

COMMUNICATIONS

VISUAL DISTORTION IN AMBLYOPIA*

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To assess accurately the vision of an amblyopic eye is in itself a problem. In an earlier investigation (Pugh, 1954), the recording of visual acuity in the amblyopic eye gave difficulty in every one of 150 patients. The usual test with a Snellen chart gave inconsistent results when tested on five or six consecutive charts during one examination. The patient's ability to read the letters appeared to alter with the shape of the letters, with the number of letters in the row, and also with the position of the letter in that row. These apparently erratic answers were given by good and less good observers alike. When visual acuity was very poor, this was understandable because the patient might be experiencing difficulty in holding a central fixation, but the same discrepancies occurred when the visual acuity had improved to 6/12 or better and central fixation appeared to be held without any difficulty. A detailed analysis of such inconsistencies has therefore been made.

Investigations

Method.—In this group, the patients' ages varied from 10 to 32 years. The visual acuity in the weaker eye at the beginning of this inquiry was 6/18, either having been already improved to this degree by treatment or being untreated in new patients. Thirty patients were selected for their intelligence and accuracy of observation, and because the visual acuity was such that targets subtending 20' or smaller could be resolved (Polyak, 1941; Jones and Higgins, 1947).

Initial routine investigations included age at onset, amount and direction of deviation, retinal correspondence, binocular vision, and the refractive error of the eyes (Table, overleaf).

Patients with irregular astigmatism were excluded. The significant examinations for this investigation were monocular and concerned with analysing first the defect of the image of a letter as seen by the amblyopic eye, and secondly how this defect was influenced by such factors as the proximity of other letters, the position of the letter in a row, and the conditions of lighting.

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TABLE
PARTICULARS OF 30 SELECTED CASES

Visual Acuity of the Amblyopic Eye	None less than 6/18 at the beginning of the investigation	6/18
Refractive Error	Small error or none (less than 1 D sph. or cyl.)	2
	Hypermetropia	26
	Myopia (acquired)	2
	Astigmatism only (2) Anisometropia (6)	
Direction of Heterotropia	Esotropia	11
	Esotropia with vertical factor	13
	Esotropia with vertical and torsional factor	5
	Mainly vertical and/or torsional	1
Degree of Deviation (with correction if required)	0 to 3°d	8
	4 to 6°d	16
	7 to 10°d	6

Apparatus.—The lighting installation consisted of a battery of eight 5-foot fluorescent “new warm” white 80 watt tubes suspended from the ceiling. This arrangement increased the amount of light on the test charts by 100 foot lamberts. When these top lights were turned off, the normal lighting of the Snellen type was 32 foot lamberts.

By this means the usual illumination on the Snellen type chart could be increased from 32 foot lamberts to 132 foot lamberts when the top lights were lit, the surround being at a luminance of 100 foot lamberts. The battery of lights could be put through a flashing mechanism which allowed varying speeds of flashing per second.

The usual roller type of Snellen chart was used in which three lines of the smaller letters can be shown at the same time through the opening in the metal frame. When required, this opening was covered with matt black paper which then served as a background for single letters which could be slotted into any position needed to correspond with the underlying chart. The advantage of this arrangement was that a series of single letters was shown and the answers recorded and these were then compared with the answers which were given either when a full line of the chart was visible, or when the same letters were seen under the same conditions of lighting and position but with additional letters either side and/or above and below. A scale was marked along the bottom edge to correspond with the centre area of the 6-metre tangent scale, and gave an approximate position of $\frac{1}{4}$, $\frac{1}{2}$, and $\frac{3}{4}$ degrees of movement as the eye looked along the line from right to left of centre. A slide of the tangent scale was also used in the orthoptoscope so that the exact angle of the direction of fixation could be noted as soon as the affected numbers appeared blurred.

Twelve letters were chosen: T F E H for the horizontal and vertical lines; X Z A N for the oblique lines with either horizontal or vertical lines; O C D U for the circular type of design.

The letters were printed in black, one on each white card 6" square so that there were eight sets of twelve letters corresponding in size to each grading of the Snellen type chart from 6/60 size to 6/5 size. A second set with a white letter on a black

background was also used. Two other cards were used: a black circle on a white background and a white circle on a black background subtending 50' at 6 metres.

Calibration of Light.—The lighting during the tests was varied in a definite sequence. The first recording was done with the standard 32 foot lamberts; the top lights were then put on and the vision again recorded, with the object of deciding whether the increase in the intensity of illumination would succeed in activating the more central parts of the fovea. Finally the top lights were flashed on and off at varying speeds and any further improvement was noted.

Procedure.—In all the tests the patient's dominant eye was first padded so that no light could enter and affect (by binocular light balance) the reaction of the amblyopic eye. When correcting lenses were needed, these were put into a trial frame in front of the amblyopic eye to ensure that they were correctly positioned. The trial frame also allowed varying sizes of pin-holes to be used, so that the tests would not be affected by any small amount of irregular astigmatism which might have escaped observation.

At each visit the visual acuity was taken on the Snellen chart in the usual way; it was then taken showing one line only and finally recorded when each letter of the same line was isolated by a large black mask with a hole in it. The difference between the acuity under these three conditions was noted.

The separate letter cards were kept in packs so that they could be shown easily and recordings were made showing which letters were faulted and how they were misnamed. The covering black paper was slipped over the Snellen chart and the separate letters were placed in turn in the central position on this black background. Thus each letter appeared black on a small white surround on a main black background, or white on a black background. The results were recorded, and as long as any letters were read correctly the next smallest series was put up and the visual acuity was noted until a point was reached at which no letter of that size could be read. In this way, at each visit, an accurate record was made of the letters most easily seen and also of recurring errors.

A detailed analysis of each letter was made. Each patient was asked whether all the component lines of the letter were equal in clearness of outline, blackness (or whiteness), and thickness. They were also asked to draw the letters exactly as they saw them to correlate with their verbal descriptions.

The patient's head was free but placed so that the amblyopic eye lined up approximately with the central point of the letter. While the patient fixed the central single letter, a second letter was placed to the side but within the width of the Snellen chart and therefore at an angle of $\frac{1}{2}$ or $\frac{3}{4}^\circ$ of abduction or adduction to the primary position. The effect of a second subsidiary image on the sharpness of the central letter was noted. Finally, the single letter was moved from one side to the other, and the patient turned his eye to follow the letter and reported any noticeable difference.

Results

The records of these patients showed several constant features:

- (1) When a full Snellen chart was shown and, for instance, the 6/24 line

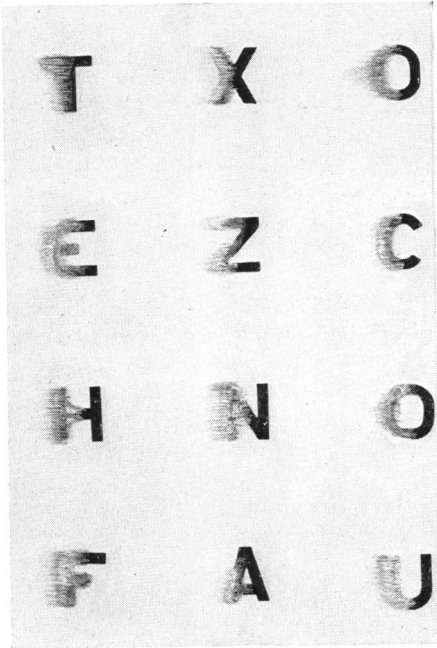


Fig. 1 (a)

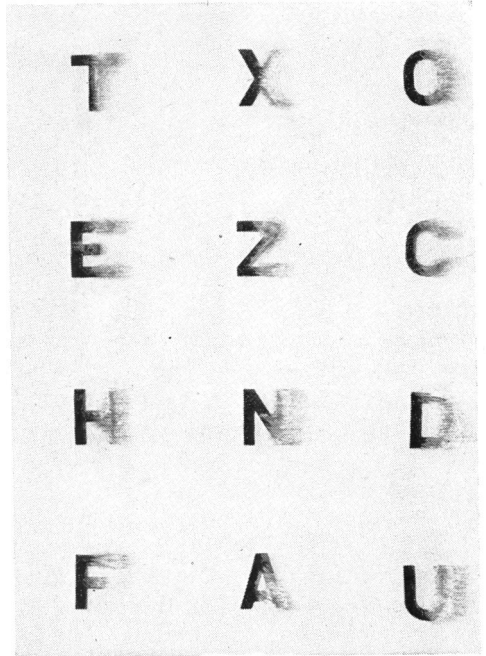


Fig. 2 (a)

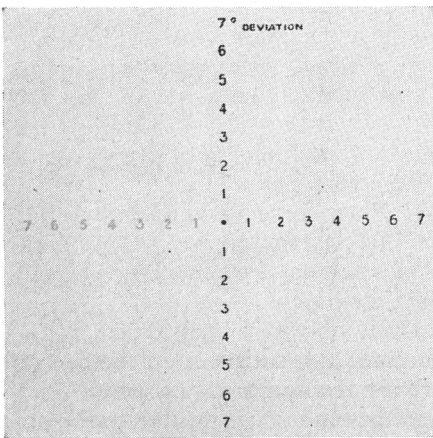


Fig. 1 (b)

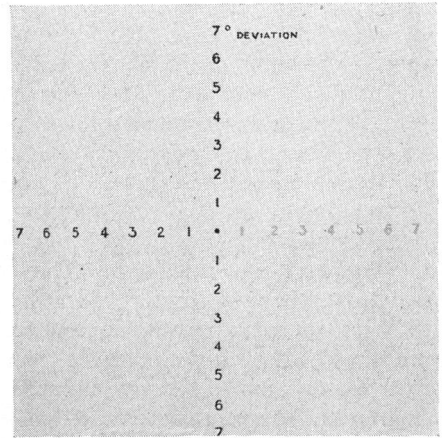


Fig. 2 (b)

was the smallest line read easily, the next line 6/18 was attempted with complaints that the central letters ran together defeating judgment. As soon as each letter was isolated with a black surround it became quite clear and steady and was read correctly, and usually the next line of isolated letters was read in part. In every case the patient read at least one more line as soon as the adjacent letters were covered. At the limit of resolution it was obvious that even when isolated, the shape of the letter made a difference, some being much more easily read than others.

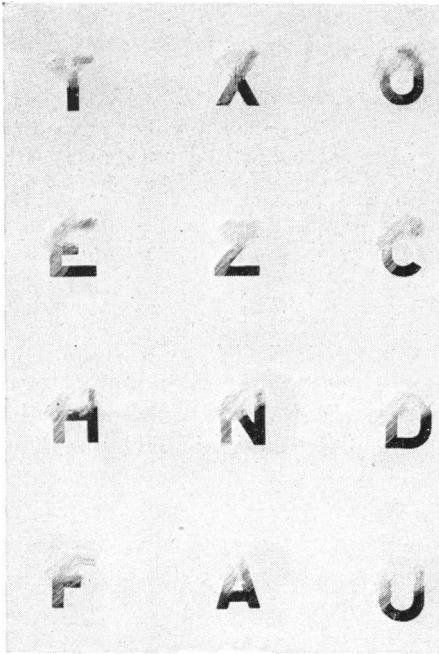


Fig. 3 (a)

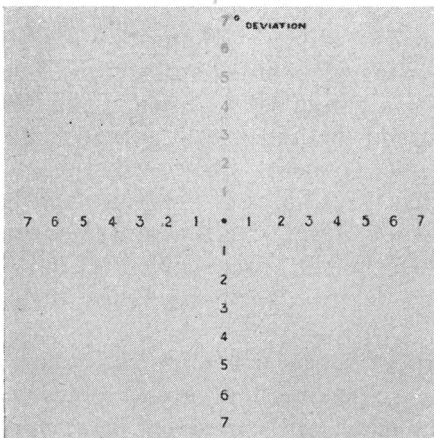


Fig. 3 (b)

(2) When separate letters were shown, it was found that certain letters favoured by the patient were sometimes read two or even three Snellen grades smaller than the initial test-line or the whole chart. A detailed analysis of each letter revealed that in every case the description showed that most of the letters were seen with a consistent distortion; consistent that is for each patient. At first the main difference between the descriptions given by different patients appeared to be that those with a left amblyopic eye appeared to see the pattern of the letter disturbed on the left side, while those with a right amblyopic eye had trouble with the right side of the letter, but this was often not so simple. Some patients found a pattern interference in the oblique lines, so that a part of one diagonal of an X might be much clearer than the other segments but the whole length of the oblique line was not affected as might be the case if the blurring were due to an astigmatic error of refraction. These variations led to the use of the round black circle on a white background as a key to help elucidate the areas of abnormality. Thus a patient with a left amblyopic eye might find it easy to explain that from 12 o'clock through 3 o'clock down to 6 o'clock the black

circle had a good outline and was uniformly black in colour, whereas on the opposite side through 9 o'clock the outline became "jagged", "dragged", "smudged", or "rubbed", the blackness faded, and the circle appeared to be flattened. This would agree with the pattern distortion described for the individual letters: the vertical letter H would be seen with a clear black stroke on the right side, but the left upright would be described as thinner, with blurred edges, and greyer in colour. The letter T would be seen with a clear black edge on the right of the crossbar, while the left side would be rounded, blurred, and indefinite.

A left eye of a subject who had a small degree of esotropia, without any vertical deviation or large degree of astigmatism to complicate the design, showed the following errors when examined monocularly:

The pattern disturbance was similar through all the twelve letters, the right side being sharp, and the left side abnormal. This defect led to recurring mistakes in reading letters, the circular letters such as D O U and C were mixed and often indistinguishable from other letters; an X would look rather like a K owing to the blurring of the left side of the letter.

Conversely, the right eye of a subject with esotropia had difficulty in resolving the right side of the letters.

The position of the area of faulty perception as described by the patient remained constant throughout many examinations over a period of months or even years. Alterations occurred not of position but of degree as the visual acuity improved to normal, but did not disappear completely until the acuity was 6/6.

Factors which had to be considered included refractive error, especially if complicated with astigmatism, lateral deviation, and vertical or torsional deviation. The simple lateral pattern disturbance described above occurred in patients with a small degree of esotropia only (some as little as one degree). When a small vertical deviation was present, the direction of the "drag" might be shifted slightly up or down. This could affect the shape of letters with oblique lines such as X, shortening one segment and possibly making it look like a Y, and confusing an N with an H. When the letter X was considered not as two oblique lines but as four segments of the letter, the disturbance was usually described as occurring in separate halves, often giving, for example, the lower left corner as the best and the upper right corner as the worst. A number of patients described one segment as being shorter and running into the background, and the other three limbs of the X as varying in order of clearness; such a description would agree with the answers given on the circle card test. For instance, when the left lower segment of the X was defective, the circle would have been described as being faulty in its contour in the region of 7 o'clock.

When astigmatism and/or a small vertical deviation and/or cyclophoria were present, a correlation between the subjective finding and objective measurements was difficult. Single cases had to be considered because of the rarity of the combinations. Thus one girl aged 13 years had a vertical deviation of 3 to 4° following a naevus which developed on the right upper lid at the age of 2 months. Radiotherapy restored the lid to normal by the age of 5 years but the eye was amblyopic. The refraction of the eye had changed

from a hypermetropic astigmatism to $\frac{-3.25}{+3.5}$ 90, and with this correction

the visual acuity had developed from 6/36 to 6/9 in the last 3 years. Her description of letter shapes was consistent letter to letter and through the

stages of treatment the top left area of the circle between 10 and 12 o'clock was the poorest part of the pattern improving towards 2 o'clock, and the clearest was between 3 and 5 o'clock but fairly good right round to 10 o'clock. This seems to exclude the astigmatism as the single or even as the primary factor. On the other hand, the deviation was 0° variable, 2 to 4° right hypophoria, and 5° exocyclophoria. Without attempting detailed correlation, the connexion would seem to be a deviation downwards of the right eye with a disturbance of the resolution when the eye fixes upwards.

Thus there appeared to be a relationship between the direction of the usual deviation of the amblyopic eye and the direction of fixation which was reported as giving a distorted design. A right esotropic eye saw the pattern "dragged" on the right side and conversely with the left eye. An additional slight vertical deviation would complicate the direction of the "drag" to shift it up or down. A main vertical deviation downwards gave distortion on upward fixation. The astigmatic error had an effect, but this was secondary to, and modified by, the deviation.

In monocular tests on the orthoptoscope, the patient was asked to look at a tangent scale, to alter fixation from the left figure 1 to the right figure 1, and then to 2 3 4 5 6 7 in turn, and to compare the clearness of the right and left numbers, each figure representing one degree more adduction or abduction from the primary position. The results were the same as in the letter tests. The girl with the vertical deviation saw no difference when she changed her fixation from right to left but found that the figures above the horizontal were seen less well when fixed than the lower letters. In this test the actual amount of movement made as each number was fixed in turn was known because they were the numbers of the tangent scale. Further monocular tests with Chavasse slides showed differences which agreed with the other tests.

Since single letters were seen so much better than the Snellen chart lines, additional letters were placed at the side of the single letter to test whether this would have an effect on the acuity. This was found to be the case, the effect of the additional letters being to make the resolution of the first letter more difficult. Some detailed observations by a young science student aged 21 seem to be worth including.

His right eye had a refractive error of $\frac{+0.5}{+1.75}$ 60, and his visual acuity was 6/18

with or without correcting lenses. Binocularly, the amblyopic eye was 3° esotropic and 1° hypotropic. On analysis he described the usual difficulty in seeing the right side of the letters but with more careful observation than applied by most of the patients. For instance, each T H E and F was blacker and more definite on the left side, but, towards the right, definition faded away so that there was no clear end to the horizontal bars of the E F and the T, and the right-hand side of the H was less steady than the left. He explained that, whereas he could examine the left upright of the H from top to bottom easily and could see that the horizontal

bar was attached to it, the horizontal line faded towards the right and he found it very hard to keep his eye focused on the right vertical upright. The horizontal bar tended to appear lower and the letter was often confused with U.

When the oblique letters N X Z and A were shown to him separately, much the same effect was described, except it was complicated by the different axes of the oblique lines. He described the N, both the black letter on the white background and the white letter on the black background, as being in five grades of grey, the white letter being slightly easier to analyse; the left vertical line was very much better than the oblique line or the right vertical line. In the letter X he gave four grades of tones—again the two left sections were sharp, fading off toward the right. In the letter A he described one sharp left line which gradually faded through five tones to an indefinite smudgy right edge.

He found the circular letters O C D and U the most difficult of all to identify. The poor right edge of the O prevented him from distinguishing the O from the C. The U gave less difficulty, but again had a very smudgy right-hand vertical.

The vision was recorded on many visits during 8 months under the same conditions, and the patient's answers were consistent during each session and on each visit. Disks with small pin-hole apertures were used to see if they made any alteration in the pattern and to exclude the possibility of the pattern's being due to irregular astigmatism. There was no alteration through the small holes, but the patient thought sometimes that they did help to "shut out the surround". They made no difference to his answers. The difference between the visual acuity assessment was that, whereas the patient could read the vertical letters when they were as small as the 6/9 Snellen type, the oblique letters needed to be of the 6/12 size and the circular letters were not differentiated until they were 6/18 size. A whole line shown at the same time was read at 6/18 with difficulty because the letters ran together. The patient described this confusion as due to an "iridescence" from the adjacent letters.

After 10 months of obsessional application in his spare time this young man could read the chart down to 6/9 and all the 6/6 line except the fifth and sixth letters out of the seven. On any chart the letters in this position ran together and were difficult to disengage. His head and eye were free to turn as he wished, but, in spite of this, he found the letters confused in this one particular direction of regard.

All patients were able to read about half to one line more when the extra light was employed but they tended to tire more quickly. A flashing apparatus was used with speeds varying from one to five flashes per second; this did have an effect but made the analysis of the letter shapes more difficult. The effect of flashing will be considered separately from this investigation.

Discussion

The foregoing results gave evidence that an amblyopic eye can resolve single letters much more easily than letters of the same size presented in a row. This effect is not found in non-amblyopic eyes, although it has been noted that certain shaped letters are normally seen with more irregularity than other shapes. Tscherning (1904) observed that some letters are easier

to read than others and thought that the legibility of a letter did not depend entirely on the size of the intervals separating the different lines. Hartridge and Owen (1922) agreed with this. The suggestion was that some retinal astigmatism was present and that some of the inconsistencies could be due to small astigmatic errors of refraction which could not be corrected by lenses. However this may be for the slight irregularities seen by a normal eye, the presence of any significant retinal astigmatism or defect of the refractive media as a cause for the distortion described by the patient using an amblyopic eye is disproved by the improvement and final correction of the condition by treatment.

The pattern disturbance, which the patient described as occurring when his amblyopic eye examined a certain region of a letter (this region being particular and constant for himself), was an asymmetrical distortion of the letter form. When the disturbance occurred in the significant part of the letter, the difficulty in naming the letter was greater than if the blurred pattern happened, for example, to the right-hand side of a C, where there would be an absence of contour. There was in all cases a consistency of this pattern distortion. Irregular astigmatism, which might have been the cause of an asymmetrical image, was excluded by pin-hole tests.

This distortion of pattern had been found previously to be a regular feature of the visual acuity of an amblyopic eye and was thought to be possibly due to lack of central fixation in an eye with a defective visual acuity. To exclude any such complication, these patients were chosen with visual acuity of at least 6/18 at the beginning of the investigation (many improving to 6/12–6/9–6/6 later). Since a 6/12–6/9 letter subtends 10 or 7.5 minutes of arc at the fovea, the receptors involved in resolving letters of this size must be the slender cones of the floor of the fovea centralis.

In normal subjects, Higgins and Stultz (1948) reported:

“A better visual acuity is obtained from measurements with a parallel-line test object when the lines are vertical or horizontal than when they pass diagonally through the visual fields.”

The pattern disturbance described by these patients was always asymmetrical whether the letter was composed of vertical and horizontal lines, diagonal or curved lines.

The problem is that an eye with good central fixation, when moved freely to fix all parts of a letter, can resolve one side of the letter easily but has difficulty and a sensation of frustrated fixation on the other side. The abnormal appearance of this side of the letter was described variously, the visual effect being apparently outside the usual visual experience of the normal eye; descriptive terms such as “iridescent”, “dragged”, “unreal”, “splintered”, even “not in the same plane”, suggested the same quality of pattern disturbance. The effect described was quite unlike that of suppression, the letter sometimes appearing to have rather more to it than less. Several descriptions

suggested a doubling of one section of the letter, the doubled part being ghostly and pale (no irregular astigmatism was present and the doubling subsequently disappeared with treatment). There is no explanation in the theory of the optics of the formation of the image to account for these effects so described, or for the directional preference in resolution of one side of a letter as opposed to the other side.

If a single letter is the target object and a second letter is placed to the side of the distorted outline, some increase of disturbance occurs, but if the second letter is placed to the side of directional preference, the target letter becomes much more confused in outline and, when a full Snellen chart line is visible of a size letter which is easily read singly, considerable confusion of letters occurs. This was explained by patients as being due to the letters running together; the *mesial* letter (for that eye) appeared discrete and steady but, as the eye fixed the subsequent letters, these appeared to run together "as if a fold occurs to run one letter into the other". Since each letter became clear and was read correctly when isolated, the confusion must have been due to the presence of the extra letters in the row. Many good observers explained that, although they could see one end letter easily, they could not disengage the following letters one from the other and had difficulty in counting how many of them there were in that direction.

A subject with heterotropia will have one eye which, under ordinary conditions, is turned (however slightly) so that the optical system and pupil of the eye receive the incident light obliquely as the dominant eye fixes its target object. In considering what difference this may make to the response to the light stimulus by the foveal receptors of such an eye, the observations of Stiles and Crawford (1933) may have significance. To recapitulate, they demonstrated that "rays entering the pupil at points distant from the axis are not so effective visually as rays entering along or near the axis", also that "pencils reach the retina with approximately equal intensities but the brightness-producing efficiency of rays incident on the retina varies with their angle of incidence"; they suggested "that the variation of luminous efficiency is probably retinal rather than pre-retinal".

O'Brien (1950), working on local variations of the Stiles and Crawford effect, found a phenomenon which appeared to be due to localized tilting of groups of cones. O'Brien (1951) examined the relationship of the structure of the retina to the three factors influencing visual acuity (*viz.*, pupil size, luminance, and position of the image on the retina). He elucidated the optical mechanism whereby the spread of rays after focus (with consequent loss of image quality) is prevented. The optical processes within the cones were considered and demonstrated with large model cones and a suggested explanation of the Stiles and Crawford effect was made by these processes. When light enters axially into the larger end of a cone it does not escape before reaching the cylindrical outer segment and is then reflected down the outer segment to escape only at its outer end. Most light absorption occurs in the outer

segments of the cones. According to this theory of cone geometry, a ray entering not parallel to the axis will not be reflected totally down the cone and light will escape into the intercellular fluid.

This explanation of cone behaviour may supply some explanation of the behaviour of the cones of the fovea centralis of an amblyopic eye. If these receptors were in normal alignment, there would be no possibility of incident rays reaching neighbouring cones and spoiling the sharpness of the image. But the evidence is that several letters in a row appear to interfere one with another, an effect suggesting that the image of the target letter is being confused by secondary or ghost images cutting across and disturbing the primary image. This suggests that the receptors themselves are either tilted or disorientated, producing the effect that light rays entering the receptors parallel to their axes will have entered the optical system from a point slightly away from the line of the normal position of the visual axis. It is also possible that an oblique stimulus falling on the fovea through the years may have some effect locally on receptors designed to receive light stimuli axially into their outer segments. Although phototropic movements have not been shown to occur in man and the evidence is that they occur only to a small degree in mammals (for summary see Duke-Elder, 1932), it might be that under abnormal conditions some such changes could occur in man.

Summary

(1) The visual acuity of an amblyopic eye appears to be one, two, or three grades worse when tested on a whole line of a Snellen chart than when these letters are isolated or separate Snellen letters are shown.

(2) The difficulty a patient has in reading consecutive letters in a row appears to be due to an effect of one letter overlapping another and the patient's inability to disentangle one letter from another.

(3) The power to resolve single letters varies with the shape of the letter. This was found to be due to a distortion of outline which occurred when the patient fixed one side of the letter but was not present when he fixed the other side. When the area of pattern disturbance coincides with a special feature of the letter's shape, that letter is not resolved correctly.

(4) The direction of pattern disturbance is consistent and constant and appears to be directly related to the heterotropia which is present binocularly. This direction appears to be opposite to that of the heterotropia, but may be modified by a significant astigmatic error acting as a secondary factor.

(5) This directional effect can be corrected with treatment, thus proving that it is not due to irregular astigmatism or other organic irreversible conditions. The effect is quite unlike that due to suppression.

(6) The graduated single letters used subtend 10 to 7.5 minutes of arc at the fovea and therefore must be resolved by the slender cones on the floor of the fovea.

(7) There seems to be no accepted theory of vision to account for these effects, but if the constantly tilted position of the visual axis causes a tilting of the foveal receptors, an explanation can be suggested. The possibility of phototropic movements may possibly be considered.

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