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The role of local contrast in the visual deficits of humans with naturally occurring amblyopia

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We measured the positional acuity of amblyopic observers and their sensitivity to the local contrast information which provides the cue for the position judgement. Our results suggest that there exist fundamental differences in the neural losses in humans with strabismic and anisometropic amblyopia. The losses in positional acuity of anisometropic amblyopes may be accounted for on the basis of the reduced contrast sensitivity and increased neural pooling of the underlying visual filters; whereas strabismic amblyopes, like the normal periphery, show an *extra* loss, which may be accounted for on the basis of scrambling, or jitter in the topographic mapping of information from retina to cortex. Since neurons in the striate cortex of monkeys show precise positional coding [9], it would be of particular interest to examine the positional acuity and local contrast sensitivity in cortical neurons of monkeys with experimental amblyopia using the same stimuli to measure both.

Amblyopia is a developmental abnormality, usually associated with anisometropia (unequal refractive error in the two eyes), strabismus (a turned eye) or both, which can result in profound losses in visual resolution, contrast sensitivity, and positional acuity [2, 6]. In an effort to understand the nature of the neural abnormalities underlying amblyopia, we have used a novel stimulus to study the positional acuity of amblyopic observers and to measure their sensitivity to the local contrast information which provides the cue for the position judgement. Our results suggest that the loss of positional acuity in *anisometropic* amblyopes can be readily understood on the basis of their local contrast sensitivity. However, strabismic amblyopes, like the normal peripheral retina, show additional losses in positional acuity which cannot be readily accounted for on the basis of local contrast sensitivity. We hypothesize that the additional loss is due to a multiplicative effect of imprecision in the topographic mapping of information from retina to cortex.

The strategy of our experiments is to compare the observer's positional acuity to their local contrast sensitivity, using a thin line as the probe for *both* tasks. When a thin line is added to a suprathreshold edge, it produces a Vernier offset (Fig. 1). On the other hand, the *detection* threshold of a thin line on a uniform field can be related to the integration area for contrast, Ricco's critical area. The diameter of Ricco's critical area is defined as the width of a line whose contrast is equal to the edge detection contrast threshold. It has recently been shown both experimentally and mathematically that the diameter of Ricco's area predicts the Vernier acuity of normal observers for low contrast edges [5], and thus provides an estimate of the observer's sensitivity to the edge Vernier cue at low edge contrasts.

The stimulus for our positional acuity task consisted of two abutting horizontal contrast edges (Fig. 1, top), and the observers' task was to judge whether the left edge was higher or lower than the right edge (Fig. 1, bottom). The edge Vernier threshold corresponds to the offset yielding 84% correct performance ($d' = 1$). A shift in the position of one of the edges is equivalent to adding a thin line (middle) to one edge; thus, the local contrast information needed to accomplish the edge Vernier task is the detection of the thin line added to the edge. When the contrast of the edge is low, the task is reduced to the detection of a line [5]. Thus, we also measure the contrast detection thresholds for an edge and a thin line using the same signal detection methodology [6, 7]. Ricco's diameter is obtained by taking the ratio of the line (in units of % min) to the edge (in units of %) detection thresholds. It is specified in minutes since the contrast (%) in the nu-

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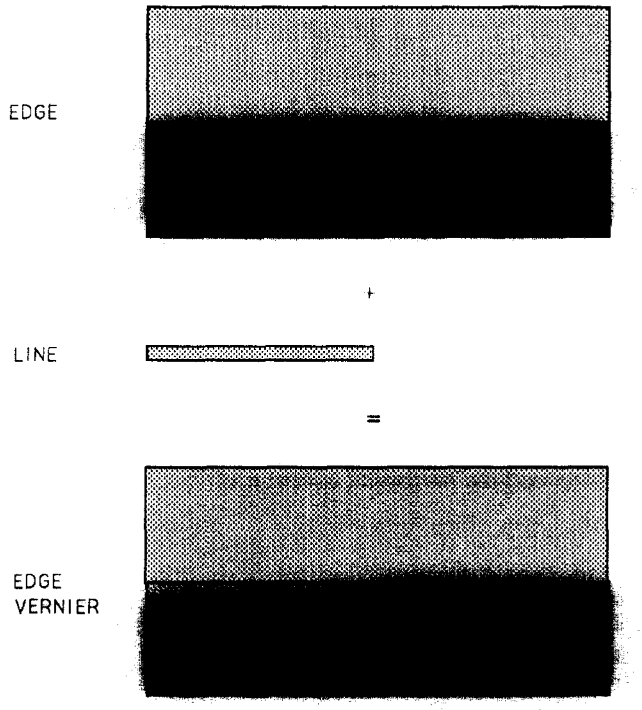

Fig. 1. The stimulus for our positional acuity task consisted of two abutting horizontal contrast edges (top), and the observers' task was to judge whether the left edge was higher or lower than the right edge (bottom). The edge contrast is defined as the Weber contrast ($\Delta L/L_{\mathrm{mean}}$) (i.e. this is twice the Michelson contrast). In Fig. 2, we specify the edge contrast with respect to the observers' edge detection threshold. The line contrast is defined as $c=\Delta L/L_{\mathrm{mean}}$.

merator and denominator cancel. All stimuli were generated on a Tektronix 608 monitor with a mean luminance of 132 cd/m^2 using a Neuroscientific Venus visual stimulator. We tested 20 observers with naturally occurring amblyopia due to anisometropia (7), strabismus (5) or both strabismus and anisometropia (8), and 2 normal observers. All observers were provided extensive practice.

Fig. 2 shows edge Vernier thresholds (circles) plotted as a function of the edge contrast. For the non-amblyopic eyes edge Vernier thresholds improve as a power function of contrast (exponent ≈ -0.5 to -0.7) up to about 30–50 times threshold, and then saturate at a threshold value of about 0.1 min of arc [11]. In normal foveal vision this asymptotic threshold represents a 'hyperacuity' because it is much smaller than the size or spacing of foveal cones, and considerably smaller than the resolution limit [12]. The triangles in Fig. 2 show the diameter of Ricco's integration area. For the non-amblyopic eyes, the edge Vernier threshold extrapolated to an edge contrast of 1 (i.e. the edge detection threshold) is very close to the Ricco integration diameter (Fig. 3a), suggesting that when the line cue is detected, the observer can accurately judge its relative position [5].

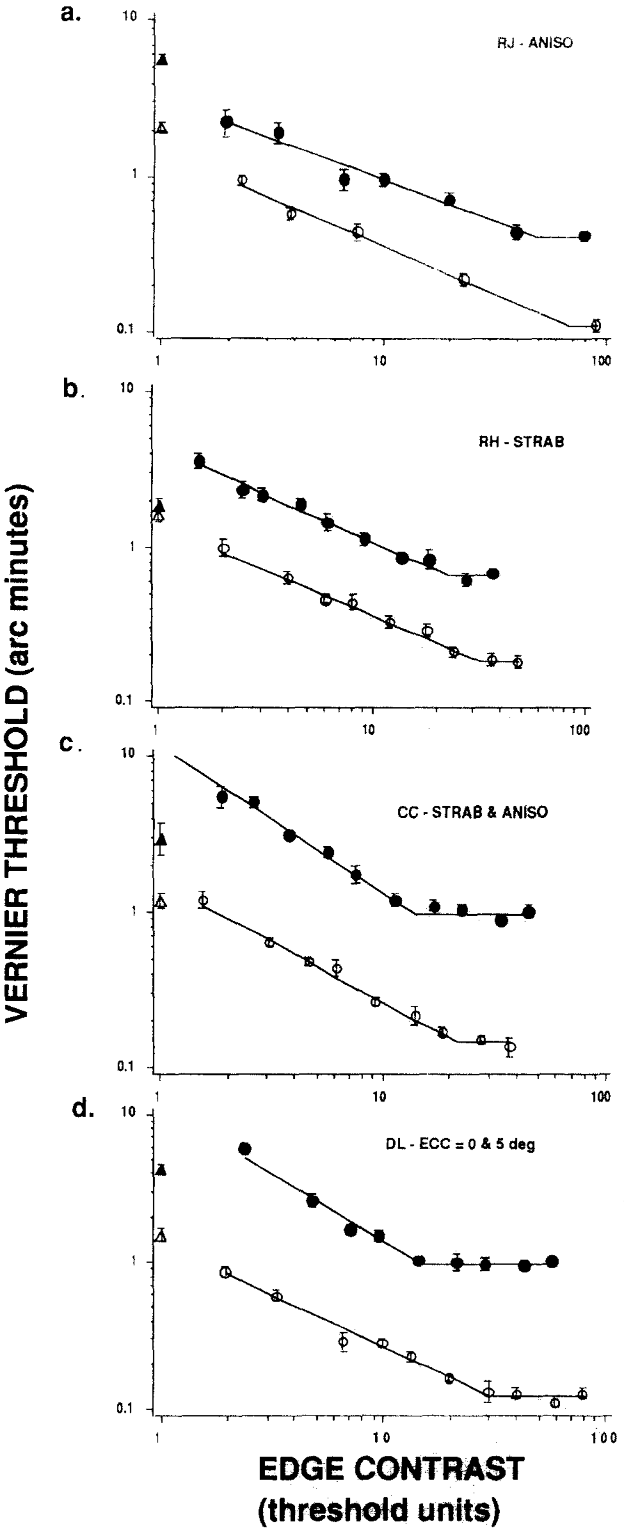

Fig. 2. Edge Vernier thresholds (circles) plotted as a function of the edge contrast (specified relative to the edge detection threshold) for 3 amblyopes: one with anisometropia (a), strabismus (b) and both strabismus and anisometropia (c). Open symbols are the preferred eyes; solid symbols are the amblyopic eyes. Also shown are data for a normal observer (d) viewing foveally (open circles) or 5 degrees in the lower visual field (solid circles). The triangles show the diameter of Ricco's integration area. Ricco's diameter is obtained by taking the ratio of the line (in units of % min) to the edge (in units of %) detection thresholds. It is specified in minutes since the contrast (%) in the numerator and denominator cancel.

The Vernier acuity of amblyopic eyes shows a similar dependence on contrast to the non-amblyopic eyes, so the *loss* of Vernier acuity is generally uniform across contrast levels [1] or increases slightly at high contrasts because the amblyopic eye saturates at lower contrast levels than the fellow eye (filled circles in Fig. 2). Note that for the *anisometropic* amblyopic eyes the edge Vernier thresholds are elevated by approximately the same factor as the Ricco integration diameter (Fig. 2a and large circles in Fig. 3).

Results of 20 amblyopic observers are summarized in Fig. 3. The ordinate in Fig. 3a represents the edge Vernier threshold extrapolated to an edge contrast of 1 (i.e. the edge detection threshold). The extrapolation is accomplished by a broken line non-linear regression, as shown by the solid lines in Fig. 2. The extrapolated values of edge Vernier acuity at the edge detection threshold are plotted against Ricco's integration diameter. For the anisometropic amblyopes (large circles), the data fall close to the line with a slope of 1, suggesting that for anisometropic amblyopes, like the normal fovea, edge Vernier acuity is limited by sensitivity to the local contrast information. However, for the observers with constant unilateral strabismus (Fig. 2b,c and Fig. 3 large triangles and squares), the loss of edge Vernier acuity in the amblyopic eye is greater than predicted by the increase in the integration diameter, suggesting that strabismic amblyopes show an extra loss in positional acuity, not accounted for on the basis of their sensitivity to the local contrast information; all of the strabismic amblyopic eyes' data fall above the line in Fig. 3. A measure of the extra loss is given by the ratio of ordinate to abscissa in Fig. 3a. For the mildest strabismic amblyope the ratio is 1.3; however, the ratio increases with the severity of the strabismic amblyopia, and for the most severe amblyopes it is close to a factor of 10. This represents an *extra* loss in positional acuity not accounted for on the basis of the observers' sensitivity to the local contrast information in the stimulus. This is not simply a consequence of the depth of amblyopia, since anisometropic and strabismic observers with similar losses in line contrast sensitivity (Ricco's diameter) show different losses in Vernier acuity (Fig. 3).

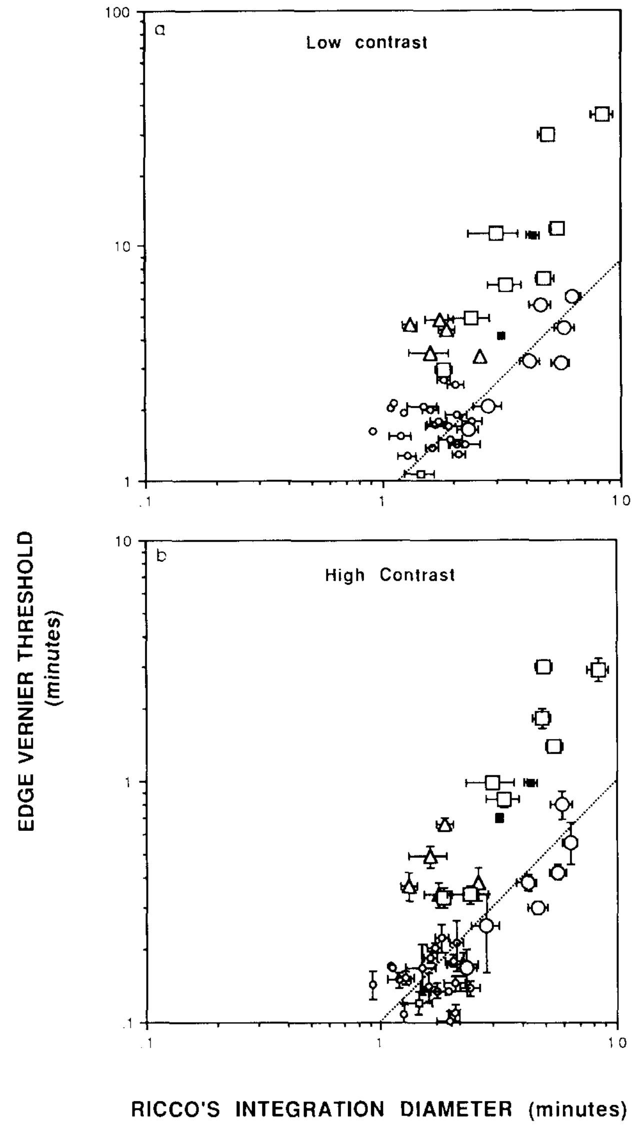

Fig. 3. a: the edge Vernier threshold extrapolated to an edge contrast of 1 (i.e. the edge detection threshold) is plotted vs. Ricco's integration diameter. The small square shows mean data of two normal observers, viewing foveally. Small circles are the non-amblyopic eyes; large symbols are the amblyopic eyes of anisometropes (circles), strabismics (triangles) and amblyopes with both strabismus and anisometropia (squares). For the 7 anisometropic amblyopic eyes tested, the data fall close to the line with a slope of 1. Observers with constant unilateral strabismus show a loss of edge Vernier acuity in the amblyopic eye which is greater than predicted by the increase in Ricco's integration diameter. The normal periphery (5 degrees in the lower visual field-filled squares) also shows an 'extra' loss in positional acuity. b: the asymptotic (high contrast) Vernier threshold plotted against Ricco's integration diameter. For the non-amblyopic eyes, and the amblyopic eyes of anisometropic amblyopes, the asymptotic edge Vernier threshold is about 1/10 of the integration diameter and the data of the anisometropic amblyopes fall close to the 1:10 line. The data of *strabismic* amblyopes and the normal periphery (5 degrees in the lower visual field-filled squares) clearly depart from this linear relationship.

A similar picture is evident at high contrast levels. Fig. 3b shows the asymptotic Vernier threshold plotted against the integration diameter. The asymptotic values of edge Vernier acuity, obtained from our broken line non- linear regression correspond to the height of the horizontal segment of the solid line fit to the data in Fig. 2. For the non-amblyopic eyes, and the amblyopic eyes of anisometropic amblyopes, the asymptotic edge Vernier threshold is about 1/10 of the Ricco's diameter and the data of the anisometropic amblyopes falls close to the 1:10 line, as was the case at low contrast levels. The data of *strabismic* amblyopes, however, clearly departs from this linear relationship, and for the most severe amblyopes the asymptotic edge Vernier thresholds approach the size of the integration diameter (1:1). For the strabismic amblyopes, the loss at high contrasts is greater than at low, because several of the strabismic amblyopes exhibit saturation of their position thresholds at relatively low contrast levels (e.g. CC in Fig. 2c). Interestingly, the normal peripheral visual field exhibits many of the same characteristics as the strabismic amblyopes (Figs. 2d and 3a,b). For example, at 5 degrees in the lower visual field, the integration diameter has increased by about a factor of 3; however, the periphery shows an extra loss of positional acuity, not accounted for on the basis of local contrast sensitivity.

The present results are reminiscent of our previous findings, that anisometropic amblyopes show similar losses in Vernier acuity and grating cutoff spatial frequency, while strabismic amblyopes, like the normal periphery show greater losses in Vernier acuity [6]. The present study found similar results when the observer's positional acuity is directly compared with the local contrast 'cue' for the task. These results, and those of others [3, 4, 6, 7, 13] imply that the neural losses of anisometropic and strabismic amblyopes differ. The present results may also be helpful in understanding the nature of the neural losses. Our method of comparing the positional acuity to the observers' contrast sensitivity using the same test probe (a line) provides a model-free approach to the question of whether the reduced precision of positional coding in the amblyopic visual system can be attributed to increased intrinsic blur and the reduced contrast sensitivity of the underlying visual filters [1, 7, 13]. The 'model-free' hypothesis predicts that positional acuity and line contrast sensitivity (or Ricco's diameter) will be linearly proportional, as they are in our *anisometropic* observers. Our experiments also rule out a simple 'floor effect' model of positional uncertainty or jitter in the topographic mapping of visual information from the retina to cortex [8, 10, 13] to account for the extra loss in positional acuity in both the normal periphery and the strabismic amblyopes, since they show an extra reduction in positional acuity at *all* contrast levels. Rather, our results point to a multiplicative loss which causes positional acuity to be degraded at all contrast levels. Such a loss would occur if the position threshold is determined by the convolution of the mechanism receptive field with its positional jitter [13].

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