>stereoblind</td>
<td></td>
</tr>
<tr>
<td></td>
<td>LE*</td>
<td>+4.75</td>
<td>0.08</td>
<td>2.5° temporal, unstable</td>
<td>near −4°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J.W.</td>
<td>RE</td>
<td>+0.25 = −0.75/150°</td>
<td>1.25–1.6</td>
<td>foveolar</td>
<td>far −2° – VD2°</td>
<td>stereoblind</td>
<td>Primary large-angle esotropia. Surgery at 10–11 years. Family history.</td>
</tr>
<tr>
<td></td>
<td>LE*</td>
<td>+6.25 = −2.5/8°</td>
<td>0.08</td>
<td>5° nasal, unstable</td>
<td>near +5° – VD3°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M.F.</td>
<td>RE</td>
<td>+0.75 = −0.75/15°</td>
<td>1.25</td>
<td>foveolar</td>
<td>far +4°</td>
<td>stereoblind</td>
<td></td>
</tr>
<tr>
<td></td>
<td>LE*</td>
<td>+1.75</td>
<td>0.12</td>
<td>3.5° nasal, 1.5° up, unstable</td>
<td>near +10°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R.D.</td>
<td>LE</td>
<td>+0.5 = −0.5/15°</td>
<td>1.25</td>
<td>foveolar</td>
<td>far +6°</td>
<td>stereoblind</td>
<td>Strabismus from early childhood. Glasses from 3–5 years.</td>
</tr>
<tr>
<td></td>
<td>RE*</td>
<td>+1.0 = −0.5/25°</td>
<td>0.5</td>
<td>foveolar, nystagmiform</td>
<td>near +8°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U.R.</td>
<td>RE</td>
<td>+0.5 = −0.5/15°</td>
<td>1.25</td>
<td>foveolar</td>
<td>far +1°</td>
<td>stereoblind</td>
<td>30°–480°</td>
</tr>
<tr>
<td></td>
<td>LE*</td>
<td>+0.25 = −0.25/65°</td>
<td>0.5–0.6</td>
<td>foveolar</td>
<td>near +1°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D.M.</td>
<td>RE</td>
<td>+0.5 = −0.25/15°</td>
<td>1.25</td>
<td>foveolar</td>
<td>far +1°</td>
<td>stereoblind</td>
<td>140°–480°</td>
</tr>
<tr>
<td></td>
<td>LE*</td>
<td>+4.0 = −2.5/35°</td>
<td>0.6</td>
<td>foveolar</td>
<td>near +1°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B.H.</td>
<td>RE</td>
<td>−0.75/15°</td>
<td>1.0–1.25</td>
<td>foveolar</td>
<td>far +17°</td>
<td>stereoblind</td>
<td>Occlusion therapy at 6–9 years.</td>
</tr>
<tr>
<td></td>
<td>LE*</td>
<td>+0.5 = 0.5/70°</td>
<td>0.6–0.8</td>
<td>foveolar</td>
<td>near +20°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M.F.o.</td>
<td>LE</td>
<td>−1.0 = −2.75/178°</td>
<td>1.25–1.6</td>
<td>foveolar, nystagmiform</td>
<td>LF far +15° + VD3 – 6° near +17° + VD 3° near 0° – +4°</td>
<td>stereoblind</td>
<td>Early large-angle esotropia. Surgery at 17 years.</td>
</tr>
<tr>
<td></td>
<td>RE</td>
<td>−4.75 = −3.25/175°</td>
<td>1.0</td>
<td>foveolar, nystagmiform</td>
<td>LF far +15° + VD2° near +17°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F.E.</td>
<td>RE</td>
<td>+4.5</td>
<td>1.25</td>
<td>foveolar</td>
<td>RF and LF far 0° near 0°</td>
<td>stereoblind</td>
<td>First glasses at 5 years. Occlusion therapy at 5–7 years. Family history.</td>
</tr>
<tr>
<td></td>
<td>LE</td>
<td>+5.5</td>
<td>0.8–1.0</td>
<td>foveolar</td>
<td>RF far +12° + VD 2° near +20° + VD 3° near 17° + VD 4°</td>
<td></td>
<td>First glasses at 5–6 years. Red–green color-deficient.</td>
</tr>
<tr>
<td>L.D.</td>
<td>RE</td>
<td>−0.75</td>
<td>0.8–1.25</td>
<td>foveolar</td>
<td>RF far +12° + VD 2° near +20° + VD 3° near 17° + VD 4°</td>
<td>stereoblind</td>
<td>Sudden onset of large-angle esotropia at 2 1/2 years. Operated at 5–6 years.</td>
</tr>
<tr>
<td></td>
<td>LE</td>
<td>−1.5</td>
<td>1.0–1.25</td>
<td>foveolar</td>
<td>RF far +25° + VD 2° near +28° + VD 3° near 25° + VD 2°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G.Z.</td>
<td>RE</td>
<td>−0.25</td>
<td>1.25</td>
<td>foveolar</td>
<td>RF far +25° + VD 2° near +28° + VD 3° near 25° + VD 2°</td>
<td>stereoblind</td>
<td></td>
</tr>
<tr>
<td></td>
<td>LE</td>
<td>−1.75</td>
<td>1.25</td>
<td>foveolar</td>
<td>LF far +20° near +25° + VD 2°</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Anisometropic amblyopes</th>
</tr>
</thead>
<tbody>
<tr>
<td>P.S.</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>R.M.M.</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>J.R.</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

* Amblyopic eyes are indicated by asterisks.
Strabismus: + esotropia; − exotropia; VD vertical deviation, + VD right hypertropia, − VD left hypertropia.
RF right eye fixating, LF left eye fixating.
TABLE 2. Correspondence status

<table>
<thead>
<tr>
<th>Subjects</th>
<th>LR</th>
<th>LRΔ</th>
<th>DR</th>
<th>DRΔ</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strabismic amblyopes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O.L. excl.</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>P.H. excl.</td>
<td>—</td>
<td>—</td>
<td>excl.</td>
<td>—</td>
<td>excl.</td>
</tr>
<tr>
<td>J.W. excl.</td>
<td>H</td>
<td>UH</td>
<td>UH</td>
<td>UH</td>
<td>H</td>
</tr>
<tr>
<td>M.F. UH</td>
<td>UH</td>
<td>UH</td>
<td>UH</td>
<td>UH</td>
<td>H</td>
</tr>
<tr>
<td>R.D. excl.</td>
<td>H</td>
<td>—</td>
<td>UH</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>U.R. excl.</td>
<td>H</td>
<td>—</td>
<td>UH</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>D.M. excl.</td>
<td>H</td>
<td>H</td>
<td>—</td>
<td>H</td>
<td>—</td>
</tr>
<tr>
<td>B.H. excl.</td>
<td>UH</td>
<td>UH</td>
<td>—</td>
<td>UH</td>
<td>UH</td>
</tr>
<tr>
<td>Strabismic alternators</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M.F 6 excl.</td>
<td>UH</td>
<td>UH</td>
<td>UH</td>
<td>UH</td>
<td>—</td>
</tr>
<tr>
<td>F.E. excl.</td>
<td>H</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>G.Z. excl.</td>
<td>UH</td>
<td>N</td>
<td>UH</td>
<td>UH</td>
<td>UH</td>
</tr>
<tr>
<td>Anisometropic amblyopes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P.S. excl.</td>
<td>N</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>R.M.M. excl.</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>J.R. excl.</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

B Bagolini; LR light red filter test; LRΔ light red filter test with prism for correction of squint angle; DR dark red filter test; DRΔ dark red filter test with prism; C Cuppers bifoveal correspondence test; excl. exclusion of the image of the nondominant eye; H harmonious anomalous correspondence; UH unharmonious anomalous correspondence; N normal correspondence; — not tested.

The light of the Maddox cross together with the Bagolini striated glasses, with the aid of moving polarized stimuli (see “motion-in-depth” experiment), or with a phase-difference haploscope.

Procedure

The subjects were seated in front of the screen at a distance of 1.14 m. Using red–green glasses, the red and green squares were seen separately by the right and left eye, respectively. The observers were asked to report the subjectively perceived position of the two stimuli for 23 locations in the visual field. The length of the edges of the squares and the distances between the fixation marks—both known to the subjects—were used as references. For central vision, the perceived displacement corresponds to the subjective angle of squint.

The subjects were asked to keep the eyes constantly in primary position, that is, to turn the head when they shifted their gaze to the next fixation point. At least two measurements were performed for each visual field position of the stimuli. Strabismic alternators were tested while fixing with each eye in turn.

In a control experiment, a subject fixated either the central light or the numbers on the horizontal or vertical wing of the Maddox cross through the Bagolini striated glasses. When this subject (M.F.) focussed her attention on the amblyopic eye, she could perceive a double-image of the light, which in addition to the crossing stripes helped her to localize the image of the amblyopic eye. The positions of the images seen with the two eyes had to be reported.

In two additional control experiments, several normal and amblyopic observers were tested with the stimuli being dissociated by polarizing filters or by a phase-difference haploscope.

Results

Correspondence in the Central Visual Field

First, we analyzed the correspondence in the central visual field, that is, with the nonsquinting eye fixating the test stimulus. This is analogous to the situation in most of the clinical tests for retinal correspondence.

In strabismic subjects, the direction of the perceived displacement of the square seen by the deviated eye depended on the direction of squint. In a case of exotropia (eg, of the left eye), the stimulus was seen as shifted to the right; with an esotropia of the left eye the perceived displacement was to the left. The amount of displacement, however, did not depend systematically on the direction or the size of the squint. Although the exact angle of squint was not known for the test distance of 1.14 m, we concluded by interpolation of the orthoptic data whether correspondence was approximately normal, harmonious or unharmonious anomalous. In subject P.H. this was verified by measuring the squint angle at the test distance of 1.14 m.

Correspondence in the Peripheral Visual Field

Normal subjects: Subjects with normal vision perceived the red and green test stimuli as vertically aligned at most of the tested positions in the visual field. There were, however, very rare situations when an otherwise compensated phoria caused a slight deviation of the visual axes under the somewhat dissociating test conditions. For subject K.W., the test stimuli were always perfectly aligned, independent of their position in the visual field. Two of the controls (J.H., R.S.) reported a displacement of one test stimulus for some peripheral positions. The direction of the displacement varied and the amount of displacement was usually less than 0.5°; it rarely reached 1°. Temporarily, the control subjects experienced some form of rivalry which prevented them from seeing the two test stimuli simultaneously. Therefore, position judgements were made only while both squares were visible.

Strabismic subjects: In the majority of the subjects, correspondence was not uniformly distributed in different parts of the visual field. In four strabismic sub-
jects tested with the red-green filters (J.W., M.F., P.H., M.Fö.), the displacement of the square seen by the squinting eye was more pronounced in the central visual field than in the periphery. Figure 1 (upper panel) shows the results of this dichoptic localization test for a subject with an untreated small-angle constant esotropia of the left eye (M.F.). The distances between the open and the closed circles (connected by lines) in the figure represent the direction and the amount of the perceived displacement from the true position of the square seen with the amblyopic eye. These displacements were larger in the central visual field than in the periphery, suggesting a more complete compensation in the peripheral than the central visual field. In this subject, the area with the larger displacements (less successful compensation) extended more into the left than into the right hemifield.

For stimuli in the far periphery, the subject was sometimes unable to make a statement about the relative localization of the squares. She saw a bright spot, but could not decide whether it was composed of two stimuli, and hence report their relative position. These positions are indicated with question marks in Fig. 1.

We verified the results of this strabismic amblyope with the aid of Bagolini striated glasses and the Maddox cross. The subject fixated either the light or numbers on the horizontal or vertical wing of the cross through the striated glasses and reported the position of the images. The results are shown in Figure 1 (lower panel). Again, the subjective localization of the images seen with the two eyes was tested at different positions of the visual field. The displacements in the two testing conditions (Fig. 1) were not exactly the same; however, in both tests the central and near left visual field tended to show more displacement than the rest of the periphery.

Almost identical results were obtained for this subject when the stimuli of the two eyes were dissociated with a phase-difference haploscope, or with the aid of polarized filters (not illustrated).

Figures 2 to 5 include four strabismics tested with red-green stimuli. For the two esotropes (B.H., M.Fö.), the perceived displacement of the stimulus seen by the deviated eye went in the opposite direction than for the two exotropes (P.H., O.L.). Considering her large angle of squint (±17°), subject B.H. adapted successfully to her strabismus and showed nearly harmonious anomalous correspondence (Fig. 2). In subject P.H., the displacement was about the size of the squint in the central field and decreased.
towards the periphery (Fig. 3). The long lines in Figures 4 and 5 suggest that the two operated subjects (especially O.L.) have poorly compensated for their present squint.

It is common to all the subjects shown in Figures 2, 3, 4 and 5 that the judgement of the relative stimulus positions was not uniform in the tested regions of the visual field. In some of the subjects (B.H., P.H., M.Fö.) a puzzling inversion occurred: while the stimulus in the squinting eye was shifted for most visual field positions towards the direction predicted from their deviation, some peripheral positions showed a consistent displacement to the opposite direction.

Another interesting observation was made by two of the mild amblyopes (B.H., M.Fö.) and a strabismic alternator (G.Z.—not illustrated): at some positions in the visual field the stimulus in the squinting eye remained at the original position, but the square seen by the fixating eye seemed to be shifted (dotted lines in Figs. 2, 5).

For many subjects, there was a vertical component in the perceived displacement of one square. The direction of this shift was usually consistent with a vertical deviation of the visual axes, but for unclear reasons it varied in some subjects (e.g., B.H., M.Fö., O.L.) for different positions of the stimuli in the visual field.

Two strabismic alternators with large angles of squint (L.D., G.Z.) compensated successfully for their deviation. Considering their squint angles of 12–20° (L.D.) and 20–28° (G.Z.), the subjectively perceived shift of 1–3° was small. Figure 6 shows the shifts reported by subject L.D. The amount of displacement of the square seen by the nonfixating eye differed slightly for different positions in the visual field.

Anisometropic amblyopes without strabismus: For two anisometropic amblyopes without strabismus
the squares appeared to be vertically
aligned with the exception of an occasional displace-
ment of at most 1°. Only for subject P.S. was (results
in Fig. 7) the perceived displacement more frequent,
and sometimes exceeded 1°. His eyes probably con-
verged slightly during this test, due to an otherwise
compensated esophoria. This supposition is sup-
ported by the finding that in the even more dissociat-
ing circumstances of the correspondence test with the
dark red filter, his eyes converged as much as 3°.

Control experiments: The question arises as to how
well a displacement of a stimulus can be detected and
estimated in the central and the peripheral visual
field. Could the difference in the angle of anomaly
between the central and peripheral visual field of
strabismics be explained by differences in displace-
ment sensitivity? To clarify this point, we examined
an observer with normal vision (R.S.) and a strabis-
mic amblyope (M.F.), by presenting the test squares
either vertically aligned or with the red square dis-
placed horizontally by differing amounts. The sub-
jects were asked to report the relative position of the
stimuli. The results are shown in Figures 8 and 9.

In the central visual field, very small amounts of
interocular displacement were easily detected by the
normal subject. The crosses in Figure 8 represent po-
sitions where the subject detected correctly the small-
est displacement available (0.5°). In the periphery,
more displacement was necessary for the subject to
observe a shift. The rectangles in the figure show how
much the red stimulus could be displaced until the
subject just noticed a misalignment. This displace-
ment was up to 3° to either side in the far periphery.
Occasionally, the thresholds to detect a misalignment
were asymmetrical; this is shown by a decentration of
the rectangles in Figures 8 and 9.

These results show that there is a difference in po-
sition sensitivity between the central and peripheral
visual field of normal observers. However, the stra-
bismic subject M.F. (Fig. 9) showed practically no
differences in position sensitivity between central and
peripheral visual field. This subject needed more dis-
placement in the central visual field than the control
subject to detect a difference in the relative position
of the stimuli from the misalignment of the two
squares shown in Figure 1. Thus, the difference in
correspondence between the central and peripheral
visual field of strabismic observers cannot be ex-
plained by a progressive loss of localization sensitivity
with increasing eccentricity.

Discussion

In a series of dichoptic localization experiments,
we measured the subjective angle of squint, that is,
was not always uniform across the visual field. There was a tendency in some strabisms to show a more complete compensation in the peripheral than in the central visual field. Beside this general tendency, inversions and irregularities may occur.

Evaluation of the Results

The interpretation of tests for the state of correspondence is complicated by the fact that the images of the two eyes have to be labeled differently, so that the observer is able to distinguish between them. The labeling introduces unnatural viewing conditions that are different from one test to the other.

It is legitimate, however, to compare states of correspondence in different regions of the visual field, if all the data are collected with the same test. That was the case in our dichoptic localization tasks.

With red–green stimuli we found that the relative dichoptic localization is not uniform across the visual field of strabismic subjects. A very similar pattern was obtained when the images of the two eyes were dissociated with the Bagolini striated glasses (which are less dissociating than a red–green test), with polarized filters, or with the phase-difference haploscope.

A difference in position sensitivity was found between the central and peripheral visual field of normal observers; however, this difference was much attenuated in a strabismic amblyope. Thus, this cannot account for the center–periphery differences encountered in strabismic subjects.

Although the eye position was not monitored during testing, differences of eye position between test locations are unlikely to introduce artifacts, since our subjects were asked to keep their eyes constantly in primary position by turning the head when shifting their gaze from one fixation point to the next.

Comparison with Previous Studies

The distribution of correspondence across the visual field of squinters has been investigated previously, with various methods and with partly contradictory conclusions. Kretzschmar, after an extensive mapping of corresponding points, was convinced that there is an “en-bloc” shift of retinal coordinates in anomalous correspondence (although some of his results are not consistent with his conclusions).

Wilczek found a uniform shift of coordinates in only 30% of his subjects; the other 70% showed more or less irregular correspondence across the visual field. Several other authors also found differences in states of correspondence between different parts of the visual field of strabismic subjects. These studies can be separated into those who found anomalous retinal correspondence (ARC) (frequently close to harmoniously anomalous) in the central field and less harmonious or closer to normal correspondence (NRC) in the periphery, and those with the opposite conclusions (NRC or close to NRC in the central field and harmonious ARC or close to harmonious ARC in the periphery).

Some of these investigations were limited to single case descriptions of squinters without amblyopia and with unusual clinical histories. Burian found in a
study with 75 strabismic alternators the whole range of possible states of correspondence: uniform NRC or ARC in the whole field, and a combination of NRC and ARC (either ARC between the two foveae and NRC between the fovea of the fixating and the simultaneously stimulated peripheral area of the squinting eye or NRC between the two foveae and ARC between fovea and peripheral corresponding area). It is not evident, however, from the presented results, which is the most common situation.

Our own results support the notion that the shift of retinal coordinates is not an "en-bloc" shift, but composed of different adaptation patterns across the visual field.

These results are in agreement with the examples shown by Flom. If the perceived displacements of targets presented along the horizontal meridian to the deviated eye are reversed, under the assumption that the targets presented to the two eyes would then be seen in alignment, hypothetical horopter surfaces can be constructed which, for our esotrope M.F. and exotrope P.H. are similar to the data obtained for such subjects by Flom.

Possible Mechanisms Involved in the Establishment of Anomalous Correspondence

The differences in the distribution of correspondence across the visual field of adult strabismic amblyopes could be explained by the postnatal refinement of acuity, combined with the difference in spatial grain known to exist between the central and peripheral visual field of adult observers.

In young infants, visual resolution is low, not only in the central, but also in the peripheral visual field. Therefore, an exact alignment of visual axes is not critical for the occurrence of binocular correspondence (see Fig. 10A).

With age, as acuity develops, the extent of corresponding areas in the two eyes decreases, and even a slight misalignment can produce double images (see Fig. 10B). To avoid diplopia, young squinters are likely to suppress the image of one eye. In small-angle strabismus, diplopia (and hence interocular suppression) is confined to the central part of the visual field. In the periphery, where the corresponding areas are larger, binocular interaction is less likely to be disrupted, but could become anomalous on the basis of a mechanism of experience-dependent selective stabilization (Fig. 10C).

Our earlier findings on the distribution of interocular suppression in the visual field support this speculation: suppression is pronounced in the central visual field of strabismic amblyopes, but nearly absent in the periphery. In the peripheral visual field, in the -

regions with nearly harmonious anomalous correspondence, functional binocularity can be demonstrated. Some of the strabismic subjects, although stereoblind in the clinical tests, perceive motion-in-depth in the peripheral visual field (ref. 3, and unpublished results from some of the subjects included in the present study).

Note, however, that this postulated mechanism can explain the systematic differences between central and peripheral visual field, but not the inversions in correspondence shown by some of our subjects.

The occurrence of systematic differences in the pattern of correspondence in some strabismic subjects raises the question of whether the difference in space values between center and periphery, observed dichoptically, has a consequence on the monocular relative localization of objects. If this is so, a consistent misalignment of stimuli presented along a vertical line should be observed in strabismic amblyopes. In the accompanying paper we show that, in several instances, this is indeed the case.

Relevance to Animal Studies

More knowledge about the basic anatomical and physiological mechanisms involved in adaptation processes in strabismus and amblyopia would be helpful for the interpretation of data obtained in psychophysical experiments with human squinters. Currently, we have only fragmentary information about
reorganization mechanisms in the central nervous system in response to events interfering with the normal development of the visual system. Attempts have been made to create animal models for strabismus and amblyopia, but it is not clear whether they are suitable to study the particular problem of anomalous correspondence.

In the only behavioural study to date, Olson23 concludes from a dichoptic spatial localization task that in one of two tested kittens reared with a surgically induced exotropia, a compensatory shift of retinal correspondence has occurred, thus showing that anomalous correspondence can be found in animal models.

Electrophysiological recordings suggest that the striate cortex of the cat is able to compensate, within limits, for a vertical misalignment or a rotation disparity between the two eyes.24-27 However, there is no mention of a compensation in area 17 for the lateral displacement of images caused by strabismus in any of the numerous papers dealing with the effects of a surgically or optically induced squint, neither in cats nor in monkeys.

It thus seems that single cells in area 17 of strabismic animals maintain their retinotopic organization (normal retinal correspondence) at the expense of a binocular input.

In area 18 of exotropic cats, Cynader et al28 described occasional binocular units with receptive fields in the squinting eye shifted in such a way that simultaneously stimulated areas in the two eyes correspond, rather than retinotopically arranged ones. However, since these units were the exception rather than the rule (four out of 29 penetrations), it is not clear whether they can provide the physiological basis of anomalous retinal correspondence.

More binocular units than in area 17 and 18 are encountered in other visual structures of strabismic cats (superior colliculus29; lateral suprasylvian area30,31). In the lateral suprasylvian area, the preservation of binocularity seems to depend, at least in part, on the existence of an intact corpus callosum.31 Preliminary observations from our own laboratory suggest that, in addition to the increased proportion of binocular cells, a significant number of cells in the lateral suprasylvian area (PMLS) show a compensatory shift of receptive field position.32 It is, therefore, conceivable that the adaptation of the coordinates of the strabismic eye to those of the nondeviated eye depends on the activity of cells located at a "higher" processing level in the visual pathway, possibly in conjunction with the corpus callosum. Indeed, it has been shown33-35 that, in strabismic cats, abnormally extensive areas of the visual cortex are connected via the corpus callosum, resembling these connections in young kittens. The selective preservation and consolidation of these juvenile connections might provide the anatomical substrate of anomalous correspondence.

Further investigations, and especially recordings in primates raised with a concomitant strabismus, are needed to understand the neural mechanism of these fascinating adaptation phenomena.

Key words: human amblyopia, retinal correspondence, strabismus, anisometropia, peripheral visual field

Acknowledgments

We are grateful to Prof. Wolf Singer for his support of this study. Thanks are due to Birgit Katz for thorough orthoptic examination of the subjects, to Sabine Alznauer for preparing the figures, and to Gisela Knott for typing the manuscript.

References

16. Nelson JI: A neurophysiological model for anomalous corre-