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THE PERCEPTION OF A LUMINOUS POINT.

PART I.

By J. HERBERT PARSONS.

DURING the middle of last century much attention was paid to the optical conditions of the eye, and our modern conceptions on the subject are the outcome of the researches of Listing (1845), Donders (1866), von Helmholtz (1867), and others. Listing propounded the idea of a "schematic" eye which would represent the optical properties of the emmetropic eye. In it refracting surfaces of perfectly spherical curvature, representing the cornea and lens, were centred upon an axis, the optic axis. The curvatures of the dioptric surfaces, their distances from each other, and the refractive indices of the intervening media were near approximations to measurements derived from observations upon normal eyes. These measurements have been many times repeated, and slight modifications have been introduced, but the essential principles of the schematic eye have been constantly used for the elucidation of ophthalmic problems. Gauss (1840) had previously shown that in such a homocentric system calculations were facilitated by the use of certain imaginary points, the position of which could be easily deduced for any given system. These "cardinal points" consisted of two principal foci and two principal points; to these Listing added two nodal points. The cardinal points lie upon the axis and are of such a character that rays which pass through a principal focus are, after refraction, parallel to the axis; rays which pass through a principal point after refraction pass through the other principal point; rays which pass through one nodal point after refraction pass through the other, and the direction of the refracted ray is parallel to the direction of the incident ray. Fig. 1 is a diagram of the schematic eye, giving the positions of the various points.

Such an eye is a mathematical conception to which the normal human eye is merely an approximation. In such an eye a luminous mathematical point at infinity forms an image which is also a mathematical point at the second principal focus. In order that the image shall be a point it is necessary:—

(1) That only rays very near the axis shall undergo refraction;

(2) That the dioptric surfaces shall be of perfect spherical curvature;

(3) That the rays shall meet the dioptric surfaces almost at right angles;

(4) That the dioptric surfaces shall be accurately centred upon the axis;

(5) That the media shall be absolutely homogeneous;

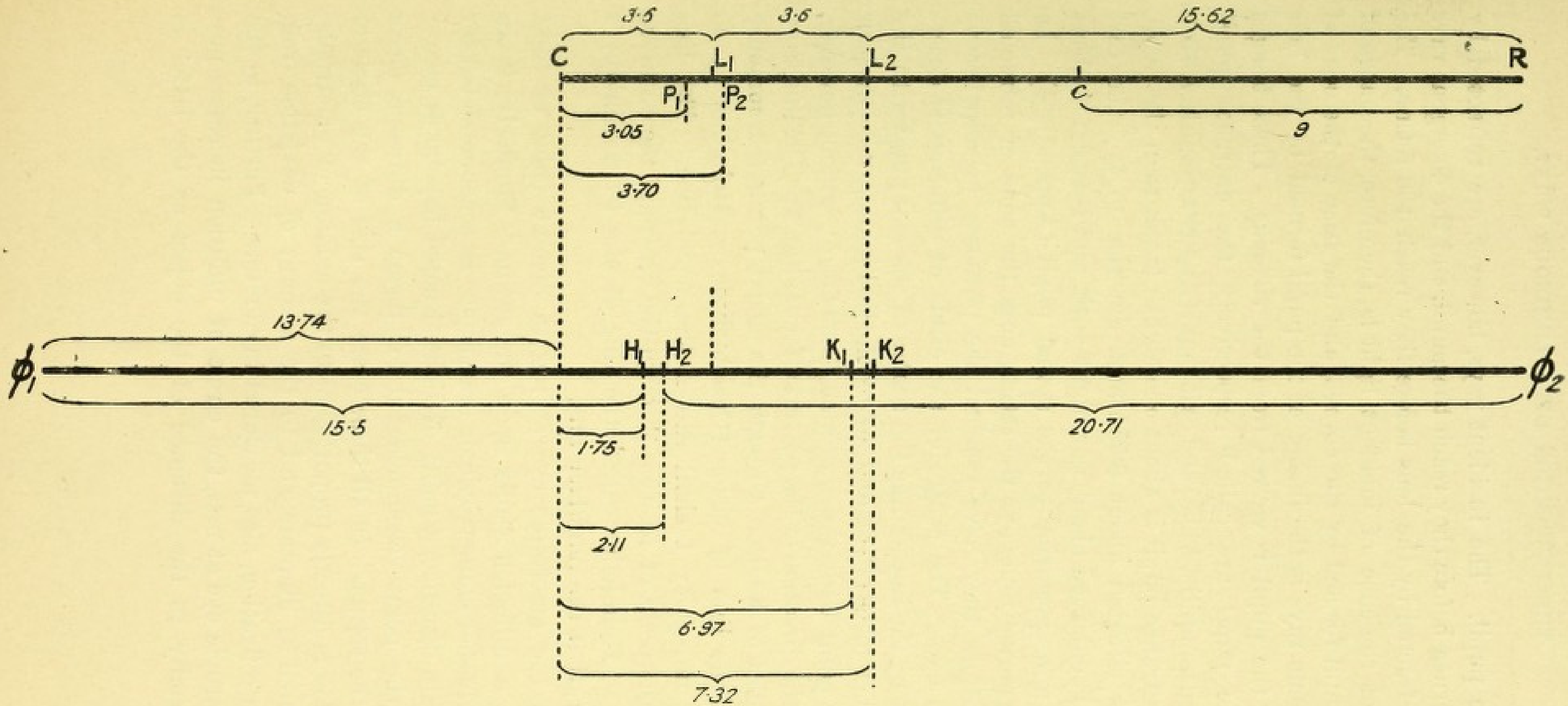
(6) That the rays of light shall all have the same refractivity, *i.e.*, that they shall have the same wave-length.

None of these conditions is accurately fulfilled by the human eye under ordinary circumstances. It must, therefore, be concluded that a punctate image of a luminous point is never formed upon the retina of the eye, and it is the object of this paper to discuss the aberrations which occur.

Presuming, in the first place, that all these conditions are fulfilled, an almost infinitely distant point of light, such as a star, will form a punctate image upon the retina of the emmetropic eye only if the percipient layer of the retina is situated at the exact position of the posterior principal focus of the system. The eye is seldom so perfectly emmetropic that this condition is fulfilled, and in the various forms of ametropia it is widely departed from. In these circumstances, the retinal image is a diffusion circle which varies in size and in the distribution of light over its surface according to the nature and amount of the ametropia.

The size of the diffusion circle is determined by the size

Fig. 1.



C, anterior surface of cornea; L_1, anterior surface of lens; L_2, posterior surface of lens; P_1, entrance pupil; P_2, exit pupil; *c*, centre of rotation of eye; R, retina.

ϕ_1, ϕ_2, anterior and posterior principal foci; H_1, H_2, anterior and posterior principal points; K_1, K_2, anterior and posterior nodal points.

of the pupil. The incident rays, however, are refracted by the cornea before they reach the pupil, and the emergent rays are refracted by the lens before they reach the retina. The base of the cone of incident light is, therefore, the image of the pupil formed by the cornea, and the base of the cone of emergent rays is the image of the pupil formed by the lens when the pupil is viewed from the vitreous. These images of the pupil are called respectively the entrance pupil (Eintrittspupille, Abbe) and exit pupil (Austrittspupille, Abbe). The entrance pupil is about one-eighth larger than the pupil, and is situated about 0·554 mm. anterior to it; the exit pupil is enlarged about one-eighteenth, and is situated about 0·105 mm. posterior to the actual pupil (Appendix I). In the hypermetropic eye the retina cuts the cone of refracted rays before they have reached the posterior principal focus of the eye. The centre of the circle of diffusion is determined by the line joining the centre of the exit pupil with the posterior focus ($P_2 b$), and *not* by the line joining the posterior nodal point with the posterior focus ($K_2 b$), which, however, gives the direction of the posterior focus (Fig. 2). The line from the point of fixation through the nodal points is commonly called the line of vision (Gesichtslinie, v. Helmholtz); to avoid ambiguity I shall call it the nodal line. The line from the point of fixation through the centre of the entrance pupil v. Helmholtz called the line of aim (Visierlinie); I shall call it the pupillary line.

In the ametropic eye at rest, a distant point of light forms a diffusion circle upon the retina. Similarly, if an eye, whether emmetropic or ametropic, is accommodated for a certain distance, a point of light situated beyond or nearer than the point accommodated for forms a diffusion circle upon the retina. In all these cases the size of the circle of diffusion is directly proportional to the amount of ametropia, measured in diopters, and to the amount of deviation from accurate fixation, also measured in diopters. Further, in the emmetropic eye at rest, the circle of diffusion increases proportionally to the distance of the object as the latter is

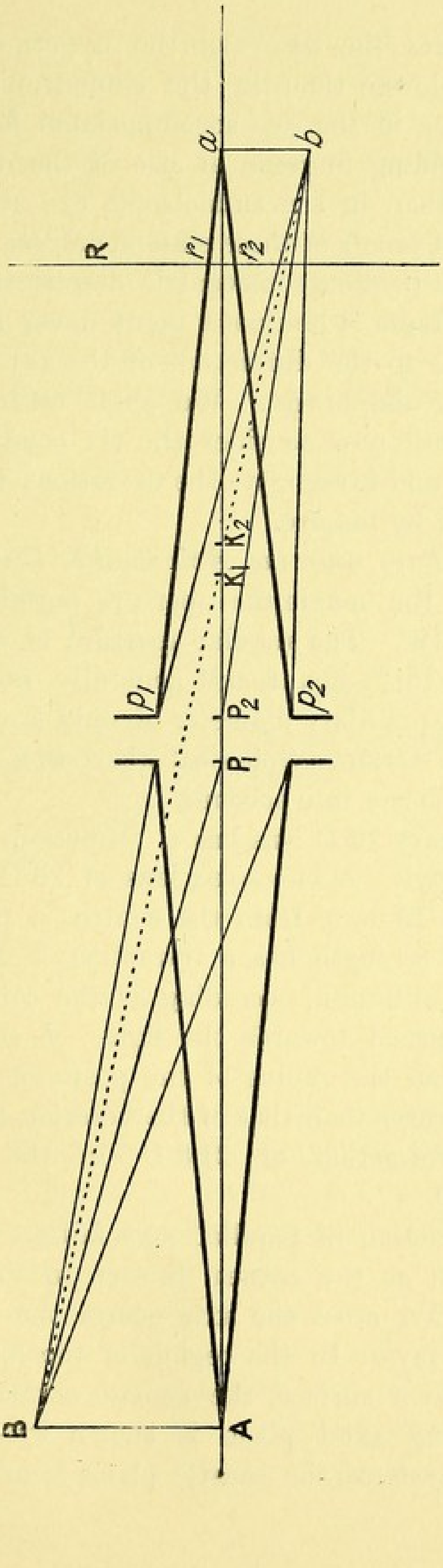


FIG. 2.

brought nearer the eye. In the hypermetropic eye this increase is slower than in the emmetropic eye. In the myopic eye, or in the eye accommodated for a near object, the corresponding increase in size of the diffusion circle is more rapid than in the emmetropic eye at rest. (For the mathematical proofs of these statements, see Appendix II.)

Even in a perfect homocentric dioptric system provided with a diaphragm, a luminous point never forms a punctate image, owing to the diffraction of the rays of light by the edges of the diaphragm. We shall return to this point later. We will now consider the six conditions previously enumerated, and investigate the deviations from them which are exhibited by the eye.

1. *Only Rays near the Axis shall be Utilised.*—In optical instruments the maximum aperture permissible is usually from 10° to 12°. The angular aperture of the eye is always greater than this amount, and generally very much greater. Thus, with a pupillary diameter of only 4 mm., the aperture of the cornea is 20°. Spherical aberration has therefore to be taken seriously into account.

An ordinary 20 D lens has a refraction of 25 D for the peripheral rays. A bi-convex lens of 20 D has a refraction of 22·9 D at 15 mm. from the centre; a plano-convex lens of the same strength has a refraction of 21·95 D or 27·7 D in the same situation, according as the convex or the plane surface is turned towards the light. A so-called "crossed lens," in which the radius of the posterior surface is about six times greater than that of the anterior, is more aplanatic, having a refraction of 21·8 D in the same situation (Tscherning).

The refraction of parallel rays falling upon a spherical surface, such as the cornea, is seen in Fig. 3. The more peripheral rays cross the axis nearer the surface than the more axial rays. In the region of the focus the rays are tangential to a surface, the caustic surface, the section of which in any axial plane is shown by the line *ab*. In converging systems the caustic plane is arrow-shaped, with the apex directed away from the incident light; in diverging systems the apex is towards the incident light. The former systems are said to have positive aberration, or to be over-corrected; the latter to have negative aberration, or to be under-corrected.

In a system with positive aberration the image of a luminous point is a circle of diffusion, the distribution of light upon which varies with the position of the receptive surface. At *b*, which is called the practical focus, the definition is best, the circle of diffusion being very bright at

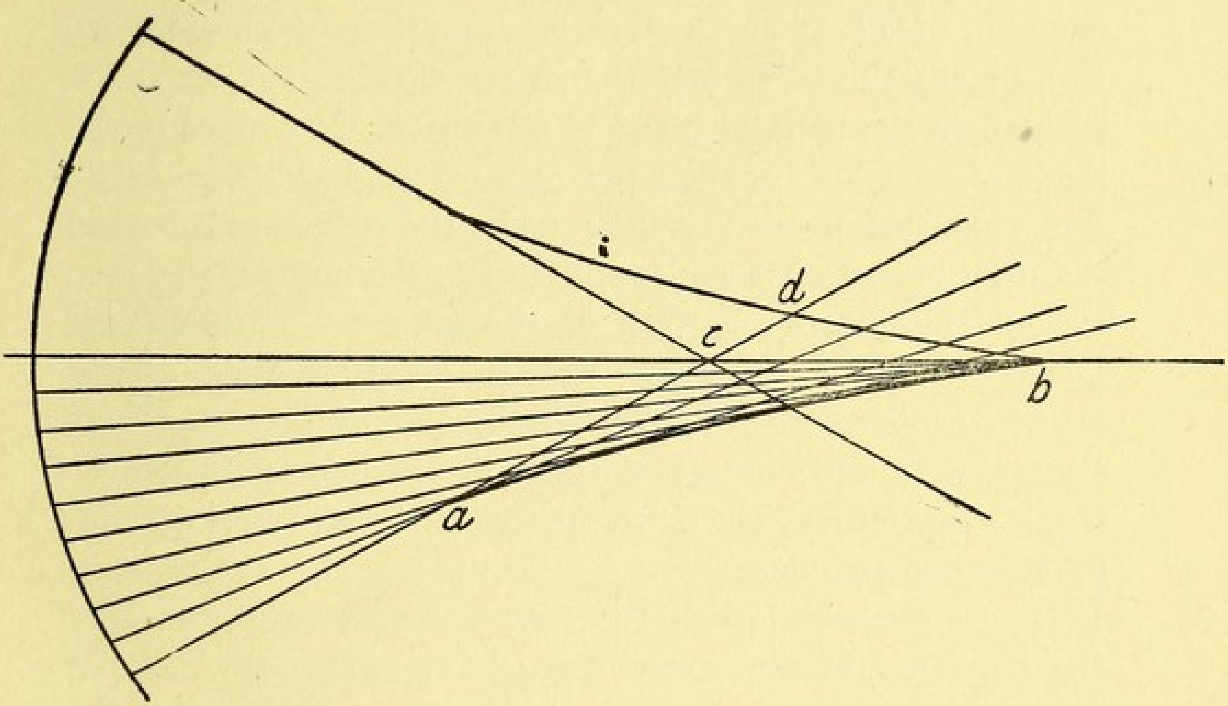


Fig. 3.

the centre and dim at the periphery. At *a* the circle is dim at the centre, and is limited peripherally by a bright area. At *d* the circle of diffusion is smallest, and its radius is the measure of the lateral aberration. The interval *cb* is the measure of the longitudinal aberration.

Spherical aberration increases with the square of the aperture of the system, and with the third power of its refractive force. It also varies with the distance of the object and the character of the refractive surfaces, these variations being dependent upon the angle of incidence of the light. In general, the aberration increases with the angle of incidence, a point of special importance in considering the aberration of the eye. With paraxial rays the angle of incidence to the cornea is small, and the rays refracted by the cornea fall almost perpendicularly upon the anterior surface of the lens. For rays actually normal to the surface the aberration is nil, and it is negligible for rays directed towards what is termed the aplanatic point. This point is situated a distance equal to nr behind the centre of curvature of the surface, where n is the index of refraction of the refracting medium as compared with that of the incident medium, and r is the radius of curvature of the surface. For the anterior surface of the lens r equals 10 mm., and n is the ratio of the total index of refraction of the lens to the index of refraction of the aqueous, *i.e.* $1{\cdot}4371 : 1{\cdot}336 = 1{\cdot}076$. The aplanatic point therefore lies $10 + 10{\cdot}76$ mm. behind the anterior surface of the lens, or $20{\cdot}76 + 3{\cdot}6$ mm. $= 24{\cdot}16$ mm. behind the anterior surface of the cornea. Parallel rays incident to the cornea are directed towards its posterior principal focus, which is situated 31 mm. behind it. They are therefore directed not far from the aplanatic point of the anterior surface of the lens, so that the aberration of this surface is negligible.

It is otherwise with the posterior surface of the lens, the incidence of the rays being very unfavourable. Its aberration exceeds that of the cornea. Tscherning has calculated the aberration of a large eye and a small eye of about the normal limits with different pupillary apertures. They are as follows:—

	Large eye.			Small eye.		
Apparent diameter of pupil ...	4 mm.	6 mm.	8 mm.	4 mm.	6 mm.	8 mm.
Aberration of—	D.	D.	D.	D.	D.	D.
Cornea...	1·0	2·2	4·6	1·6	4·1	9·7
Anterior surface of lens ...	—	0·1	0·4	0·2	0·3	0·8
Posterior surface of lens ...	1·0	2·5	5·5	1·9	5·0	11·7
Complete system	1·6	3·8	8·2	2·8	7·2	17·3

Though these figures give extreme results it is clear that the spherical aberration of the eye is considerable. Other deviations of the eye from the homocentric scheme, however, tend to modify the results.

2. *The Dioptric Surfaces shall be of Perfect Spherical Curvature.*—The dioptric surfaces of the eye are not usually perfectly spherical. The surface which is easiest to investigate is the cornea, and it is also the most important surface because it separates the media which have the greatest difference of refractive index, viz., air and aqueous. The index of refraction of the cornea itself may be regarded as equal to that of the aqueous (cornea, 1·377; aqueous, 1·3365). Early investigations of the corneal curvature led to the conclusion that the central part is ellipsoidal, but subsequent research has shown that this is not so. Aubert and Matthiessen came to the conclusion that the central or optical part was approximately spherical, and the more recent work of Sulzer and Eriksen has confirmed this view. Eriksen found that in most normal eyes the area in which the refraction differed not more than one diopter from the centre had an angular extent of 16·5° outwards, 14° inwards, 12·5° upwards, and 13·5° downwards, corresponding to a circle of about 4 mm. diameter. Beyond this area the refractive power diminishes, the cornea being flatter. The nearest approach to an axis of symmetry is in a direction about 5° temporal to and slightly below the visual (nodal) line. Sulzer found the nasal side flatter than the temporal and the upper than the lower (" dissymmetry of the cornea "). The point of greatest curvature is a little to the outer side, and usually a little above or below the horizontal meridian (" decentration of the cornea," Javal). The pupil is not concentric with the nodal line, its centre being on an average 5° to the temporal side, thus corresponding more or less accurately with the decentration of the cornea, a result confirmed by Brudzewski. Gullstrand, by a very accurate photographic method, has confirmed most of Sulzer and Eriksen's

conclusions. He finds that the optical zone has no axis of symmetry and is not centred on the nodal line but somewhat outside and below it. The peripheral flattening begins nearer the centre in the vertical than in the horizontal meridian. Though the flattening tends to render the surface aplanatic there is still positive spherical aberration in the mid-periphery.

Gullstrand illustrates the corneal aberration in Fig. 4.

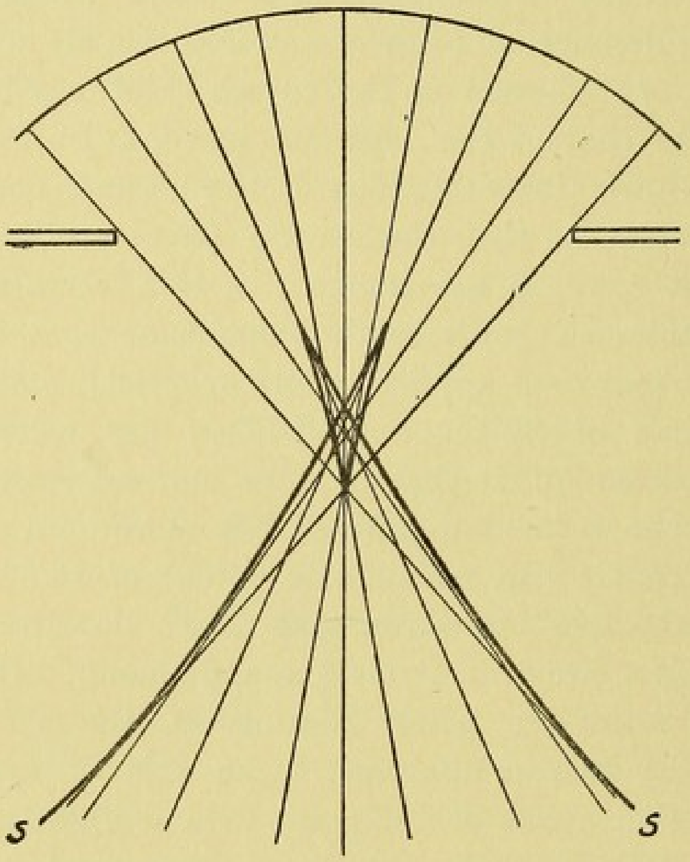


FIG. 4.

Owing to the flattening of the corneal periphery the outermost rays pass through the practical focus of the more spherical central region. If the pupil is smaller these outer rays are cut off and the whole bundle shows positive aberration. If the pupil is larger it is as if the whole bundle showed negative aberration. This relationship between the peripheral and the central rays Gullstrand calls peripheral total aberration.

The radius of the anterior surface of the cornea in the optical zone varies from 7 to 8·5 mm., with an average of 7·8 mm. The thickness of the cornea is about 1 mm. The radius of the posterior surface of the cornea is 6·22 mm. (Tscherning). The refraction at the posterior surface can be neglected, since the difference in the refractive indices of the cornea and aqueous is so slight.

The mean of the measurements for the radii of the anterior and posterior surfaces of the lens is 10 mm. and 6 mm. respectively; the periphery is flatter, but accurate estimates cannot be made. Indeed, Tscherning points out that the error of observation is great in these measurements, probably 0·5 mm.: owing, however, to the comparatively small difference in the indices of refraction such an error corresponds to only about 0·3 D, whereas a similar error in the corneal measurement would correspond to about 3 D.

In addition to the defects of curvature already mentioned, most eyes show slight and many eyes considerable regular astigmatism. In regular astigmatism the refractive surface is toric, *i.e.*, the curvature is greater in one meridian than in the meridian at right angles, though both are spherical. In the eye most of such regular astigmatism is due to the cornea, and the vertical meridian has the greater curvature (" regular astigmatism according to the rule "). Sometimes the horizontal meridian has the greater curvature (" regular astigmatism against the rule "), or the axes are oblique.

The march of the rays in a regular homocentric astigmatic system were first satisfactorily worked out by Sturm in 1838. The general features of Sturm's conoid are familiar and need not be discussed in detail here. It will suffice to note that in astigmatism of this type there are two planes of symmetry, corresponding to the meridians of greatest and least curvature. Gullstrand has stated that, as regards the eye, Sturm's conoid is not accurate. It must be admitted that Sturm's conoid is accurate only for infinitely thin bundles of rays, and the pupillary aperture is large. Further, the focal lines are regarded as straight in the conoid, whereas they are in reality slightly curved. Gullstrand's observations, however, apply to a system with a crystalline lens of homogeneous structure, whereas we know that the lens consists of layers, the refractive indices of which increase from the periphery towards the nucleus. We may probably accept Sturm's conoid as a very near—probably the nearest possible—approximation to the conditions obtaining in the eye.

The earliest proof of the occurrence of regular astigmatism in the eye was given by Thomas Young, and is especially noteworthy in that he proved it to be due in his own case to the lens, for it was not abolished by immersion of the eye in water. Direct observations on the curvatures of the lens surfaces in various meridians are few in number and open to considerable error of experiment. The best were made by Tscherning, Stadfeldt, and Awerbach with the ophthalmophakometer. In all these cases the anterior surface showed astigmatism according to the rule, the posterior surface generally astigmatism against the rule. The refractive effect of a given amount of corneal astigmatism is four or five times as great as that of the same amount of error in the lens. The posterior surface of the cornea is generally more curved in the vertical than in the horizontal meridian (Tscherning), but, as it is a concave surface, the effect is an astigmatism against the rule. The effect, however, is very slight, owing to the index of refraction of the cornea being so near that of the aqueous.

Estimations of the total regular astigmatism of the eye compared with those of the cornea alone by the ophthalmometer show that lenticular astigmatism is common and is usually, though by no means always, in the opposite sense to that of the cornea. Javal gives the following rules, which should be accepted with reserve :—

1. If the corneal astigmatism is nil, the total is generally a slight astigmatism against the rule.

2. If the corneal astigmatism is against the rule, the total is generally in the same sense and greater.

3. If the corneal astigmatism is according to the rule and between 1 D and 3 D, the total is generally about the same and in the same sense.

4. If the corneal astigmatism is according to the rule and more than 3 D, the total is generally in the same sense and greater.

Further, it must be pointed out that astigmatism cannot be corrected by partial contraction of the ciliary muscle.

3. *The Rays shall meet the Dioptric Surfaces almost at Right Angles.*—Rays which do not fulfil this condition but fall obliquely upon one or other surface are astigmatic. For a point of light situated upon the axis of the homocentric system the condition is merely a special case of spherical aberration. Astigmatism of this type differs from the regular astigmatism already referred to (Gullstrand's first type) in having only one plane of symmetry (Gullstrand's second type). Gullstrand describes a third type in which the axial ray does not cut the axis of the system and which has no plane of symmetry.

If a small cone of rays from a luminous point O (Fig. 5)

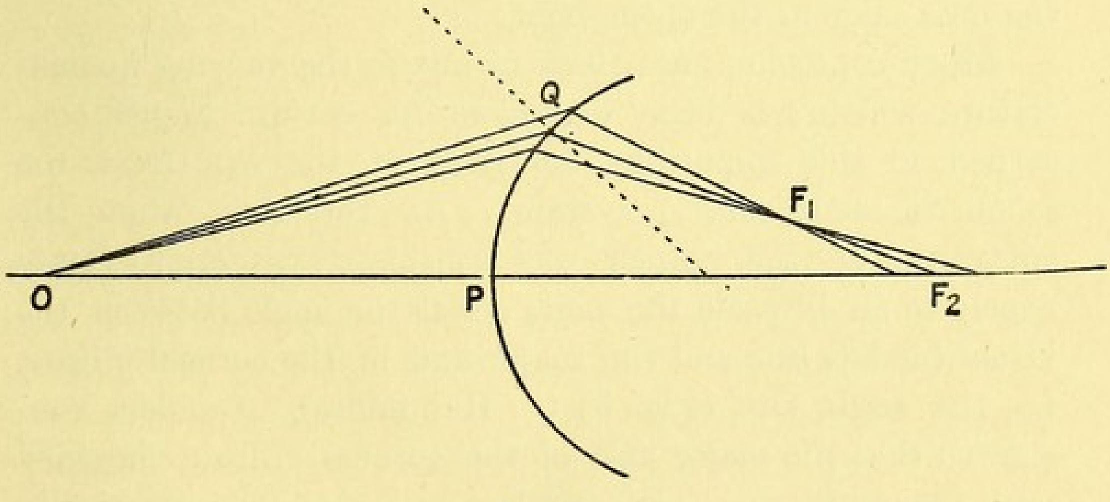


Fig. 5.

on the axis meets a spherical surface at Q, then P may be regarded as the pole of the surface and the rays in the plane of the paper will be meridional rays, and those at right angles to them equatorial or sagittal rays. [illegible] same distance from the axis OPC will undergo the same refraction and will come to a focus on the axis, so that they will form a focal line there as at F_2. The meridional rays will cross before they reach the axis, those more distant from the axis being more refracted than those nearer. They will form a linear focus, which for a small cone may be regarded as a straight line, perpendicular to the plane of the paper as at F_1. (See Appendix III.)

4. *The Dioptric Surfaces shall be Accurately Centred upon the Axis.*—We have already seen that the latest and best investigations of the cornea show that it has no axis of symmetry, so that mathematical accuracy of centring cannot come into question. Tscherning has shown by the ophthalmophakometer that the lens exhibits slight errors of centring, but these are usually small and negligible.

Most important, however, is the fact that the fovea, the most sensitive spot of the retina and that used for most accurate vision, does not lie upon the optic axis, the axis of approximate centring of the dioptric surfaces. In hypermetropia and in less degree in emmetropia the fovea lies to the temporal side of the optic axis; in myopia it may lie to the nasal side of the optic axis.

Much confusion has arisen owing to the varying nomenclature which has been employed for certain angles concerned in this important deviation of the eye from the schematic homocentric system. At the time when the curvature of the cornea was considered to approximate nearly to an ellipsoid the angle α was the angle between the visual (nodal) line and the major axis of the corneal ellipse, *i.e.*, the angle Oba (Fig. 6) (v. Helmholtz). Donders considered that the major axis of the corneal ellipse coincided with the optic axis. His angle α was therefore practically the angle $OK_1\phi_1$. Since it has been shown that the corneal curvature is not an ellipsoid the term angle α has entirely lost its old meaning. Tscherning, however, continues to use it to signify the angle between the visual (nodal) line and the optic axis, *i.e.*, the angle $OK_1\phi_1$. To add to the confusion this angle has been called the angle β by Brubaker.

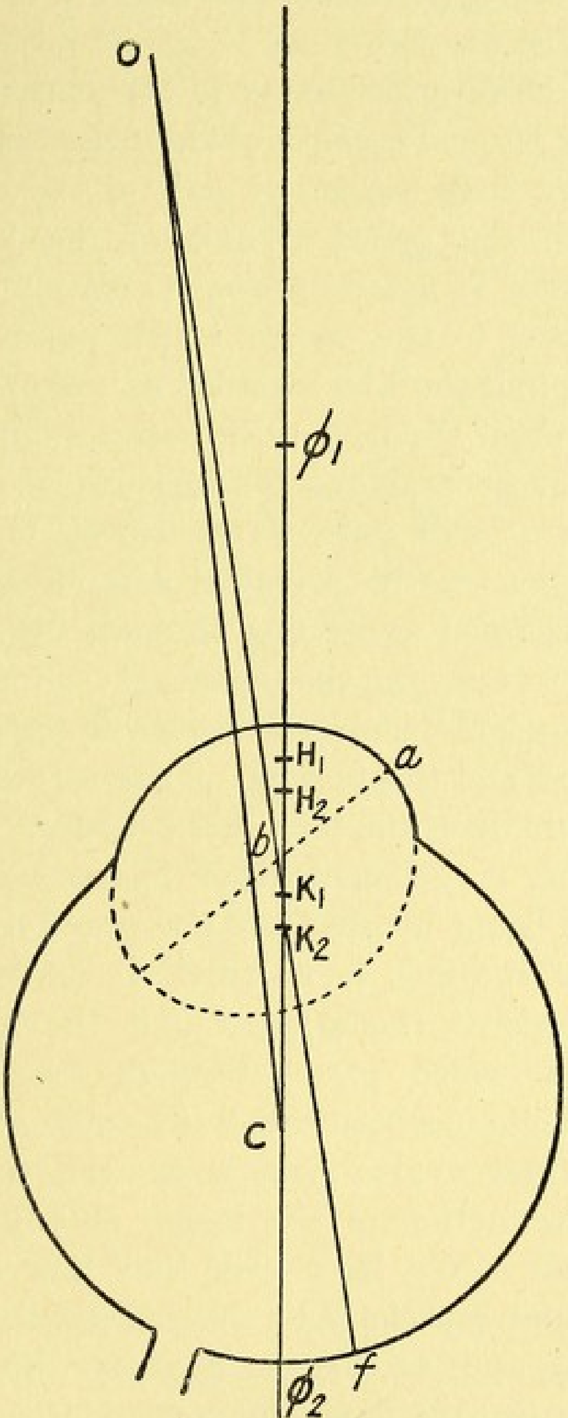


FIG. 6.

The angle γ is the angle between the line of fixation (Blicklinie, v. Helmholtz) and the optic axis. The line of fixation is the line joining the point of fixation with the centre of rotation of the eye; the latter point lies approximately upon the optic axis. The angle γ is therefore the angle $OC\phi_1$ (Fig. 6).

Difficulty, however, arises as to the optic axis. At the time when the corneal curvature was regarded as ellipsoidal it was assumed that the major axis of the corneal ellipse coincided with the principal axis of the lens. As the corneal curvature is not ellipsoidal Gullstrand recommends that the normal to the cornea which passes through the centre of the pupil shall be regarded as the optic axis. The centre of the pupil is not, however, always opposite the pole of the lens. In general and for purposes of calculation no appreciable error will arise if the centre of the pupil is regarded as lying on the principal axis of the lens, and if the latter is regarded as passing through the middle of the base of the cornea, *i.e.* the chord of the corneal curve. Gullstrand therefore defines the angle γ as the angle between the fixation line and the normal to the cornea which passes through the middle of the base of the cornea.

Since there is no method of measuring the angle γ directly, there being no guide to the position of the centre of rotation of the eye, it is usual to measure the angle between the visual (nodal) line and the normal to the corneal surface which passes through the centre of the pupil. This angle has been called the angle κ (Landolt).

None of these angles gives the angle required for the accurate determination of the image of a luminous point upon the fovea. We have seen that this is determined by the pupil and especially by the ray passing through the centre of the pupil, *i.e.*, by the pupillary line (Visierlinie). The angle between the pupillary line and the optic axis has not yet been measured; it is shown in Fig. 7 (after Gullstrand). Here V_1p represents the ray from the fovea which passes through the centre of the pupil: after refraction it passes out of the eye in the direction cV. AA_2 is the optic axis, *i.e.*, the normal to the cornea through the centre of the pupil (Gullstrand), and A_1N is the normal to the cornea at the point *c*. V*a*A is therefore the angle between the pupillary line (Visierlinie) and the optic axis. Gullstrand adopts the value 5° for purposes of calculation, the optic axis lying to the temporal side of the pupillary line outside the eye, as in Fig. 6.

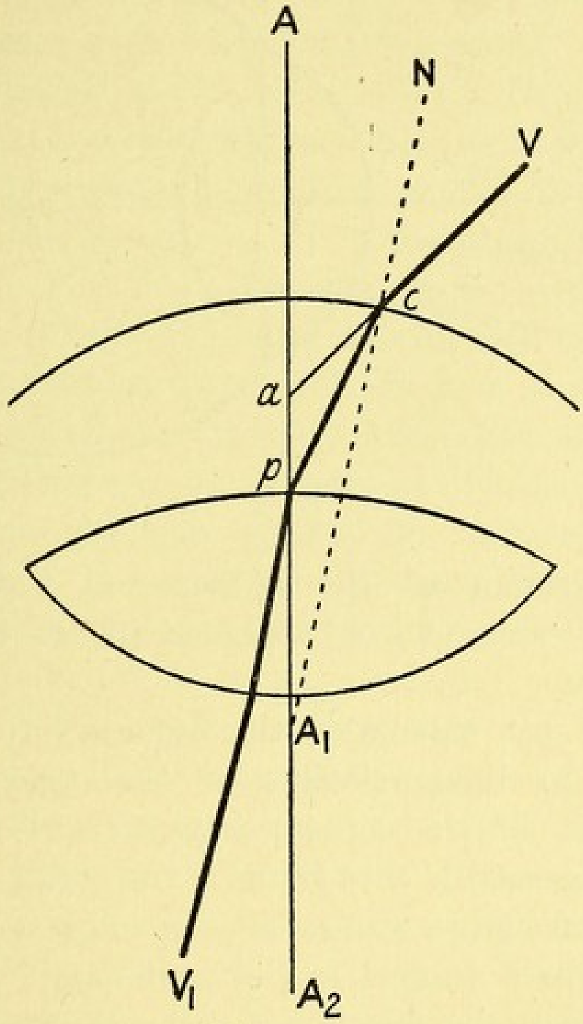


FIG. 7.

It is clear from the above remarks that the light incident to the eye from a luminous point is oblique, and that therefore the refraction is astigmatic, and that the astigmatism is of Gullstrand's second type with a single plane of symmetry (*cf.* Fig. 5). Since the pupillary area is completely filled with light the axial ray passes through the anterior nodal point of the system (Fig. 8), and therefore undergoes no deviation; hence there is what is called oblique centrical refraction. The meridional rays (p. 251) are the rays in horizontal meridian of the cornea. They are brought to a focus sooner than the equatorial rays, and consequently the astigmatism produced is against the rule. The course of the rays is indicated in Fig. 8. If D is the refraction of the

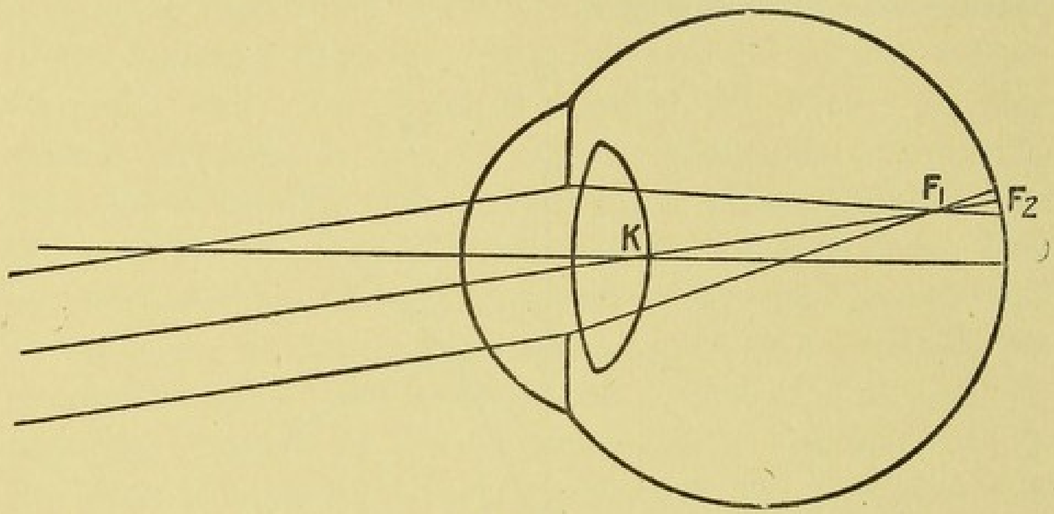


FIG. 8.

horizontal meridian of the cornea and i the angle of incidence the amount of astigmatism is $D(1-\cos^2 i)$. (Tscherning.)

Tscherning has calculated the amount of astigmatism corresponding to different values of the angle α ($OK_1\ \phi_1$). For angle α of 5° the corneal astigmatism is 0·35 D, the lenticular astigmatism 0·14 D, and the total astigmatism 0·49 D. For moderate values of the angle α the inverse astigmatism varies from $\frac{1}{2}$ to $\frac{3}{4}$ of a diopter. The formula applies only when the pupil is very small, but even so the results are too high.

Gullstrand has calculated the focal lines for an angle of 5° between the pupillary line and the optic axis, with a pupil diameter of somewhat less than 2 mm. The longitudinal aberration is then 0·03 mm., corresponding to an astigmatism of 0·1 D. The first area of least diffusion is in the situation of the first focal line and is 0·002943 mm. long and 0·002240 mm. broad. With increasing size of the pupil the long diameter increases as the radius of the pupil and the broad diameter as the square of the radius. The calculated amount of astigmatism under the given conditions is too slight seriously to affect visual acuity. Gullstrand has shown that the shape of the lens, especially its greater posterior curvature, tends to neutralise the effect of the corneal astigmatism which arises from oblique incidence. The angle of incidence to the *cornea* is therefore the important factor in this type of astigmatism.

5. *The Media shall be Absolutely Homogeneous.*—The refractive media of the eye are not homogeneous. Apart from the familiar muscæ volitantes of the vitreous irregular refraction in the lens can easily be demonstrated by entoptic observations. For the most part these result in irregular astigmatism which will not be further discussed here. A most important peculiarity of the lens must, however, be mentioned. In all the previous investigations of the course of the rays in the eye the *total* refractive index of the lens has been employed as sufficiently accurate. The lens consists of many layers and it was long ago discovered that the refractive indices of the layers are not the same, but that there is a gradual increase in refractive index from the cortex towards the nucleus. The curvature of the nuclear layers is greater than that of the more superficial layers, consequently the latter act as concave menisci in relation to the former. The investigations of Matthiessen and others show that it is possible to devise an imaginary lens having the same curvatures as the crystalline lens and the same refractive power. Such a lens would have a refractive index which is termed the total refractive index of the lens, an idea first enunciated and calculated by Thomas Young. The total refractive index is greater than that of any of the layers of the crystalline lens. Though such a lens gives a near approximation to the course of rays through the central parts of the crystalline lens, its behaviour as regards aberrations of various kinds is different and must therefore be taken into account in our considerations.

Apart from the shortening of the focal length the most striking feature of the laminated lens is its compensatory effect upon both spherical aberration and aberration due to oblique incidence. The schematic eye with as large an aperture as the human eye would possess a high degree of positive spherical aberration. The measure of spherical aberration is given by the deviation of the system from the sine condition. A certain amount of compensation occurs from the peripheral flattening of the cornea. Further compensation is brought about by the weakening of the refraction of the peripheral parts of the lens. Stadfeldt's measurements show that in a central zone of about 4 mm. diameter the lens is nearly aplanatic; in the zone between 4 mm. and 6 mm. the aberration is over-corrected; beyond 6 mm. the aberration is under-corrected. The mean central refraction is 18 D, paracentral 16 D, and peripheral 20 D. The diminution of the refraction in the paracentral zone is to be attributed to the diminution of the refractive index towards the periphery, whilst the increase of the refraction in the peripheral zone is due to the increased curvature of the surfaces in this situation. The numbers are for incident parallel rays and cannot be directly applied to rays which have already undergone corneal refraction and are thus convergent. Brudzewski found slight negative aberration in the lens from comparison of the corneal curvature and the total skiascopic refraction. Gullstrand from his own measurements considers the positive spherical aberration to be too great to be accounted for by the cornea alone. Hess suggests that the difference may be due to age. In spite of slight displacement forwards of the lens in advanced life the eye becomes relatively hypermetropic, owing to diminution in the total refractive index of the lens.

The effect of the lamination of the lens is not less marked upon the aberration of obliquely incident pencils of rays. L. Hermann has exhaustively discussed the problem of the refraction of obliquely incident rays. He found that there is minimum aberration if the nucleus is spherical and of higher refractive index than the peripheral layers, conditions which are nearly satisfied by the crystalline lens. This property increases the field of clear vision.

The crystalline lens, therefore, provides a powerful compensatory mechanism for the aberrations which have already been discussed. Unfortunately it is difficult, if not impossible, to measure and correlate accurately the various factors; hence the extreme importance of experimental observations on the eye as a whole.

6. *The Rays of Light shall all have the Same Refractivity.*—In everyday life monochromatic light occurs only under precise experimental conditions. Chromatic aberration is not corrected by the ocular mechanism. Fraunhofer made the first measurements and found a difference of 1·5 D to 2 D for parallel rays of light of the wave-lengths of the C and F lines of the spectrum. Von Helmholtz found similar values for his own eye. Wolf found the longitudinal difference between the foci for red light of the B line and violet light of the H line to be 0·75 mm.; for C and G 0·5 mm. Kunst measured the refractive indices of the media for the D and F lines, and Einthoven calculated the cardinal points of the schematic eye for these lines, the posterior focal lengths showing a difference of 0·2719 mm. If the eye is adapted for light of medium wave-length the diffusion circle for red and violet light has a diameter of 0·0426 mm. (v. Helmholtz). If an eye is adapted without accommodation for violet rays and the focus of the red rays is 0·5—0·6 mm. behind the retina the diameter of the diffusion circle is 0·1 mm. Von Helmholtz found that there was no improvement in his visual acuity by making his eye achromatic.

Owing to the angle γ the diffusion circles for blue and red are not concentric; colour stereoscopy depends upon this fact. Thus, in Fig. 9, if AA is the optic axis, pc the visual (nodal) line, the eye being adapted for blue rays and r being the focus for red rays, then in the diffusion circle r_1r_2, br_2 is greater than br_1 (Einthoven).

Finally we will briefly consider the effect of diffraction by the pupil. This depends upon the wave-length of the light

If a point of monochromatic light is viewed through a small circular aperture the effect is the same as if a bright spot surrounded by a series of dark and bright rings of rapidly

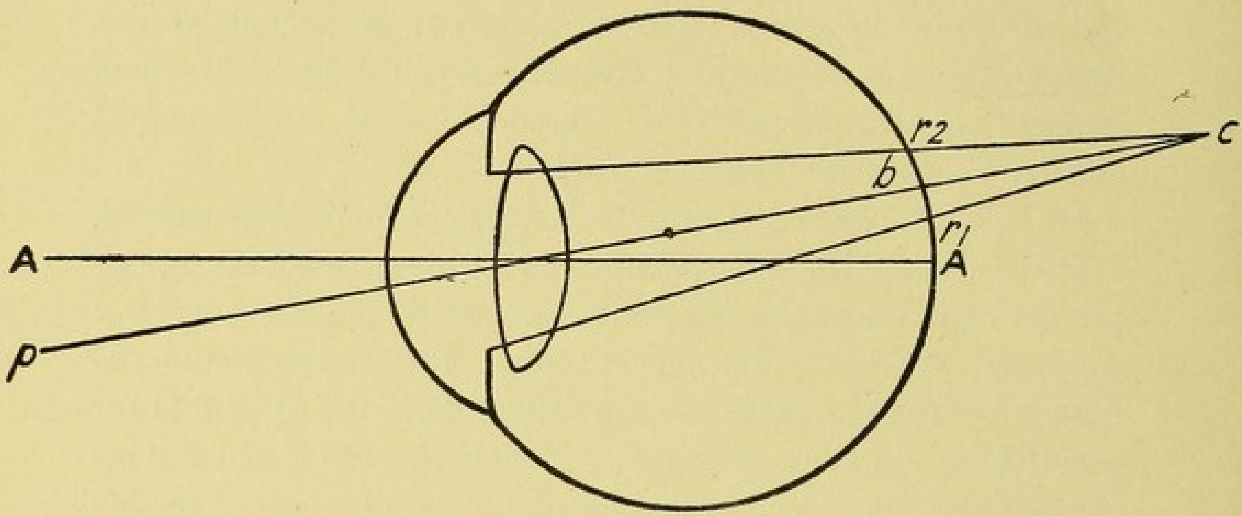


FIG. 9.

diminishing intensity were observed from a great distance. If θ is the angle which the central spot of light subtends at the centre of the diaphragm, then $\theta = 3{\cdot}832\,\lambda/2\pi r$, where λ is the wave-length of the light and r is the radius of the diaphragm. For a distant point of light seen by the eye the angle subtended at the centre of the pupil is inappreciably different from the visual angle subtended at the anterior nodal point. Moreover, under the same conditions the image on the retina is equal to the visual angle multiplied by the anterior focal length of the eye (θf). Therefore, for $\lambda = 550\,\mu\mu$, about the brightest part of the spectrum, a pupil diameter of 4 mm., and an anterior focal length of 15 mm., the diameter of the diffusion circle on the retina is 0·005 mm. For a pupil of 2 mm. diameter it is twice, and for a pupil of 1 mm. diameter four times as large.

In these measurements the eye is supposed to be free from aberration, the light is monochromatic, and the rings of the diffraction areola are left out of account. It is clear, therefore, that the diffraction circle upon the retina is of appreciable size.

APPENDIX I.

The position of the entrance pupil is given by the formula

$$\frac{n_1}{f_1}+\frac{n_2}{f_2}=\frac{n_2-n_1}{r}$$

(See Parsons, Elementary Ophthalmic Optics (E.O.O.), p. 33). Here n_1 = refractive index of the aqueous = 1·3365; n_2 = refractive index of air = 1; f_1 = distance of the real pupil from the anterior surface of the cornea, *i.e.*, depth of the anterior chamber = 3·6 mm.; f_2 = distance of the entrance pupil from the anterior surface of the cornea; r = radius of curvature of the cornea = 7·829 mm. Therefore

$$\frac{1{\cdot}3365}{3{\cdot}6}+\frac{1}{f_2}=\frac{1-1{\cdot}3365}{-7{\cdot}829}=\frac{0{\cdot}3365}{7{\cdot}829},$$

and

$$f_2=-3{\cdot}046.$$

The negative sign shows that the image is on the same side of the cornea as the object. The entrance pupil is therefore 3·6−3·046 = 0·554 mm. nearer the cornea than the real pupil.

The size of the entrance pupil is given by the formula

$$\frac{o}{i}=-\frac{n_2}{n_1}\cdot\frac{f_1}{f_2} \qquad \text{(E.O.O., p. 39).}$$

Therefore

$$\frac{i}{o}=-\frac{1{\cdot}3365\times 3{\cdot}046}{3{\cdot}6}$$

$$=-1{\cdot}131.$$

Therefore the entrance pupil is 1·131 times as large as the real pupil.

The position and size of the exit pupil are given by the same formulæ. As the pupil is in contact with the anterior surface of the lens only refraction at the posterior surface need be considered. Here n_1 = total refractive index of the lens = 1·4371; n_2 = refractive index of the vitreous = 1·3365; f_1 = distance of the real pupil from the posterior surface of the lens = thickness of the lens = 3·6 mm.; f_2 = distance of the exit pupil from the posterior surface of the lens; r = radius of curvature of the posterior surface of the lens = 6 mm. Therefore

$$\frac{1{\cdot}4371}{3{\cdot}6} + \frac{1{\cdot}3365}{f_2} = \frac{1{\cdot}3365 - 1{\cdot}4371}{-6}$$

and $$f_2 = -3{\cdot}495.$$

The negative sign shows that the image is situated on the same side of the posterior surface of the lens as the object. The exit pupil is therefore 3·6 − 3·495 = 0·105 mm. behind the real pupil.

$$\frac{i}{o} = -\frac{1{\cdot}4371 \times 3{\cdot}495}{1{\cdot}3365 \times 3{\cdot}6}$$

$$= -1{\cdot}044.$$

Therefore the exit pupil is 1·044 times as large as the real pupil.

Appendix II.

In Fig. 2 let p be the diameter of the exit pupil, the centre of which is at P_2. Let z be the diameter of the circle of diffusion formed by the point A at the retina, R. Let $P_2R = l$, and $P_2a = m$. Then from the similar triangles ar_1r_2, ap_1p_2,

$$\frac{z}{p} = \frac{m-l}{m} = 1 - \frac{l}{m} \qquad (1)$$

The formula

$$\frac{n_1}{f_1} + \frac{n_2}{f_2} = \frac{n_2 - n_1}{r} \qquad \text{(E.O.O., p. 33)}$$

can be written in the form

$$\frac{n_2}{f_2} = \frac{n_1}{f_1} + \frac{n_1}{F_1} = \frac{n_1}{f_1} + \frac{n_2}{F_2} \qquad (2)$$

if the convention of giving both focal distances the same sign is adhered to. The "convergence" of the incident or refracted rays is measured by the reciprocal value of the distance of the object or image from the first or second principal point respectively. Convergence can therefore be measured in diopters, since the diopter as a unit is merely the reciprocal value of a metre.

To compare the distances of object and image in media of different refractive indices the distances must be reduced to the same medium.

If b is the distance of a point in an object in a medium of index n, then $1/b$ is the convergence of the bundle of rays in air, and n/b is its reduced convergence. (2) may therefore be written in the form

$$B = A + D, \tag{3}$$

where $$A = \frac{n_1}{f_1}; \ B = \frac{n_2}{f_2}; \ D = \frac{n_1}{F_1} = \frac{n_2}{F_2}$$

(E.O.O., p. 34)

the distances being measured in metres. The introduction of this convention by Gullstrand greatly simplifies the formulæ used in physiological optics. In the following discussion I give the problem of diffusion circles as set out by Hess in Graefe Saemisch Handbuch.

In formula (2) the reduced convergence of the refracted rays B is n/b. If l is the true axis length, the reduced axis length is $\lambda = l/n$. Inserting these values in (1) we have

$$z = p(1 - \lambda B),$$

or, from (3),

$$z = p(1 - \lambda D - \lambda A). \tag{4}$$

If the eye is adapted for a point at a distance a_1, for which $D = B - A$, then for another point a_2

$$D = B_1 - A_1$$

and $$\frac{z}{p} = 1 - \lambda A_1 - \lambda D$$
$$= 1 - \lambda A_1 - \lambda B + \lambda A.$$

Since the image of a_1 lies on the retina $B = 1/\lambda$, and

$$z = p\lambda(A - A_1). \tag{5}$$

$A - A_1$ is the measure in diopters of the failure of an eye adapted for a_1 to see the point a_2, *i.e.*, the effort of accommodation necessary to see a_2 clearly. Hence, the circle of diffusion corresponding to the requisite accommodative effort, *i.e.*, the dioptric failure of adaptation, is proportional to the diameter of the pupil and to the reduced axis length. If the eye is adapted for infinity, $A = 0$ and $z = p\lambda(-A_1)$.

(4) may be written

$$\frac{z}{p} = \lambda(-A) + (1 - \lambda D).$$

Hence, (i) if

$$\lambda D = 1 \quad \text{then} \quad z = p\lambda(-A),$$

the circle of diffusion is proportional to the distance of the object. The condition $\lambda D = 1$, or $D = 1/\lambda$, means that the eye is adapted for parallel rays, and the result is the same whether the eye is emmetropic or a hypermetropic eye corrected for distance by accommodative effort.

(ii) if $\lambda D < 1$ then $\frac{z}{p} = \lambda(-A) + N$,

where N is a proper fraction. Therefore as A increases, *i.e.* as the object is brought nearer, the circle of diffusion increases slower than the distance diminishes. The condition $\lambda D < 1$ means that the eye is adapted for a point at a finite distance *behind* it, since then $D < 1/\lambda$ and $1 - \lambda D > 0$. In other words, the refractive power of the system is smaller than the reduced convergence of the bundle of rays upon the retina. Here, too, the accommodative condition does not affect the result so long as $D < 1/\lambda$.

(iii) if $\lambda D > 1$ then $\frac{z}{p} = \lambda(-A) - N$.

Therefore the circle of diffusion increases more rapidly than the distance of the object diminishes. The condition $\lambda D > 1$ means that the eye is adapted for a point at a finite distance *in front of* it, since then $D > 1/\lambda$, and $1 - \lambda D < 0$. Here, too, the result is not affected whether the adaptation is due to elongation of the axis or to accommodative effort.

Appendix III.

In Fig. 5, let $OQ = u$, $QF_1 = v_1$, $QF_2 = v_2$, the radius of the spherical surface $= r$, the refractive index of the first medium $= \mu$, that of the second $= \mu'$, the angle of incidence $= \phi$, and the angle of refraction $= \phi'$, then for the meridional rays the formula

$$\frac{n_2}{f_2} - \frac{n_1}{f_1} = \frac{n_2 - n_1}{r} \qquad \text{(E.O.O., p. 33)}$$

becomes

$$\frac{\mu' \cos^2 \phi'}{v_1} - \frac{\mu \cos^2 \phi}{u} = \frac{\mu' \cos \phi' - \mu \cos \phi}{r},$$

and for the equatorial rays

$$\frac{\mu'}{v_2} - \frac{\mu}{u} = \frac{\mu' \cos \phi' - \mu \cos \phi}{r}.$$

The proof involves the use of the differential calculus, and is given in Percival's Optics, p. 270.

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THE PERCEPTION OF A LUMINOUS POINT.

PART II.

By J. HERBERT PARSONS.

IN Part I I have discussed the physical conditions which subserve the formation of an image of a luminous point upon the retina. It has been shown that owing to the aberrations of the optical system, to the heterogeneity of the light, and to the diffraction at the margin of the pupil, the retinal image of a point of light is always a diffusion circle. So far as the refractive aberrations are concerned the size of this circle is minimised by maximal constriction of the pupil. So far as diffraction by the pupil is concerned the size of the diffusion circle is minimised by maximal dilatation of the pupil. Under no circumstances, therefore, is it possible to obtain a punctate image of a luminous point. The diameter of the diffusion circle due to optical aberration with a pupil of 4 mm. diameter may be taken as a mean at 0·06 mm., to which must be added 0·04 mm. for chromatic aberration. If therefore the eye with a 4 mm. pupil is accommodated for the circle of least diffusion of the spherical aberration the size of the diffusion image is 0·1 mm. in diameter.

Let us suppose for the moment that any overlapping of two such diffusion areas involves fusion of the sensations so that two points so situated as to produce any overlapping of the images will be seen as a single point. If the points are situated 15 mm. from the eye the images will overlap if the points are less than 10 cm. apart. Obviously therefore the supposition is not justified.

Before discussing the explanation of the fact that two points so situated that their retinal images overlap may yet be discriminated as separate points it will be well to review the experimental evidence available for the measurement of maximal visual acuity.

Regarding the question first from the purely physical point of view, visual acuity must be measured by the size of the retinal image: the eye which perceives a luminous point whose retinal image is minimal should have maximal visual acuity. As a matter of fact it will be shown that no direct deduction as to visual acuity (*i.e.*, acuity of perception of forms) can be made from the perception of a single luminous point.

The earliest researches were due to astronomers, and from the time of Archimedes (De Arenæ Numero) the angle subtended at the eye by the luminous object was taken as the measure of vision. Kepler (1604; Ad Vitell. Paralipomena, V, 5) first pointed out that the apex of the visual angle is at the optical centre of the eye, but he wrongly placed this point in the centre of the vitreous. Scheiner (1619), with remarkable intuition, placed it correctly on the optic axis in the posterior part of the lens and distinguished it clearly from the centre of rotation of the eye, which he placed in the centre of the scleral sphere. Two hundred years later Volkmann placed the nodal point at the centre of rotation, and Johannes Müller placed the latter at the posterior pole of the slerotic.

In a dissertation on the "Various Accidents of Vision" (1693) de la Hire says: "On peut voir facilement à 4000 toises de distance une aile de moulin à vent que je suppose de 6 pieds de large . . . la peinture de cette aile sera dans le fond de l'œil sur la rétine de 1/8000 de pouce, et par conséquent, puisque cette peinture fait impression sur le nerf optique, et qu'elle est distinguée d'un autre objet qui en est proche, il faut tout au moins qu'un des filets du nerf optique ne soit que de la largeur de la huitième partie de celle d'un filet de ver à soie = 1/8000 de pouce." One eight thousandth of an inch is equivalent to about $3\,\mu$, or a visual angle of $42''$. In spite of the phrase "qu'elle est distinguée d'un autre objet qui en est proche" it is very doubtful if de la Hire fully recognised the distinction between the minimum visible angle and the minimum separable angle or the minimum angle subtended by two points in order that they may be discriminated as separate.

Buffon (1743) accepts the angle of 1′ and distinguishes between " vue claire " and " vue distincte," or the recognition of objects and the recognition of their details. It can scarcely be admitted with some French authors, *e.g.*, Sulzer, that de la Hire and Buffon made any scientific distinction between the minimum visible and the minimum separable.

Humboldt (Kosmos, III, p. 70) records the extraordinary acuteness of vision of Indians in South America. His companion, Bonpland, was climbing the volcano Pichincha. The Indians were able to see his white poncho or cloak against a background of black basalt at a distance of 27½ km. Humboldt calculated that as it fluttered in the wind the angular dimensions varied from 12″ to 7″. Humboldt also experimented with Gauss' heliotrope, which reflected sunlight, and found that a 3-inch spot was visible at a distance of 213,000 Paris feet, which is equivalent to an angle of 0·43″.

Plateau (1830; Pogg. Ann., xx, p. 328), for a white square on a black background, illuminated by direct sunlight, found a minimum angle of 12″; by diffuse daylight, 18″. Aubert (1865; Physiol. d. Netzhaut) confirmed these values.

Hueck (1840; Müller's Arch., p. 86), for a white spot on a black background, illuminated by sunlight, arrived at the angle 10″.

The angle is greater for a black spot on a white background: Tobias Mayer (1754; Comm. Soc. Götting.), 30″—36″; Hueck (1840), 30″; Aubert (1865), 25″—29″.

Much smaller values are given for the perception of lines. Humboldt (Kosmos, III, p. 68) and Adams (1710; Phil. Trans.) pointed out that a long narrow bar is visible much farther off than a square of the same breadth. Jurin (1755; in Smith-Kästner, Lehrbegriff d. Optik, p. 502) found 2·5″ for silk threads, 3·5″ for a silver wire on white paper. (These values are unreliable.) Volkmann

(1836 ; Neue Beiträge, p. 202) found the values 13·7″ for a filament of spider-web, 13·8″ for a hair.

In all these experiments there was comparatively great contrast between the object and the background. Aubert investigated the influence of contrast.

Background darker than object.	White object.	Background brighter than object.	Black object.
57 times	15″—18″	57 times	25″—29″
17 „	32″—34″	43 „	35″—33″
10 „	34″—37″	29 „	35″—37″
7 „	36″—39″	15 „	35″—37″
3·8 „	39″—44″	8 „	37″—38″
2 „	46″—50″	5·66 „	38″—42″
		3·3 „	39″—45″

These experiments show that the minimum visual angle increases with diminution of contrast. If, however, the extreme values be neglected it is seen that the change is slight for moderate degrees of contrast. Thus between 43 and 7 the visual angle varies from 32″ to 39″. Taking the average at 35″ and the distance of the posterior nodal point from the retina as 15 mm., the size of the retinal image is 2·5 μ.

From these observations, in spite of apparent discrepancies, we may conclude with confidence that the clear perception of minute luminous objects is not entirely dependent upon the size of the diffusion image. The explanation is to be sought in (1) the distribution of light in the diffusion image; (2) the anatomy, and (3) the physiology of the retina.

(1) *The distribution of light in the diffusion image* varies according to the cause of the aberration. In spherical aberration, if the eye is accommodated for the circle of least diffusion, the light is evenly distributed; if, however, the eye is accommodated for the focal point of the central rays, as is probably the case generally, the central part of the circle is brighter than the peripheral. Physiological astigmatic

aberration causes less enlargement of the image, and is therefore negligible in dealing with the distribution of light. Diffraction at the pupillary margin leads to rings of light which diminish rapidly in intensity from the centre to the periphery. With regard to chromatic aberration v. Helmholtz has shown that even if the brightness of the colours were constant throughout the spectrum the central part of the diffusion circle would be incomparably brighter than the peripheral, given that the eye is accommodated for the rays of medium wave-length. This is due to the fact that the more (violet) and less (red) refrangible rays are more widely distributed over the area than the medium rays; the periphery of the area is therefore illuminated only by the red and violet ends of the spectrum. Seeing that the spectrum is not uniformly bright throughout, but is much brighter in the central part, the difference in brightness between the central and peripheral parts of the diffusion image is very great. In general, therefore, there is a very marked and rapid diminution in brightness in passing from the centre to the periphery of the diffusion image.

It may be noted that Hering calls those areas of diffusion which are due to defects of the dioptric apparatus *aberration areas* (Aberrationsgebiete), whilst he reserves the term *diffusion areas* (Zerstreuungsgebiete) for those due to defective accommodation.

Fixed stars viewed by the naked eye or with a telescope are mathematical points of light, yet it is customary to classify them according to their "magnitude." Aubert pointed out that the apparent "magnitude" is really the apparent brightness, and this is true also for telescopic observation (Herschel). Volkmann explains the apparent increase in size as follows. If A (Fig. 1) is the centre of a diffusion circle of radius AA_3, and BD_2A_3 represents the fall of light intensity from the centre to the periphery for a bright luminous point, whilst CD_1A_3 represents the fall of light intensity for a less bright point, then if AD is the light intensity which falls within the limits of perception the circle of radius AA_2 will be perceptible for the stronger light, that of radius AA_1 for the weaker light.

It should be pointed out that there are good physical reasons for differences of visibility between white spots on black backgrounds and black spots on white, and for lines. In the former case the distribution of light in the diffusion image is fundamentally different in the two cases. Thus, supposing the white spot is 57 times brighter than the black. At a certain zone of the diffusion circle it adds 1/10 of its brightness to the black, which may be taken as = 1. At this zone it is 5·7 times brighter than the background. At the same zone of the black diffusion circle 1/10 of the brightness of the white background is taken away; *i.e.*, its

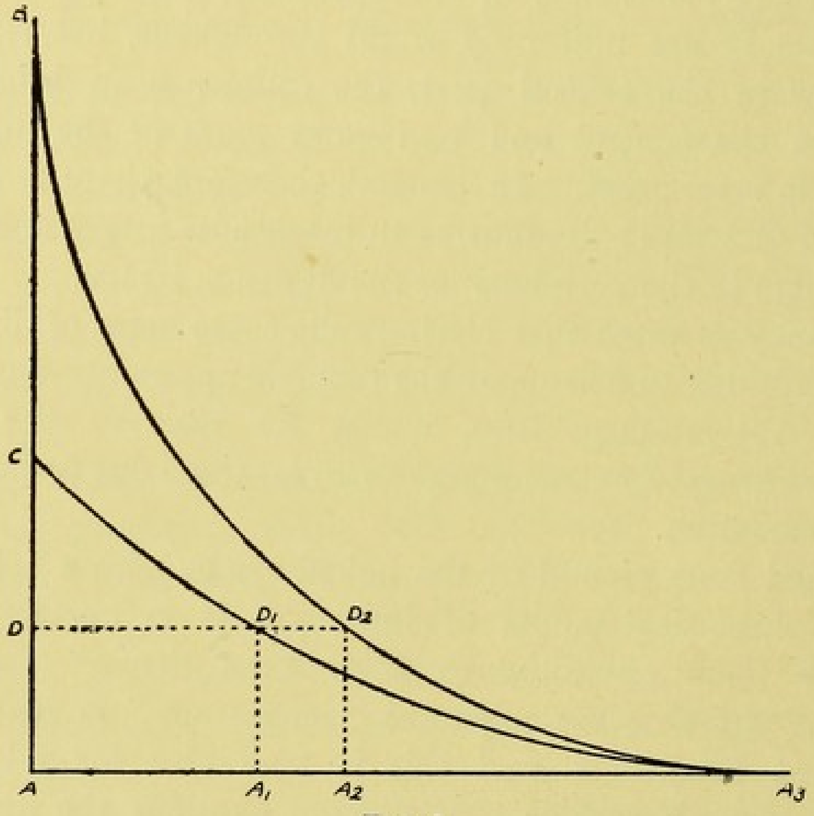

FIG. 1.

brightness is as 57 − 5·7 to 57, or it is about 9/10 darker than the surrounding area. Whilst a 5·7 times brighter zone may be perceptible a 9/10 darker zone may be imperceptible.

With regard to lines it is obvious that the brightness of the diffusion image falls off laterally in the same manner as that of a spot, but in the direction of the line it falls off similarly only at the ends of the line.

Aubert (1865) found this reasoning substantiated by experiment. A 10 mm. white square on a black ground was visible under an angle of 18·1″; two such separated by 10 mm., 13·7″; a white rectangle 10 mm. by 30 mm., 12·1″; seven 10 mm. squares separated from each other by 10 mm. each, 9·8″; a white rectangle 10 mm. × 130 mm., 6″.

(2) As regards *the anatomy of the retina* it is certain that the site of stimulation is the neuro-epithelium, and that in the macular region, with which alone we are at present concerned, cones alone are present. The retinal image is formed upon a mosaic of cones, closely packed together. The following are some measurements of the diameter of the foveal cones:—Max Schultze, 2·8 μ; H. Müller, not more than 3 μ; Merkel, 3 μ; Welcker, 3·1—3·5 μ; Wadsworth, 2·5 μ; Kuhnt, 2—2·5 μ; Kölliker, 4·5—5·4 μ; Koster (1895), 4·4 μ; Greeff, 2·5 μ; Dimmer, 3—3·5 μ.

The foveal region is an elliptical area with the long axis horizontal. The long axis measures about 0·3 mm., the vertical 0·2 mm., and the total area is 0·5–0·6 sq. mm. Taking the diameter of the inner limbs of the foveal cones at 0·3 μ, there are about 300 in the long axis, and 60 in the short, or 1300—1400 in 0·1 sq. mm. The diameter of the outer limbs is 0·6—0·75 μ. The cones are arranged in curved lines (Max Schultze) or spirals (Fritsch), and are not quite regular, some being arranged as in Fig. 2, others as in Fig. 3. There are, therefore, small spaces between them, measuring 0·27 of the transverse section of the inner

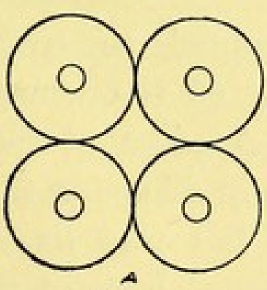

Fig. 2.

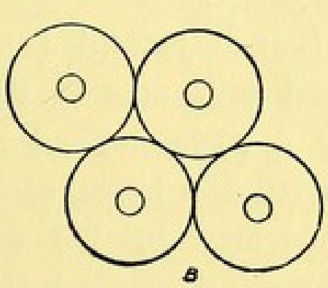

Fig. 3.

limb in the first arrangement, and 0·05 in the second. Greeff says that the cones very closely packed in the fovea, and in a specimen of Heine's were hexagonal in transverse section.

Koster examined three normal children's eyes and found that the part completely free from rods occupied a circular area 0·44—0·55 mm. in diameter, the part relatively free from rods 0·88 mm. In the eye of a youth, aged 20, the rod-free area was 0·901 mm. He concludes that in the adult the rod-free area measures about 0·8 mm. in diameter, subtending a visual angle of 3° 3′.

Three areas must be carefully distinguished :—

Fovea centralis, measuring 0·24—0·3 mm., subtending 55′—70′ ;

Rod-free area, measuring 0·8 mm., subtending 3° 3′ ;

Macula, Measuring 1—3 mm., subtending 4°—12°.

Dimmer describes a fovea centralis, 1·5 mm. in diameter (the macula of Koster), containing in its centre a foveola (the fovea centralis of Koster).

Gullstrand regarded the yellow coloration of the macula lutea as a *post-mortem* change, a view which is scarcely consistent with its absorptive capacity for coloured lights.

Fritsch describes the site of clearest vision as the area centralis, possessing a central depression, the fovea centralis, which may or may not contain a foveola.

The macular area is described by Kühne and Donders as free from visual purple, but Hering points out that it is possible that the visual purple is not wholly absent even from the cones.

Du Bois-Reymond (1886) attempted to confirm the anatomical estimates of the number of the cones in the fovea by a physiological method. A piece of tinfoil was pierced with 460 holes, each 0·2 mm. in diameter, the centres being separated by 2·5 mm. The foil was lighted from behind by daylight, and the holes were observed through a tube. Diaphragms of 1 mm. and 2·5 mm. were placed before the eye. Two distances of the foil from the eye were measured: first, when the points fused into lines, and second, when the lines fused into a uniformly lighted area. The average distances were 303 cm. and 431 cm. Taking a retinal area of 0·01 sq. mm. these distances give an average of 136 physiological points, which agrees well with the anatomical deductions of Salzer and others.

Oerum (1904) used the same method with white and monochromatic lights, finding a maximum of physiological points for red, medium for green, and least for blue.

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(3) *The Physiology of the Retina.*—Taking the maximum size, 4·5—5·4 μ, as Hess points out the diffusion circle due to diffraction alone with a 4 mm. pupil will extend beyond the limits of a single cone. On the other hand Aubert's experimental evidence of the minimum visual angle, 35″, corresponds closely with the lower value, 2·5 μ, which is probably more accurate. R. Smith (1738) called such a point a "sensitive" point, Aubert (1865) defined it more minutely and called it a *physiological point.* The relationship between what may be called the physical area and the physiological area has been studied by Mach (1866). If the retina be imagined flattened out and ordinates erected upon it whose lengths correspond with the light intensities at the given spots, the area obtained by joining the summits of the ordinates will give an area representing the light intensity, or more briefly a "light area." If the ordinates represent the apparent brightness of the light at the spots as seen by the observer, the areas obtained will represent the sensibility and are briefly termed "sensibility areas" (Empfindungs-fläche).

We may regard each cone in the mosaic as capable of an isolated stimulation. Each cone has a definite area, greater or less according as the site of origin of the stimulation is regarded as in the inner or outer limb respectively. Stimulation of separate cone areas gives rise to isolated impressions, but stimulation of different parts of a single cone area gives rise to the same impression. The impression depends upon the amount of light falling upon the area, and not to the amount of the single cone area which is stimulated. In the periphery of the retina the effective light areas may be smaller than the sensibility area, owing to the wider separation of the neuro-epithelial elements, but in the fovea and its immediate neighbourhood the sensibility area is always smaller than the light area.

A physiological characteristic of the retina having an important effect in limiting the area of sensibility is spatial induction. The phenomena of simultaneous contrast show that when one area of the retina is stimulated there is a reciprocal action in all the surrounding areas. Around a given area of raised sensibility the retina is in a condition of lowered sensibility, so that by contrast the central sensibility area gives rise to a much stronger visual impression than would be expected from the physical distribution of the light, whilst on the contrary the peripheral region is depressed, and hence the part of the retinal image which is clearly perceived is relatively small.

Summing up, therefore, we find that the diffuse retinal image of a luminous point is in general much brighter in the centre than at the periphery. The light falling upon the peripheral parts of the image is a subminimal stimulus, so that the sensibility area is smaller than the light area. Further, owing to spatial induction this area is still further diminished and more definitely delimited. The total effective area will depend upon the amount of light entering the eye and upon the condition of adaptation of the retina (temporal induction).*

* See Parsons, Scotopia, R. L. O. H. Rep., vol. xviii, 3, p. 229.

No definite value can, therefore, be assigned to the minimum visible angle. Given a sufficiently intense illumination for a given condition of adaptation of the retina a mathematical point of light will be visible. Its image on the retina is always a diffusion area, the central parts of which afford at least a minimal effective stimulus if they anywhere impinge upon a retinal cone. If the effective area is so small as to occupy an interconal space a slight movement of the eye must be predicated in order that the point may be visible. It is probable that for a given condition of retinal adaptation a subminimal stimulus for a single cone may become a minimal or effective stimulus if spread over several cones.

Riccò (1877) conducted a very careful series of experiments bearing upon this point. He found that at the threshold of perception the quantity of light entering the eye is constant, or, in other words, the light intensity and the area of the retinal image are reciprocal functions, or the product of the area into the light intensity is constant. In terms of the visual angle, the law is that the minimum visual angle varies inversely as the square root of the light intensity, or the product of the minimum visual angle and the square root of the light intensity is constant. The limit of the law is determined by the size of the foveal region; it ceases to be accurate for visual angles above 40′ to 50′.

The experiments were carried out in six different ways:—

(1) White discs of various diameters, equally illuminated by the sun or by diffuse daylight, were observed against a black background. The maximum distances, D, at which the discs are visible bear a constant relation to their diameters, δ. But the quantity of light entering the eye is directly proportional to the square of the diameter and inversely to the square of the distance, or $D^2 : \delta^2$, *i.e.*, $D : \delta$.

(2) Rotating discs of the same size, with black and white sectors, were observed against a black background by sunlight or diffuse daylight; they therefore showed different luminosities according to the proportions of the sectors. The squares of the maximum distances D bear a constant relation

to the light intensity I. But the quantity of light entering the eye is directly proportional to the light intensity and inversely to the square of the distance, *i.e.*, $D^2 : I$.

(3) White discs were illuminated by a source of light at different distances, d. The product of the distances, D and d, from the eye and from the light is constant. But the quantity of light entering the eye is inversely proportional to the square of the distance from the eye and to the square of the distance from the light; *i.e.*, $D^2 \times d^2$, or $D \times d$, is constant.

(4) Discs of various diameters were illuminated by a light at such distances that they were just visible at a constant distance from the eye. The ratio $d : \delta$ is constant. But the quantity of light entering the eye is directly proportional to the square of the diameter and inversely to the square of the distance of the light; *i.e.*, $d^2 : \delta^2$ or $d : \delta$.

(5) A rotating disc with black and white sectors was observed alternately with a white disc of different diameter. The squares of the maximum distances D of the two discs have an equal ratio to that of the quantity of light reflected from the discs, $\delta^2 \times I$. But the quantity of light entering the eye is directly proportional to the light reflected from the disc, $\delta^2 \times I$, and inversely to the square of the distance D; therefore the quantity will be constant when the ratio of the squares of the distances D is equal to the ratio of $\delta^2 \times I$ in each case.

(6) Discs of various diameters were illuminated by lights at various distances. The maximum distances D have a constant ratio to the quotient $\delta : d$. But the quantity of light entering the eye is directly proportional to the quotients $\delta^2 : d^2$ and inversely to D^2; hence the quantity will be constant when the ratio $D^2 : \delta^2/d^2$, or $D : \delta/d$, is constant.

The actual size of the minimum visual angle varies according to circumstances:—(1) According to the background. On a black background proportional in diameter to the intensity of the light it is smaller with a large than with a small background. Thus, the average angle with a background of 80 cm. diameter was 63″, with a diameter of 50 cm., 89″. (2) According to the diameter of the disc. The smaller the disc the smaller the visual angle, since the small discs are observed at a shorter distance, so that the eye is in a more favourable condition of sensibility and less light suffices for visibility. (3) According to the aperture of the pupil or diaphragm. Diminution of the aperture diminishes the quantity of light admitted to the eye, diminishes aberration, and diminishes extraneous light. Diminution of the aperture diminishes the light in proportion to the square of the diameter, but the visual angle increases in smaller proportion: *e.g.*, ratio of diameters, 0·003 : 0·002 = 1·50; inverse ratio of visual angles, 89 : 72 = 1·24. (4) According to the illumination. Only some of the experiments were available for comparison, owing to the great difference in illumination and the impossibility of measurement. In general the visual angle did not decrease proportionally to the increase in light intensity. The ratio of the squares of the angles should be equal to the inverse ratio of the intensities. The ratios for shade and sunlight gave values 1·74 and 1·71, instead of the theoretical 2·976. (5) Fatigue. (6) Adaptation, and so on.

Charpentier (1882) published a series of experiments which confirm and extend those of Riccò. He used small bright squares up to 12 mm., viewed at 20 cm. Below 2 mm. the smaller the surface the greater the minimum illumination necessary for perception. Two millimetres at this distance correspond to about 0·17 mm. on the retina, *i.e.*, about the size of the fovea. For larger areas the area has no effect. It follows, therefore, for the fovea that, in order to produce a luminous sensation, the total quantity of light, *i.e.*, the product of the area and the illumination, must attain a certain value, and that that value is constant for a given condition of adaptation. "The fovea centralis forms a sort of autonomous territory, in which the luminous excitation diffuses itself, and which always requires a certain quantity of light to be set in activity." Charpentier showed, in answer to criticisms by Leroy, that the diffusion could not be accounted for by irradiation due to dioptric aberrations.

Asher (1897) found that for the range of light intensities used by him up to a visual angle of 2′ to 3′ the apparent size depends entirely upon the quantity of the light. According to him, therefore, vision of objects subtending angles up to this size is a function purely of the light sense and not of the form sense. The earliest observations bearing upon this aspect of the subject were by Volkmann (1863) and Aubert (1865). Aubert used lines 2 mm. wide and 50 mm. long, and determined the distance the lines had to be apart in order that the interspace might look the same as the breadth of the lines. He found that when the breadth of the lines was varied by Volkmann's macroscope so that they subtended visual angles of from 10″ to 45″ the angular distance apart of the lines varied from 104″ to 112″ for black lines on a white background, and from 140″ to 153″ for white lines on a black background. Asher used small black, white and grey squares and rectangles of paper and determined the distance at which a difference of size could be detected, the light intensities of the papers being calculated by the colour top and by Hering's polarisation photometer. He found that visual angles between 23″ and 78″ might be increased by 25″ to 100″ (average 58″) under the given differences of light intensity (from 360 to 6) before a difference in size could be detected. At a great distance from the different sized objects they appear either of equal size and brightness, or, if the objective brightness of the smaller is much greater than that of the larger, of equal size but unequal brightness, the smaller being the brighter. Sometimes the smaller appeared also larger. On approaching the objects the difference in apparent brightness increased whilst the sizes remained equal. Then followed a stage in which the difference in apparent brightness diminished, the sizes remaining equal; both might even appear of the same brightness. On still further approximation the difference in brightness again became manifest, and simultaneously or shortly afterwards the larger object showed indefiniteness of the edges and greater apparent size. In many cases the size and brightness remained the same until the difference in size became distinguishable.

Asher's explanation is as follows:—So long as the objects subtend so small a visual angle that they cover a single sensibility area they appear equal, since the same quantity of light acts upon the sensibility area. With increase of the visual angle the influence of aberration becomes manifest. The larger object has a larger light area which is larger than a sensibility area, but the periphery of the light area has so low an intensity that the effective light area is not larger than a sensibility area. The smaller object, on the other hand, has a smaller light area, the effective part of which, however, is as large as a sensibility area. The ordinates corresponding to an effective brightness may extend farther from the centre for the smaller than for the larger object, so that the smaller may appear the brighter. So long as the relationship of the objects is such that the sensibility areas of both cover one or an equal number of sensibility areas they must appear of equal size, though the aberration areas may be very different. The conditions of light and contrast may easily be such that the smaller sensibility area may belong to the larger aberration area.

Asher denies that any proof has yet been given of a retinal image so small as to stimulate only one cone.

Schoute (1899) does not agree with Asher that it is impossible to stimulate a single cone, and for single cone images the impression of size is dependent solely upon the product of the area into the light intensity. If only one cone is stimulated the object always appears round, but differences in size are still appreciable. If the objects are of equal size the brighter appears the larger, *i.e.*, the apparent size varies with the light intensity. Schoute, like von Helmholtz, attributes this to psychological causes, *i.e.*, to an error of judgment.

Loeser (1905) entirely confirmed Riccò's law for foveal vision. That law is stated in one form, thus: the product of the minimum visual angle and the square root of the light intensity is constant. Loeser's results are shown in the following table:—

Distance of object, E.	Diameter of object, D.	Visual angle, D/E.	Sq. rt. of light intensity, J.	Product, DJ/E.
m.	mm.			
8	20·0	2·5	0·87	2·18
	14·0	1·75	1·27	2·22
	8·5	1·06	2·4	2·5
	5·0	0·63	3·45	2·26

The law does not apply to peripheral vision, which has been investigated by Piper, Henius, and Fujita.

Sir William Abney (1913), in his experiments on the extinction of colour and light, *i.e.*, on the point in the diminution of the intensity of light which just causes, first the colour, and then the light to become invisible, has made a series of investigations on the influence of the area stimulated. He found, as was to be expected from the results of previous observers, that the smaller the disc the less reduction in intensity of the ray was required to extinguish it, and the same ratio existed between the extinction of the different colours. Plotting curves with aperture diameters in powers of 2 as abscissæ and logarithms of light intensities as ordinates, with apertures less than 1½ inches diameter the curves become straight lines, all of which are parallel. Hence "from that point the intensity of a light which will be just extinguished with a certain diameter of aperture may be increased 10 times and yet be invisible when an aperture with one quarter of that diameter is employed; if the intensity of the light be increased 100 times, we have only to diminish the diameter of the aperture to 1/16 and it will again disappear, or if to 1/64, the light may be increased 1000 times." When the angular aperture exceeds 4 apparently the upper limit is reached, all extinctions being the same beyond it.

With regard to the point of extinction Sir William Abney says: "The light from a square, or a disc, or an oblong, just before extinction, is a fuzzy patch of grey, and appears finally to depart almost as a point. This can scarcely account for the smallest width of an illuminated surface determining the intensity of the light just not visible; but it tells us that the light is still exercising some kind of stimulus on the visual apparatus, even when all sensation of light is gone from the outer portions. The fact that the disappearance of the image takes place in the same manner whether viewed centrally or excentrically tells us that this has nothing to do with the yellow spot, or fovea, but is probably due to a radiation of sensation (if it may be so called) in every direction on the retinal surface. Supposing some part of the stimulus impressed on one retinal element did radiate in all directions over the surface of the retina, the effect would be greatest in the immediate neighbourhood, and would be inappreciable at a small distance, but the influence exerted upon an adjacent element might depend not only on its distance, but also upon whether it was or was not itself excited independently. Following the matter out further we should eventually arrive at the centre of an area as the part which was the recipient of the greatest amount of the radiated stimuli, and consequently that would be the last to disappear. With a slit aperture the slit is visible till extinction is very nearly executed, but it finally merges into a fuzzy spot at the moment before it finally fails to make any impression of light."

Burch (1912) has devised a method of measuring "visual acuity" which he describes as follows:—

"Two fine wires about 0·1 mm. in diameter are stretched across a pair of sliding frames furnished with a screw adjustment so that they can be set parallel to each other at any desired distance from contact up to 3 cm.

"The frames are mounted in a ring which can be rotated behind a circular aperture in a screen so that the operator can alter the direction of the wires without affording any clue to the observer.

"A sheet of white blotting paper is fixed at an angle of 45° a foot or more behind the screen so as to receive the light from the sky and serve for a white background against which the wires appear as black lines.

"1. Ascertain the maximum distance at which the observer can distinguish the wires when they are 2½ or 3 cm. apart. To make sure that he really does see them the operator alters the direction two or three times, and the observer indicates what he believes it to be with a short stick.

"Call the distance l, and the diameter of the wire d. Then $d/l =$ the chord of the smallest angle of black upon white that produces a visible effect.

"The chord of 1 second being $0{\cdot}00000485 = 1/206264$, it is easy to express d/l in seconds.

"This does not, however, measure the visual acuity. Owing to inevitable irregularities of refraction in addition to the errors of spherical and chromatic aberration, the image of a point is not a point but is spread over an appreciable area. And the wire is visible, not when its geometrical image is large enough to be discerned, but when the black of it, mixing with the white, and spread over that area, makes a perceptible shade of grey.

"2. Having ascertained the maximum distance l at which a single wire is visible, the observer goes to a distance $3l/2$, half as great again. He is now quite unable to see the separate wires, but when the operator by turning the screw brings them within a certain distance of each other, they suddenly appear, not as two, but as one wire. Let the distance between the wires when they thus become visible $= b$.

"Then $b \div 3l/2 = 2b/3l = \mathrm{V}$ is a measure of the visual acuity."

The application of the term "visual acuity" to this measurement is to be deprecated. What is measured is the minimal light difference under the given conditions of adaptation, etc., and is therefore a function of the light sense, not of the form sense. The difficulty of distinguishing between light sense and form sense near the threshold is the cause of much of the discordance between the conclusions of various observers. It is in some respects similar to the relationship between white perception and colour perception, the former being invariably associated with the latter, though in different degrees for different colours. Ordinary observations on form sense by the use of letters and so on introduce a further psychological complication. Probably instructive results would be obtained by a series of investigations with a simple form, such as Snellen's prong or Landolt's broken circle, in which the relation between the luminosity of the white area stimulated and that of the black area was kept constant.

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THE VISUAL DISCRIMINATION OF TWO POINTS.

By J. Herbert Parsons.

The earliest observations on the discrimination of two points, *i.e.*, the minimum angular distance which they must be apart in order that they may be seen as separate points, are derived from astronomers. We learn from Kazwini, the Persian astronomer, that the star Alcor was called Saidek or Suha, the Test, because it was used to test visual acuity. This star is not less than 11′ 48″ from Mizar in the Bear, and the two cannot be seen separately with the naked eye in Europe, but Humboldt was able to distinguish them clearly in the Cordilleras. The difficulty is due to atmospheric conditions, to the fact that Alcor is a star of the fifth magnitude, whilst Mizar is of the second magnitude, and is thus "drowned" by the light of its neighbour, and also to lack of contrast (*vide infra*). Hooke (1705) stated that scarcely one in a hundred could distinguish between stars less than 1′ apart, and this is far too low for such observations. Jupiter's satellites were first discovered by the telescope, yet the brightest third satellite is 5′ and the fourth 8′—10′ from Jupiter. Here again the satellites are "drowned" in the light of the star. Yet a shoemaker named Schön has been immortalised by Humboldt, because, in 1837, he could see Jupiter's two brightest satellites, the first and third, with the naked eye. This man is remarkable in that he saw stars and planets as bright points without rays. When the stars are of nearly the same brightness the feat is easier, and yet Mädler (1846) said that the α Capricorni stars of the third and fourth magnitude, and separated by $6\frac{1}{2}'$, could only be seen by sharp-sighted eyes. The stars ϵ and 5 Lyræ, both of the fourth magnitude, and 3′ 27″ apart, generally appear as a single oval star, but can be distinguished with the acute naked eye in very clear weather.

Experiments with black spots on a white ground, and so on, give variable results, as shown in the following table from Aubert and Helmholtz :—

Object.	Visual angle.	Observer.
Parallel wires	50″	Hirschmann.
White discs on a black background	51″	Struve (1837).
Parallel black and white lines, measured from centre to centre	52″—1′ 15″	Bergmann (1854).
White squares on a black ground, measured from edge to edge	55″	Aubert (1864).
Wire net	1′ 4″	Helmholtz (1856).
Black points on a white ground	1′ 4″	Hueck (1840).
Black squares on a white ground	1′ 8″	Aubert (1864).
Parallel black and white lines	1′ 13″	E. H. Weber (1852).
,, ,, ,,	1′ 34″	T. Mayer (1754).
Chess-board pattern	2′ 4″	T. Mayer (1754).
Cobweb filaments	2′ 28″	Volkmann (1862).

Extraordinary acuity of vision is found in the cases recorded by Kotelmann (1884) and Cohn (1898), tested in bright daylight in the open air with test types.

If two luminous points are so situated that they stimulate two contiguous cones equally only a single perception can result. Separation of the two impressions can only occur if two stimulated cones are separated by an unexcited or a differently excited cone. It is uncertain whether the impulse starts in the inner or outer limbs of the cones or even in the pigment epithelium, and is thence transferred to the cones.*

If the inner limbs of the cones are the site of excitation the distance between the centres of the diffusion circles must be at least $3\,\mu$. If it is $4\,\mu$, equivalent to a visual angle of nearly $1'$, we may have the positions indicated in Fig. 1.

Only in the (2) position will the two points be discriminated. Moreover, in order that points separated by

* If the distance of the posterior nodal point from the retina is taken as 15 mm.. then $0{\cdot}5\,\mu$ on the retina = a visual angle of $7''$, $0{\cdot}75\,\mu = 10{\cdot}5''$, $1\,\mu = 14''$, $1{\cdot}5\,\mu = 21''$, $2\,\mu = 28''$, $2{\cdot}5\,\mu = 35''$, $3\,\mu = 42''$, $4\,\mu = 56''$.

1′ may be invariably discriminated as separate points, it is obvious that minute movements about the fixation point are necessary so that the (2) position may be found.

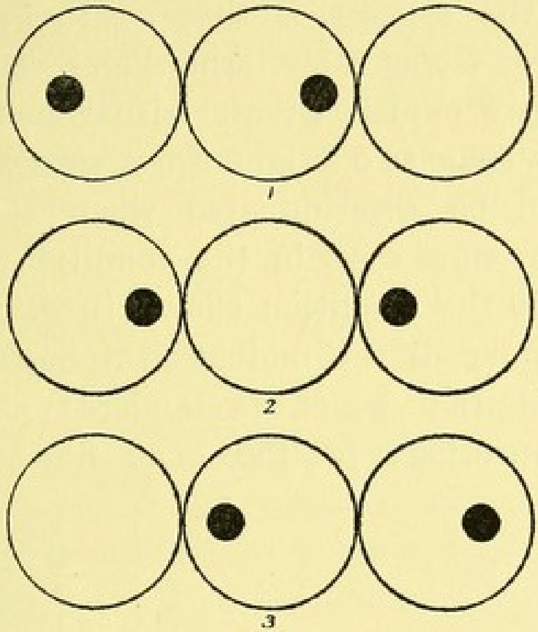


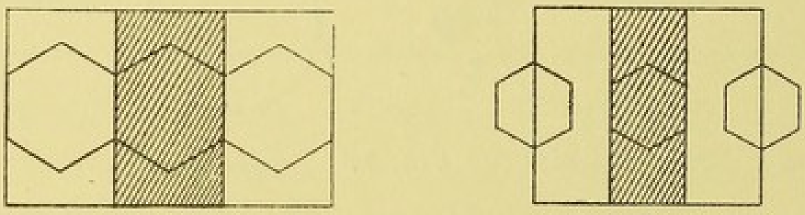
FIG. 1.

If the outer limbs of the cones are the site of the stimulation, and they are taken as 3 μ apart, such small movements must be predicated for discrimination, for it is obvious that in no fixed position can there be an unexcited or differently excited cone intervening. If such slight movements are predicated then a smaller angle of discrimination will suffice, viz., one little exceeding the diameter of the outer limb, *i.e.*, 0·75 μ or 10″. Other factors, however, militate against so extraordinary an acuity of vision. The only experimental data which approach so high a value are Kotelmann's and Cohn's, which were arrived at with test types and are thus open to some objections (*vide infra*).

Max Schultze stated that the outer limbs of the cones converged in the centre of the fovea, and it is possible that they may even touch, in which case lower values than 1′ are explicable.

If the pigment epithelium is the site of stimulation, which is then transmitted to the cones, any anatomical explanation must follow the reasoning already applied to the outer limbs.

Under the action of light the processes of the pigment cells extend forward between the rods and cones. Broca has advanced the suggestion that as the cones are thus separated more from each other and compressed the phenomenon may explain greater visual acuity under high illumination. Thus two bright areas, separated by a dark interval, would be discriminated when they are nearer together if the cones were in the condition represented in Fig. 2, *b*, than in the condition shown in *a*. Moreover, he thinks that under dim illumination groups of cones act together, a condition which is rendered possible by the horizontal connections of the cone fibres described by



a. *b.*

FIG. 2.

Ramon y Cajal. Since the movements of the pigment cells vary with the condition of retinal adaptation and with the area of retina stimulated it will be best to discuss these views more fully when dealing with the effects of adaptation and variations in the intensity of the illumination.

An important observation, first made by Hensen (1865), subsequently confirmed by Panum, Kupffer, and Volkers, and easily demonstrated by anyone, is the phenomenon occurring when the points, placed in a row, are more and more reduced in size. " The points first become cogged (*zäckig*), like the shape of a bird flying a long distance off. When the size is reduced slightly more, a very remarkable whirring (*Spiel*) begins; some points disappear, dive under, as it were, and then reappear in ever changing fashion. Some retreat whilst others dart forward, and in the most favourable circumstances quite a third of those originally present are lost to sight. I can only liken the movement of the points at their best to that of a swarm of gnats when one is standing amongst them." Hensen says expressly that the points cannot be made small enough for the images to fall on the spaces between the cones, yet the foveal visual field is thus demonstrated to be "full of holes." The phenomenon is attributed to stimulation of the outer limbs of the cones and to very fine involuntary movements of the eyes. These "diving points" (*Punkttauchen*) can be well seen when suitable groups of stars are observed.

This phenomenon is obviously similar to that observed by Purkinje, Bergmann, and v. Helmholtz, and also easily demonstrated. v. Helmholtz used parallel fine wires, 0·4167 mm. broad, and separated by the same distance. In a good light, 1·1 to 1·2 mm. from the eye, the lines appear wavy and indented, somewhat like a row of pearls. This is due to the arrangement of the inner limbs of the cones (Fig. 3, v. Helmholtz), or may be explained partly by the arrangement of the outer limbs, and partly by the spaces between them (Hensen).

Uhthoff (1887) used parallel iron wires, 0·0463 mm. in diameter, separated by spaces of the same size. Under the best conditions of illumination he found the minimum angle for the space separating the wires 27·6″ to 32·8″. This result is fairly conformable with Helmholtz' result, 1′, for the space measured from centre to centre of two wires, and agrees with a retinal image of about 2 μ.

Hering (1899) has pointed out that the measurement of the visual angle under which two points or lines can be discriminated as separate does not measure the minutest difference in position or size which the eye is capable of perceiving. This is measured by the difference in position of either line or point and the intervening space. Hence the true visual acuity, *i.e.*, the discrimination of the minimal difference in position, is at the most only half as great as the angle recorded by the majority of observers, since in their experiments the distance is measured from point to point or from edge to edge or from the centre of one line to the centre of the other. Hering distinguishes the discrimination of the minutest difference in size or position, or what he terms the optical sense of position (*optischer Raumsinn*), from visual acuity or true form sense, *i.e.*, the appreciation of detail, which he terms optical discrimination (*optisches Auflösungsvermögen*). The experiments of Volkmann, Wülfling, and Hering show that the visual angle for the former is much smaller than for the latter.

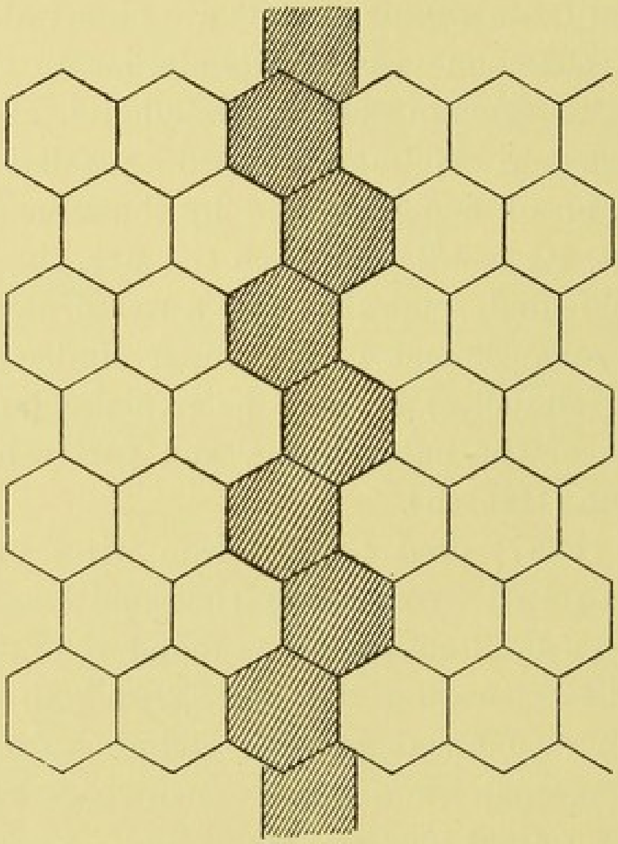


FIG. 3.

Volkmann (1863) compared two equally broad light lines on a dark background, one of which could be broadened by a micrometer screw. He found that an increase of breadth equivalent to a visual angle of only 10″ was appreciable.

Wülfling (1892) used a slit, the lower half of which could be broadened, and found that the smallest difference which could be appreciated subtended an angle of 10—12″.

Hering (1899) used a black and a white surface, separated by a vertical line. The lower half of the black surface could

C. O. Roelofs. Arch. néerl. de Physiol. II, 199–1917.

be shifted horizontally over the white. A movement of 10″ showed the line of demarcation indented.

Pulfrich (1899) obtained a similar value for the appreciation of difference in depth with binocular vision, and Heine found this value 12—13″ with normal visual acuity, 6″ with double acuity. Bourdon (1900) obtained values as low as 5″.

Hering explains these phenomena by the peculiarities of the neuro-epithelial mosaic, on the same lines as Helmholtz' explanation of the string of pearls appearance (Fig. 4).

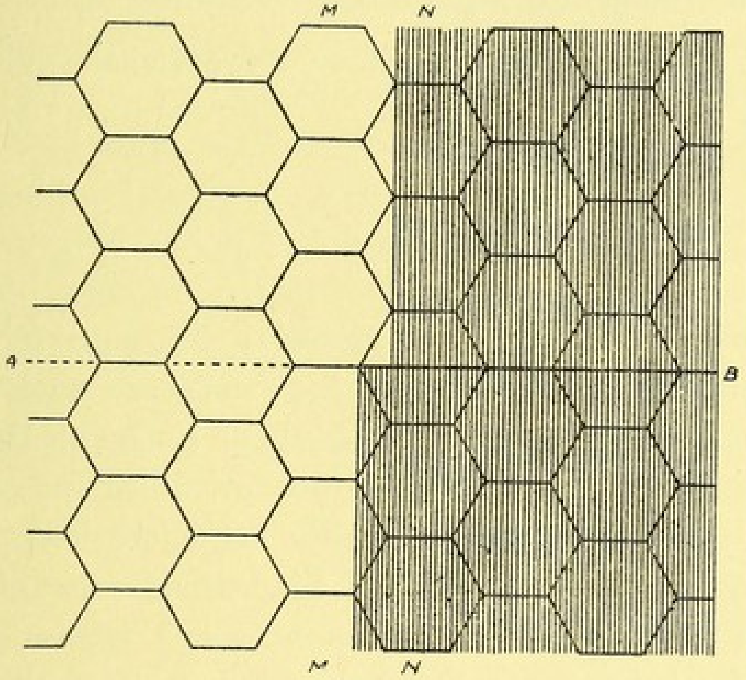


FIG. 4.

It is clear that these experiments do not give a measure of true visual acuity or form sense, but depend entirely upon the light sense.

The same criticism applies to all punctate tests, whether of stars or of black spots on a bright ground or bright spots on a dark ground, as in Guillery's tests. With regard to such tests Thorner (1910) has pointed out the importance of diffraction by the pupil. He used two lines, 0·5 mm. broad and 5 mm. apart, cut out of black paper and illuminated from behind. These subtend an angle of 1′ at 15·67 m. They were observed at this distance through a telescope giving a magnification of five diameters. With a slit of 1·6 mm. diameter the lines form a broad bright band without any indication that they are separate lines. That this is due to diffraction is shown by turning the slit through 90°. Calculation of the diffraction image shows that under these circumstances it extends to the middle of the other line. With points of 0·5 mm. separated by 5 mm. a pupil diameter of 1·7 mm. permitted them to be discriminated at 15·67 m., *i.e.*, under an angle of 1′. So far as diffraction by the pupil is concerned the discrimination of two points demands a pupil diameter of—

1·6 mm. for normal visual acuity, *i.e.*, a visual angle of				1′
3·2 mm. for double	,,	,,	,,	30″
4·8 mm. for triple	,,	,,	,,	20″
6·4 mm. for quadruple	,,	,,	,,	15″
8·0 mm. for quintuple	,,	,,	,,	12″

We have now obtained material for considering the fundamental elements of visual perceptions such as the vision of one or more luminous points or lines and the visual discrimination of two such points or lines as separate entities. Independent of all other considerations there is the purely physical problem of the *optical resolving power* of the eye as an optical instrument. The resolving power of an optical instrument depends upon the aberrations which have been discussed in a previous paper.* Of these the most important is diffraction by the pupil. Only under certain specific cases can the diffraction phenomena of a circular aperture be submitted to exact mathematical deductions, and in the case of the eye approximations only can be obtained. They have been treated in papers by Schuster, Gleichen, Drude, and Pockel, and we may accept the conclusion arrived at by Gullstrand, who states that "the limits of efficiency (*Leistungsfähigkeit*) of the eye set by diffraction, in so far as they can be calculated, are

* Parsons, The Perception of a Luminous Point, Part I, R. L. O. H. Rep., vol. xviii, p. 239, 1912.

attained by the normal eye with the size of pupil corresponding to good illumination."

The physiological elements have as their basis the light sense and show three grades of increasing complexity. It is difficult, if not impossible, to determine the relative parts played in these of purely physiological and psychological processes, but there is no doubt that as the complexity increases the psychological element becomes more important. These three grades are: (1) *the visual sense of position* (optischer Raumsinn); (2) *the visual resolving power or discrimination* (optisches Auflösungsvermögen); and (3) *the form sense* (optischer Formensinn). Three corresponding criteria have been adduced, viz.: (1) the *minimum visibile;* (2) the *minimum separabile;* and (3) the *minimum legibile* or *cognoscibile* (Hess).

As regards the minimum visibile, whether a punctate test such as a star or Guillery's point test types or Hering's test of the smallest difference of position be adopted, it is clear from what has been said in this and previous papers that many factors are involved which vary enormously under different conditions. Such are particularly the intensity of the light, whether of the point or the background, the contrast between the relatively bright and the relatively dark portions of the field, irradiation in its broadest meaning, and the condition of adaptation of the retina. Each of these factors demands further consideration.

Visual resolving power or discrimination may be defined as the ability of the eye to discriminate separate points or lines, or in a broader sense the ability to discriminate fine details. The same factors come into play as in the visual sense of position, but the complexity is increased by the greater complexity of the interaction of the factors. Thus it has been shown that the visual discrimination of the eye is far inferior, as measured by the visual angle, to the visual sense of position, and this fact is explained by the reciprocal effects, both physical (aberrations) and physiological (temporal and spatial induction), of the neighbouring stimulated areas of the retina.

When one comes to consider the so-called form sense or the ability of the eye to distinguish peculiarities and differences of form or shape one is forced to conclude, with Schenk, that it is not a physiological "sense" in the significance attached to the term when one speaks of the light sense. In the distinguishing of geometrical forms, letters, and so on, the judgment is called into play in a manner that proves that act is to a much greater extent than in the other cases psychological. This matter may, however, be left for consideration when dealing with test types and the meaning usually associated with the term "visual acuity."

In the next paper we will consider the influence of the intensity of the illumination on visual acuity.

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THE INFLUENCE OF ILLUMINATION ON VISUAL ACUITY.

By J. Herbert Parsons.

The effect upon vision of the growing light at dawn early attracted attention, and is mentioned in the Talmud (Klein). At one time day was considered to have commenced when a wolf could be distinguished from a dog. There was an old regulation in the Prussian Army to sound the réveillé as soon as print could be read (Aubert).

Tobias Mayer (1754), the astronomer of Göttingen, first attacked the subject scientifically, and attempted to formulate the relationship between minimum visual angle and light intensity mathematically. Using parallel lines as the test object, he found that the weaker the light the nearer the observer had to approach the object to discriminate the lines clearly, and that bright daylight afforded the maximum visual acuity. For low intensities he used a candle, altering its distance from the test from half a foot to 13 feet. In this manner he obtained a range of luminosity from 1 to 676. He arrived at the empirical formula $\sigma = 158'' \sqrt[3]{d}$, where σ = visual angle and d = the distance of the light. Since l, the intensity of the light, varies inversely as the square of the distance, $\sigma = 158'' / \sqrt[6]{l}$, *i.e.*, the visual acuity varies inversely as the sixth root of the light intensity.

Förster (1857) determined the minimum intensity of light with his photometer for objects subtending a given visual angle. He investigated healthy and night-blind eyes.

Aubert (1864) used a diaphragm in the window of the dark room, and tested his ability to read Jaeger types at 1 m. distance. With a 5 mm. diaphragm he read J. 20 with difficulty; with 200 mm. J. 9 well; in bright diffuse daylight without a diaphragm J. 5 well. He noted that slight differences of illumination cause well marked differences in visual acuity. His results may be compared with Carp's;

in both cases " diffuse daylight " is taken as unit of illumination, and the great difference in the results may be attributed to the variability of the illumination and of the retinal adaptation.

Aubert.		Carp.	
Vision.	Illumination.	Vision.	Illumination.
1·0	0·55	1·0	0·12
		0·96	0·07
		0·87	0·05
0·71	0·25	0·74	0·04
		0·61	0·02
0·5	0·05	0·51	0·008
		0·35	0·004
0·2	0·015	0·23	0·003
0·08	0·0006		

For the discrimination of two white squares on a dark background Aubert obtained the following results:—

Visual angle of the squares.	Visual angle for the distances at which the squares were discriminated.		
	Very clear day.	Less clear day.	
	I.	II.	III.
	Background 57 times darker.	Background 57 times darker.	Background 2·5 times darker.
114″	29″	28″	24″
91″	46″	60″	68″
76″	60″	98″	92″
65″	72″	145″	140″
57″	97″	160″	210″
51″	107″	204″	270″
46″	110″	230″	

Therefore, in general, two bright objects can be discriminated under a smaller visual angle the larger the objects, the greater their absolute brightness, and the greater the contrast with the background. For black objects on a white or grey background greater distances are necessary.

Klein (1873) investigated the relationship for normal and ametropic eyes, using a standard English paraffin candle at 1 m. as unit, and Snellen's, Giraud Teulon's, and Boettcher's types as tests. His light intensities varied from 0·4 to 10,000. He found that even for the highest intensities available there was a continually increasing acuity for increasing intensities, though the degree of increase gradually diminished, *i.e.*, the curve was asymptotic.

Posch (1876) used parallel lines, and found that for variations of light intensity from 1 to 16 the rule holds good that the visual acuity increases as the logarithm of the light intensity, *i.e.*, the visual acuity increases in arithmetical proportion as the light intensity increases in geometrical.

Carp (1876) investigated the effect of diminishing the light by tinted glasses on the vision of emmetropes and ametropes, using Snellen's prong (⊔) figure as a test. Generally in emmetropes daylight might be reduced to 0·05 without reduction of vision. Reduction occurred earlier in myopes. Some emmetropes showed reduction when the light was diminished to 0·12 of its original brightness (*vide supra*).

Doerinckel (1876) employed the same method on elderly people. Carp and Doerinckel found marked individual differences. Doerinckel found diminution of acuity in old people.

Riccò (1877) experimented with relatively small variations of intensity, altering the intensity of the light by rotating sectors (episcotister).

Albertotti (1878) used Snellen's types and variations of light intensity from 1 to 32,400.

Sous (1878) used Badal's optometer and light intensities from 0·5 to 0·015.

Javal's (1879) experiments have reference chiefly to reading and will be referred to again.

Cohn's (1879) investigations also were of a practical nature, bearing upon school hygiene.

Manolescu (1880), using round spots and lines, formulated the rule that the product of the distance of the light and the distance of the eye is constant, *i.e.*, the minimum visual angle is inversely proportional to the square root of the light intensity. His intensities varied from 1 to 64.

Macé de Lépinay and Nicati (1881, 1883) investigated the visual acuity in monochromatic light. Celsius (1735), Buffon (1743), and Herschel had already used the ability to read print in different parts of the spectrum as a test of their luminosities, and Snellen and Landolt (1877) founded a method of photometry upon this principle. The authors attempted to put this method of photometry on a sure scientific basis. They came to the conclusion that the visual acuity varied with the luminosity only and was independent of the colour, at any rate for wave-lengths from the extreme red to 507 $\mu\mu$ (bluish green). From 507 $\mu\mu$ to the end of the violet the acuity increased and diminished more slowly. They draw the deduction therefore that visual acuity depends chiefly upon the less refrangible rays. In a later paper (1884) they found binocular acuity equal to monocular with double light intensity, a result much greater than that obtained by other observers.

Charpentier (1882) made very accurate experiments to distinguish small bright squares.* Four holes, 0·2 mm. in diameter, were placed at the four corners of a square of 1 mm. sides, the distance from the eye being 20 cm. At the minimum visible luminosity there was a uniform diffuse light, with no indication of the points. On increasing the illumination, suddenly and without irradiation the points became distinguishable. Dark adaptation lowered the minimum visible luminosity, but had no effect upon the illumination necessary for the discrimination of the points. Altering the size of the points, or their number, or their

* See Parsons, The Perception of a Luminous Point, Part II, R. L. O. H. Rep., vol. xix, 1, p. 116, 1913.

distance apart, had no effect so long as the area covered was less than 2 mm., corresponding to the foveal area. Hence, when multiple excitations are applied to the foveal area the first effect is a uniform diffusion over the whole area; only when the excitation is increased to a certain definite point do the individual elements which subserve the discrimination of details respond. The conclusions arrived at by Charpentier from his experiments are sufficiently important to be given in some detail:—

1. The minimum illumination necessary for the perception of small luminous areas is inversely proportional to their areas.

2. The minimum illumination necessary for the perception of large luminous areas is independent of their areas.

3. The limits of the retinal area beyond which the area of illumination ceases to be of effect corresponds to the dimensions of the fovea.

4. The same laws are applicable to indirect vision.

5. Luminous sensibility (*la sensibilité lumineuse brute*) must be distinguished from discriminative sensibility (*la sensibilité visuelle*); *i.e.* light sense must be distinguished from form sense.

6. Discriminative sensibility requires more light than luminous sensibility.

7. Discriminative sensibility is not affected by retinal adaptation.

8. Two points are perceived directly and without a confusion phase if they are separated on the retina by a distance greater than the width of the fovea.

9. The accurate method of measuring the visibility of several luminous points is to determine the illumination necessary and sufficient to discriminate the points.

10. The visibility of several points determined thus is independent of their number.

11. The visibility of several points is independent of the distances separating them if the interval does not exceed 35—40′.

12. The visibility of several points is proportional to

their area, and therefore to the square of their diameter for the same illumination and distance.

13. The visibility is proportional to the area of the retinal image of each point.

14. As the area of the retinal image varies inversely as the distance of the object from the eye, for a given illumination and for given dimensions the visibility of several luminous points is inversely proportional to the square of their distance from the eye.

15. The discrimination of two points illuminated by a pure colour requires more light than the perception of that colour, which itself requires more light than the sensation of simple light (*lumière brute*).

16. The perception of colours is affected by the areas of the coloured surfaces; the smaller the area the more light is required for perception.

17. The relation between the area excited and the colour threshold is not simple as for luminous sensation.

Charpentier (1883) also did some experiments with white figures on a black background, altering the intensity of the light, daylight and artificial light not accurately measured, by the episcotister (rotating sectors). He arrived at no definite conclusions, but pointed out the many variable conditions, such as minimum visual angle, contrast, form and dimensions of the retinal images, their luminosity and that of the background, accommodation, pupil aperture, and so on.

Cohn (1883) investigated normal-sighted children with different intensities of light produced by tinted glasses. He found marked individual differences. With 1/16 he obtained a mean of visual acuity equal to 4/5; 1/364, 1; 1/2604, 0·86; 1/18868, 0·78; 1/142857, 0·71.

Very careful and important researches were carried out by Uhthoff (1886) in v. Helmholtz' laboratory with the assistance of König. A range of light intensities of 1 to 3,600,000 (petroleum lamp) was used, and Snellen's prongs were observed binocularly. The lowest visual acuity was 0·0015 (Snellen CC at 10 cm.) with white light of intensity about 0·0015. Maximal visual acuity was obtained with 33 metre-candles (1175). Klein's increase with higher illumination was not confirmed. There is a very rapid rise up to 4 metre-candles (144), where vision reaches 1·59. For monochromatic lights the curves show a similar change at about the same intensity. The vision reaches its maximum slightly sooner for yellow. The general form of the curve is the same for red: the bend at 144 is more gradual, and the curve continues to rise slowly but uniformly with increasing intensities. It is therefore, unlike the white curve, asymptotic. Vision is worse in the lowest intensities for red, and Uhthoff showed that this was not entirely explained by lower luminosity. The green and blue curves show a much slower increase and are far below the other curves (at 144, green = 0·16; blue = 0·14).

Uhthoff's curves are not directly comparable, since the source of light was poor in rays towards the violet end of the spectrum, and no attempt was made to measure the luminosities of the coloured lights. He therefore performed another series of experiments (1890) with spectral lights, and these were divided into two groups. In the first group the visual acuity was measured in six parts of the spectrum (670, 605, 575, 505, 470, 430 $\mu\mu$) with increasing intensities, obtained by opening the slit of the spectroscope. In the second group the visual acuity was measured in different parts of the spectrum with the same slit opening. The curves given by the first group are shown in the figure (Fig. 1). They are similar to those in the earlier paper. The blue and violet curves are far below the yellow, the green occupying an intermediate position. From the green towards the violet therefore a much greater change of light intensity is necessary to cause the same increase in visual acuity than towards the red end. By increasing the light sufficiently Uhthoff showed that he could produce the same high acuity with blue as with yellow. This tends to show that much of the effect was due to the paucity of blue and violet rays in the source of light (gas lamp). Uhthoff does

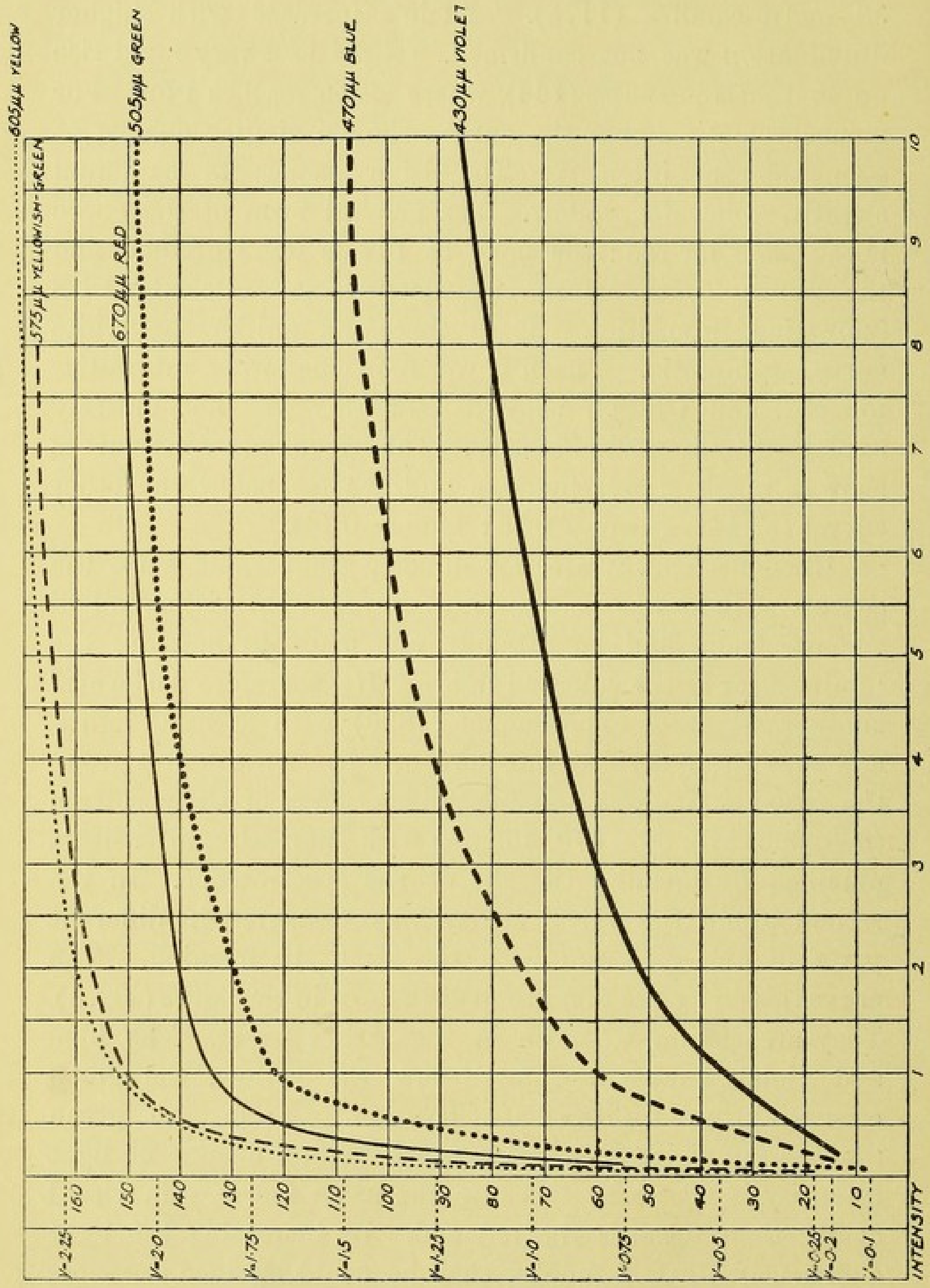

FIG. 1.—The ordinates represent the visual acuity (a) in terms of Snellen's fraction, (b) in distances (centimetres) from the test object. The abscissæ represent intensities of light.

not attribute it entirely to this reason, but invokes Purkinje's phenomenon.*

Cohn (1895) published further researches in which he brought out several points of practical importance. He emphasised the doubtfulness of daylight experiments, in which variations of illumination of 25 per cent. may pass unnoticed by the eye. Measurements with constant artificial light show the extent of individual variations. For a visual acuity of 1 the light intensity may vary up to 10 times, for 0·75 up to 12 times, for 0·5 up to 7 times the minimal value. There are eyes which have full normal vision with so low an illumination as 1½ metre-candles, and which still have half normal with 0·6 metre-candles. Of the eyes investigated full vision required not more than 16, half not more than 4 metre-candles. The mean of his results shows that if vision = 1 requires a light intensity represented by 100, then vision = 0·75 requires 71, and vision = 0·5 requires 33.

Little attention had up to this time been devoted to the condition of adaptation of the retina, though this has relatively little influence upon central vision (see "Scotopia"). In most of the experiments carried out with artificial light the eyes were probably partially dark-adapted (Albertotti, Charpentier, Uhthoff). Uhthoff's experiments, for instance, were done at night in a corridor of the Physical Institute in Berlin. Special attention was directed to this point in some researches carried out under Snellen's supervision by two of his pupils, Pickema and Laan (1897). The dark-adapted curves resemble those obtained by Uhthoff. In a lighted room, with light-adaptation, the general form of the curves is the same, but variations are superposed upon them attributable to variations in adaptation.

Broca (1894) had previously found that, with a constant pupillary aperture, visual acuity increases with dark-adaptation in feeble lights, but diminishes in strong lights, thus:—

* Parsons, Scotopia, R. L. O. H. Rep., vol. xviii, 3, p. 229.

Illumination in lux.	Visual acuity.	
	Light-adapted eye.	Dark-adapted eye.
2	0·52	0·81
17	0·86	0·97
34	1·0	1·0
170	1·55	1·15

König (1897) made very accurate observations with white and monochromatic lights. He used Snellen's prong figure, with 5′ as unit visual angle. He varied the light intensity by using different sources of light, different distances from the tests, and smoked glasses. The unit of light was one Hefner-meter. The experiments were carried out in various ways: (1) he measured the visual acuity (distance from the test) with constant illumination; (2) he estimated the illumination with constant visual acuity; (3) he compared the illumination and the visual acuity when both the distance of the observer and that of the light from the test were varied. The range of light intensities was from 0·00036 to 64,480, giving a range of visual acuities from 0·031 to 1·750. The records gave 121 points on a curve. From 1 to 20 the curve is a straight line with a slight gradient; at 20 the light intensity = 0·013, visual acuity = 0·088. From 21 to 29 the curve bends sharply. From 30 to 103 the curve is a straight line with a steep gradient; at 30 the light intensity = 0·13, visual acuity = 0·242; at 103 the light intensity = 316, visual acuity = 1·600. From 104 to 121 the curve is a horizontal straight line. He came to the conclusion that the visual acuity, S, is a linear function of the logarithm of the light intensity, B: $S = a(\log B - \log C)$, where the constant C is inversely proportional to the luminosity of the light. The factor a is independent of the nature of the light; a and C differ according to whether rods or cones are the site of stimulation. For cones a is about 10 times as great as for rods.

König conjectures that two different elements of the percipient layer of the retina are concerned in the visual acuity. The first kind (rods) functionate at lower light intensities. As the illumination increases their activity increases, but before it has reached a maximum it is overtaken by the activity of the second kind (cones). At the lower intensities fixation is slightly eccentric; as the intensity increases foveal fixation begins. In a totally colour-blind eye the curve corresponded throughout with the early part of the curve of the normal eye (see the *Duplizitätstheorie*, in "Scotopia," R. L. O. H. Reports, xviii, 3).

Druault (1898) made some observations in Tscherning's laboratory with test types under medium adaptation for light. A standard candle was used for low, and a 54-candle power lamp for higher intensities. He found the following results:—

Illumination. (1 = 1 metre-candle.)		Vision.
0·016	....	15/200 = 0·075
0·020	....	15/100 = 0·15
0·028	....	15/70 = 0·21
0·047	....	15/50 = 0·3
0·12	....	15/40 = 0·37
0·25	....	15/30 = 0·5
0·67	....	15/20 = 0·75
1·5	....	15/15 = 1
16·7	....	15/12 = 1·25
5400	....	15/10 = 1·5

Colombo (1901) examined normal, amblyopic, night-blind, and other persons with Landolt's tests (broken circles) by artificial light in a dark room. He found individual variations, conformable to no mathematical rule.

Altobelli (1903) specially tested the effect of bodily fatigue on the relationship of visual acuity to light intensity in Mosso's laboratory. The results resemble Colombo's. He found that fatigue demands higher illumination for the same visual acuity.

Matawkin (1904) used Nicol prisms to alter the intensity of the light. With gradual diminution of the illumination, he found that in emmetropes with V = 1 or more the visual acuity varies as the logarithm of the light intensity. The curve for uni- and binocular vision is the same, and has a constant type. Hypermetropes up to 1 D have the same curve, but require longer time for dark adaptation. In hypermetropes of more than 1 D, the visual acuity falls more quickly, and the same applies to low myopes, astigmatics, and the night-blind. The time of adaptation is diminished by dilatation of the pupils with 5 per cent. euphthalmin.

Possek (1907) found that in emmetropes a difference in illumination of from 30 to 10 metre-candles produced no appreciable effect. The diminution with 3 metre-candles was nearly three times as great as with 6 metre-candles. For emmetropes 10 metre-candles is a good illumination, 6 metre-candles the minimum permissible; for myopes 10 metre-candles is the minimum. He gives the following results :—

Diminution of illumination.	Diminution of visual acuity.		
	Emmetropes.	Myopes under 3D.	Myopes over 3D.
	per cent.	per cent.	per cent.
30 to 10 m.-c.	1·26	10·82	10·06
10 „ 6 „	5·86	11·74	24·94
6 „ 3 „	12·16	19·28	13·65

Oguchi (1907) used Snellen's prongs, with unit 5′ as tests, 15 minutes' dark adaptation, and Hori's photoptometer as source of illumination. Hori's instrument is a simple petroleum lamp with a square window of variable size; the light intensities are obtained by calibration with a Bunsen photometer. The light range is from 0·00217 to 0·3907 candle-power. The highest visual acuity was obtained with 1 m. distance of the light (25 mm. diagonal of the window), and 1 m. distance of observer; the lowest with 6 m. distance of light (5 mm. diagonal of window), and 6 m. distance of observer.

Within the narrow limits of light intensities employed, and omitting the lowest visual acuities, Oguchi arrived at the formula $V = \frac{1}{\sqrt[3]{3}} \sqrt[3]{L}$, *i.e.*, the visual acuity varies as the cube root of the light intensity. The rule applies to a minimum candle-power of 0·00375 and a visual acuity of 20/70. Below 0·00260 candle-power and a visual acuity below 20/80 the rule does not hold good. This level of vision, 0·25, agrees well with König's 0·242, at which his curve takes the decided bend which he attributes to the change from rod to cone vision. There is, however, a very great discrepancy in the light intensities, König's being 0·13 and Oguchi's 0·0021. As a Hefner is not far removed from 1 candle-power, some explanation is required.

It has already been mentioned that Uhthoff was able, with sufficient intensity of light, to obtain the same maximum visual acuity with blue light as with yellow. Helmholtz (1896), in the second edition of his Physiological Optics, came to the conclusion "dass wir unabhängig von der Farbe bei gleicher Helligkeit auch gleich viel sehend erkennen." König (1897) confirmed this view experimentally. Oerum (1904) threw some doubt on the point by the results of his experiments with the method introduced by du Bois-Reymond.*

Up to this period all such experiments were vitiated by the impossibility of being certain that estimates of the equivalence of luminosity of different colours were accurate. The introduction of flicker photometry has supplied a means of accurately estimating the equivalence of luminosity of white and various colours. The use of this method gives great value to the researches of Loeser, which were continued by Boltunow (1908) and finished by Loeser (1909). Boltunow used bright Snellen prongs on a dark background, Loeser

* See Parsons, R. L. O. H. Rep., vol. xix, 1, p. 111, 1913.

Roelofs + Zeeman – Arch. néerl. de Physiol. III. 528. 1919. L'acuité visuelle dans la demi-obscurité.

dark prongs on a light background; Uhthoff had found that in monochromatic light bright test-objects on a dark background gave abnormally low visual acuity as compared with the reverse. Both observers used the same glasses for producing monochromatic lights, but the green glass let through a trace of red. The following results are recorded by Loeser, the visual acuity being given in distances in metres from the test:—

Red............	4·0	4·30	4·50	4·50
Green	4·60	4·85	5·15	5·50
Red............	3·75	3·50		
White	4·45	4·80		
White	4·45	4·60		
Green	4·60	4·70		

The visual acuity, therefore, for red is markedly less than for white and green, that for green being slightly better than for white. Boltunow found white better than green.

On diminishing the light by the episcotister, the following results were obtained:—

RED.

Light intensity.									
1/4	3·40	3·50	4·0	3·70	3·60		3·50	3·60	1
1/16	3·40	2·60	3·60	3·70	3·30		3·40	3·30	2
1/32	3·50	3·10	3·50	3·30	3·15	3·40	3·10	3·30	3

GREEN.

Light intensity.									
1/4	4·50	4·20	4·30	4·45	4·30		4·50	4·40	1*a*
1/16	3·80	3·10	3·90	3·80	3·80		3·70	3·70	2*a*
1/32	3·50	3·30	3·75	3·50	3·60	3·30	3·20	3·40	3*a*

Therefore the increase of visual acuity for red with increasing luminosity is much less than for green.

Loeser repeated Oerum's experiments, using black spots, 2 mm. in diameter, on a white ground. It will be remembered that Oerum found a maximum of physiological points for red, medium for green, and least for blue. Boltunow

× Luckiesh - Bull. Abstracts. 10-1913.

found the maximum for red, medium for white, and least for green. Loeser found that the results by this method entirely confirmed those with Snellen's prongs, viz., that the visual acuity is markedly worse for red than for white and green, for which colours it is almost the same.

It appears from Loeser's researches that for moderate intensities the visual acuity is much less for red than for white and green, but that the difference is not absolute. At low intensities the curves approximate. The visual acuity is not proportional to the intensity of the light, but is also affected by differences of contrast with the background. This part of the subject requires further investigation.

Nagel (1908) with Landolt's C-figure, the luminosities being tested by a flicker photometer, found visual acuity greatest for white, and greater for green than red; but with point tests it was greater for red than green.

The Influence of the Pupil.—Many of the observers whose experiments have been discussed took into account the size of the pupil. As a rule, however, it was either found to have a negligible effect under the conditions of the experiments or an artificial pupil was used. It is clear that the function of the pupil to regulate the amount of light entering the eye is likely to have some effect on visual acuity under different conditions of light intensity. It has been shown that, *cæteris paribus*, the light reaction of the pupil varies with the condition of adaptation of the retina.

Hummelsheim (1898) has studied the influence of the size of the pupil on visual acuity under different intensities of light. He found that with Snellen's test types the visual acuity with a small pupil first outstripped that with a dilated pupil at an illumination of 1 metre-candle and over. With illuminations over 50 metre-candles the difference was slight. It will be remembered that Uhthoff found that maximum visual acuity was obtained with 33 metre-candles. Pickema and Laan found that with dark-adaptation and at low intensities of light a small artificial pupil made no appreciable effect upon the results. Probably, therefore, the influence of the pupil is negligible under most circumstances.

The synkinetic contraction of the pupil on accommodation and convergence for near objects has for its object the compensation of the increased light entering the pupil under these conditions, though it is greater than is necessary for this purpose (Fick). It also increases the focal depth of the eye (Gullstrand). Accommodation tends to diminish aberration, so that the associated pupillary movement is not directed to this end.

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THE INFLUENCE OF LATERAL ILLUMINATION ON VISUAL ACUITY.

By J. HERBERT PARSONS.

GOETHE, in 1810, said that "the eye sees no form, inasmuch as light, shade, and colour together constitute that which to our vision distinguishes object from object, and the parts of an object from each other." If we include variations in brightness or luminosity in the generic term "colour," it may be said, with Clerk-Maxwell, that "all vision is colour vision, for it is only by observing differences of colour that we distinguish the forms of objects," or, as Hering puts it, "our visual world (Sehwelt) consists essentially of differently presented colours, and objects, as seen, that is visual objects (Sehdinge), are nothing but colours of different nature and form." Hering has emphasised the importance of memory in the common, but erroneous, attribution of colours to the objects themselves, implying that the colours are properties of the objects. It is easy to show that the apparent brightness and colour of objects can be altered within a wide range without disabusing our minds of the opinion that the colours are inherent properties of the objects. Thus the paper of a book appears white and the print black, whether we read it in the morning or at mid-day, or in the evening. Yet Hering has shown by accurate measurements that the print may actually reflect more light at mid-day than the paper did in the morning. In this case the ratio of the intensity of the light reflected from the white paper to that of the light reflected from the black print remains constant under variations of illumination, and a similar constancy, within wide limits of illumination, is retained by the eye by means of suitable physiological adaptation.

In common with other senses, discrimination of stimuli depends upon differences rather than upon absolute values, a fact which is expressed by Weber's law that the just appreciable increase of stimulus bears a constant ratio to the original stimulus. For white light Fechner could distinguish a difference of 1/100, v. Helmholtz 1/167, of the light intensity.

Cobb has published some striking figures showing the enormous range of brightness to which the eye has to respond under some quite ordinary conditions of artificial lighting. "A perfectly diffusing surface with an illumination of 20 metre-candles upon it has a brightness of $20/\pi = 6{\cdot}37$ candles per square metre. The tungsten filament which illuminates it has a brightness of 1·64 candles per square millimetre (Ives and Luckiesh), or 1,640,000 per square metre; that is, a brightness 258,000 times as great as the surface it illuminates. If we go back in history a little and revert to the now humble fish-tail gas burner, we find that it has an intrinsic brightness of 0·004 candle per square millimetre, or 4,000 per square metre, still 630 times as bright as the surface illuminated. The frosted tungsten lamp is still brighter than this, giving off 9,300 candles per square metre, and being 1,460 times as bright as the white surface. The three sources thus have respectively 258,000, 630, and 1,460 times the brightness (as it affects the eye) which the object illuminated can possibly have otherwise than by specular reflection." Of the light which falls upon white paper about 80 per cent. is reflected, while a paper made as black as possible reflects about 4 per cent. Printed letters which reflect one-twentieth or less of the incident light on the paper appear "black" on a "white" ground.

The influence of lateral illumination of the eye on visual acuity is one of considerable practical importance. The disagreeable effects of a bright light in the field of vision are familiar to every one, but the cause of the distress, and how far it is seriously deleterious to the eyes, have proved difficult to discover. Theoretically various factors come into play, such as alterations in the size of the pupil, alterations in contrast (spatial induction), and fatigue. As regards contrast, if the light source is screened from the test object, but not from the eyes, the illumination and the objective contrast between the object and the background remain unchanged. Subjectively, however, the conditions are altered. Owing to the oblique incidence of the lateral light, the media of the eye are flooded with light, partly transmitted through the sclerotic as well as through the refractive media, and partly reflected from the various refracting surfaces, and thus unequally distributed. The conditions are complex and it is scarcely possible to foretell the effects.

Sewall (1884) found that lines ruled on a card were visible at a greater distance when light from the sky was thrown into both eyes from the side than when peripheral light was excluded by a mask. He explained the result on the basis of the red light transmitted through the sclera and vascular membranes. Diminution of the pupillary aperture might account for it.

Urbantschitsch (1883) found vision for details increased when his eye was exposed to light as compared with when it was screened. With dilated pupil and paralysed accommodation there was apparent brightening of the test object, but he does not say that the appreciation of details was increased. The apparent brightening may be attributed to scattered light (Cobb).

Schmidt-Rimpler (1887) focussed an electric lamp filament on the sclerotic. With low illuminations, even in atropinised eyes, there was increased acuity; with high illumination diminished. After working all day with the microscope he found that at night he could read better if the light from the lamp was shaded from the eye. He found that there was no improvement with lateral illumination in most diseased conditions (neuritis, atrophy, cataract, glaucoma), but some improvement in a case with vitreous opacities.

The first exhaustive experiments on the subject were commenced by Uhthoff (1885) and completed under his direction by Depène (1900). The test objects were numbers illuminated with 100, 4·938, 2·441, 0·938, 0·610, or 0·133 normal candles. The size of the lateral retinal image was 0·44178, 0·216475, 0·11045, or 0·03976 sq. mm.; *i.e.*, in the proportions 100 : 49 : 25 : 9. The intensities of the peripheral lights were from 0·31244 to 53·606 normal candles. Depène found that when the test object was sufficiently well illuminated to give vision equal to 1·25, *i.e.*, about 5 normal candles, or more, lateral illumination caused increase in visual acuity. At lower illuminations of the test object diminution of visual acuity was greater (1) the lower the illumination of the test object, (2) the smaller the angle made by the lateral light with the line of vision, (3) the greater the intensity of the lateral light, (4) the greater the retinal area stimulated by the lateral light. The improvement with high illumination was attributed to constriction of the pupil, since no improvement occurred when mydriatics or miotics were used. Diminution of acuity was attributed to changes in the adaptation of the retina. No difference was found whether the lateral light fell on the sclerotic or pupil alone, or on both.

Hummelsheim (1900) attacked the problem in a somewhat different manner and his results, though apparently contradicting Depène's, in reality supplement them. His test object was lighted from behind and was situated in the middle of a large grey screen opposite the window of the room. Thus the peripheral illumination of the retina was uniformly reflected daylight. It was varied from 0 to 200 metre-candles. The visual acuity showed a gradual rise, which was diminished but not abolished by mydriatics and miotics. Hummelsheim explains the increased acuity which occurs independently of constriction of the pupil by Hering's theory, viz., that it is due to spatial induction.

Borschke (1904) used a test object illuminated by a lamp placed a distance (m) behind it and surrounded by six lamps which acted as the peripheral light. The distance of clear vision was first determined with the dazzling lights off. These were then turned on, and it was found that the illumination of the test object had to be increased to make it legible. The ratio $m : n$, the shorter distance of the illuminating light from the test, was regarded as the measure of the disturbance produced by the lateral illumination. The ratio of $m : n$ was found to be approximately constant (1·9 to 2·5), and Borschke concluded that the effect was entirely due to scattered light, chiefly by the lens fibres. With a focal lateral light it was immaterial whether the image fell on the nasal or temporal side, or on the blind spot. Heymans (1901) found that vision was unaffected if the lateral image fell upon the blind spot, but he worked with threshold stimuli, so that the results are not directly comparable.

Tschemolossoff (1904) found that the visual acuity might diminish or increase under lateral illumination. Diminution occurred when the test object was feebly illuminated, and varied directly with the intensity of the lateral light and inversely with the angle of obliquity of that light. Increase occurred when the test object was well lighted or even lighted to excess. Diminution of acuity is due to the actual image of the lateral light on the retina, to diffusion of light by the media of the eye, and to contraction of the pupil causing decrease in the amount of light entering the eye. Increase of acuity is due to contraction of the pupil also, as well as to excitation of retinal sensibility by feeble oblique illumination. Central sensibility to colours is diminished more, the stronger the lateral illumination and the less the contrast between object and background. When the direct illumination of coloured objects is diminished they are less well distinguished even without lateral illumination. Two oblique sources of light at different angles diminish the appreciation of feebly illuminated objects without manifesting any simple addition of effects. When one eye is illuminated obliquely the visual acuity of the other diminishes according to the same rules as with uniocular vision, but to a less degree. Binocular central vision diminishes with double oblique illumination, but less than in the case of uniocular vision.

Cobb (1911) has investigated the subject with great care, and his papers are the best which have yet appeared. He used an extremely ingenious test object, invented by Ives. It consists of two plates of glass, ruled with 240 black lines to the inch. When these are placed in apposition and illuminated from behind, lines of various breadth can be made to appear by rotating one of the plates so that the ruled lines of one plate form angles of various sizes with those of the other. The test object can thus be varied at will without altering the intensity of the illumination. The lateral light was attached to the arm of a Wundt perimeter, *i.e.*, at a radius of 1 metre. By an ingenious method the effect of lateral illumination was compared with the effect of throwing a haze over the retinal image of the test object. Cobb's conclusions are as follow:—

(1) Light from a bright source entering the eye reduces the visibility of an object the more the brighter the source, the lower the brightness of the object, the smaller the angle subtended by the two, except that when the test object is very bright lateral illumination may cause increased visual acuity.

(2) Under a condition imitating the worst practical condition for reading—the light at 10° from the visual axis, equal illumination of the eye and test object (black letters on white ground)—the reduction in visual acuity is negligible at any intensity of illumination.

(3) The retinal image of the light source is a negligible factor in the depression of vision, at least for angles of 15° and over, since, other conditions being equal, it is indifferent whether the image falls on the blind spot or on sensitive portions of the retina.

(4) The depression of vision is due to light which, by reason of reflection or diffusion, partly from imperfect transparency of the eye media, is scattered over the retina upon and near the image of the object.

(5) Visual acuity behaves in general, but not wholly, the same with (*a*) illumination of the eye from a lateral source,

and (*b*) a haze of light thrown over the rod-free central retina (subtending 2° in the visual field) with proportional variations in the light flux in the two cases.

(6) The disagreement between the two sets of results just mentioned must be due to changes in the sensibility of the part of the retina concerned in vision of the object, induced by the scattered light in the case of lateral illumination, falling on the retina not on but about that part, and probably not farther away from it than 15° measured in the visual field (the remoteness of the blind spot).

(7) There is no parallelism between the depression of vision for detail on the one hand and discomfort and other visual disturbances classed under the head of "glare" on the other hand, resulting from a light source in the field of vision.

In his last conclusion Cobb agrees with Borschke, who says "that the unpleasant feeling of dazzling (Blendung) and the disturbance of vision produced by dazzling are totally different things, and need by no means necessarily occur to the same extent at any given time." Cobb throws out the hint that the discomfort may be associated with the eye movements.

Cobb (1913–14) has made a further series of experiments in which the test object was the same as before, but the whole of the peripheral field of vision was either dark or filled with white light. A wooden cube of 1-metre sides was constructed, the inside corners and edges being cut off by oblique surfaces tangential to an inscribed sphere, so that the whole 26-sided figure approached the shape of a sphere. The inside was painted white. In one of the vertical sides of the cube an opening was left for the observer's face and head-rest. In the oblique surface directly above this opening was a sheet of milk glass, behind which was a 100-watt tungsten lamp, illuminating the white interior. Opposite the face opening another smaller opening was made through which the test field could be observed. The test object was 180 cm. from the eye.

Experiments were made to estimate the effect of peripheral illumination on visual acuity, and on the discrimination of differences of brightness in the two halves of the test field. It was found that different individuals may show fairly wide differences in their vision of objects of very low brightness, both with and without bright surroundings. In spite of such individual differences the relative changes in visual capacity caused by differences in surroundings were found to be on the whole in the same direction in cases of the same change in the conditions. For objects of relatively low brightness the presence of a surrounding field of relatively high brightness has the effect of lowering the capacity of vision both for detail and for brightness difference. In the case where the surrounding field was slightly brighter than the test object visual discrimination was found to be actually better both as regards visual acuity and brightness difference than for a physically identical object seen in dark surroundings. Surroundings of a brightness about equal to or less than that of the test object show no consistently better or worse results than dark surroundings with the identical test object.

Comparison of the visual acuity and brightness difference curves under parallel conditions shows that as the brightness of the test object is reduced the brightness difference limen usually at a fairly definite point takes a rather abrupt rise. Visual acuity on the other hand, while always showing a slight progressive diminution beginning at the very highest brightness under a similar change of conditions, never undergoes such rapid decrease as differential sensibility. Cobb attributes this fact to the dependance of the discrimination of fine detail upon a physically perfect image on the retina and accuracy of fixation. Visual acuity therefore varies less under the influence of contrast than does differential sensibility because the retinal image is always equally perfect.

As contrasted with visual acuity, differential sensibility depends mainly upon retinal conditions, and to a very minor degree upon perfect retinal images. The essential difference is that in the case of visual acuity estimation the brightness difference of the parts of the test object is gross, while the areas involved are minimal. On the other hand in the estimation of differential sensibility by simultaneous presentation the areas of the fields compared are gross while the brightness difference is minimal. Hence small irregularities in the formation of the retinal image have little effect, but the condition of adaptation, temporal and spatial induction are prepotent factors. Spatial induction, produced by alteration in the surroundings, was found to be far more significant for differential sensibility than for visual acuity.

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SCOTOPIA ("DAEMMERUNGSSEHEN") OR VISION IN DULL ILLUMINATION.

By J. HERBERT PARSONS.

WE are all familiar with the great adaptability of the retina to variations in illumination, but all are not so familiar with the peculiarities in the sensibility of the retina under low illumination. Yet these are interesting in the explanation they afford of some everyday—or rather, every night—experiences, and they are by no means unimportant to the ophthalmologist. The following remarks are derived almost entirely from the writings of W. Nagel and von Kries :—

Dark adaptation is a relatively slow process. It is characterised by a rise in the sensitiveness of the retina to light, which is slow during the first 10 minutes of exclusion of light from the eyes, rapid during the following 20—30 minutes, and again slow or almost negligible after that period. The general character of the curve of retinal sensibility is the same in all cases, but there are marked individual variations in the rapidity and amount of the rise, thus explaining the fact that some people see very much better in a dull light than others, though variations in the size of the pupils and other factors (*vide infra*) are not without importance in this respect. In night-blind people there may be only a very slow rise, the ultimate sensibility after an hour being near the normal limit. In severe cases there is very little rise after several hours.

Adaptation is normal in the colour-blind, even the total colour-blind. Strychnin and brucin cause increase in the amount and rapidity of the rise of sensibility: santonin has no effect. Mydriatics have an indirect effect; the first slow rise is prolonged from 10 to 20 minutes but is followed by the normal rapid rise to the normal height.

Very short exposure to bright light, *e.g.*, striking a match, causes a very temporary fall without materially altering the course of the curve. The increase in sensibility after very prolonged dark adaptation is more transient than the increase during the first hour, *i.e.*, it is more quickly and completely abolished by exposure to light.

Besides this temporal variation in the sensitiveness of the retina there is a well-marked spatial variation. In the condition of light adaptation the fovea is the most sensitive part of the retina, though little attention has been paid to the degree of adaptation in the researches published on this subject. (The light sensitiveness of the various parts of the retina must be carefully distinguished from their visual acuity for form). The spatial sensibility for colours of the retina of the light-adapted eye has been worked out by Vaughan and Boltunow. They found the sensitiveness 10° from the fovea ¼, 20° 1/10, 35° 1/40 of that of the fovea itself. In dark adaptation it is the least sensitive part of the retina. In other words the fovea is a region of physiological night-blindness (v. Kries).

The relative central scotoma in dark adaptation was long ago recognised by astronomers, who noticed that stars of small magnitude were seen better if viewed somewhat eccentrically. It is strikingly exemplified in viewing the Pleiades: by direct fixation four or at most five stars are seen; by indirect fixation a number of weaker stars become visible. Different observers use different parafoveal spots for clearest vision in dark adaptation (Christine Ladd-Franklin, Simon), and the spots vary with the degree of adaptation. The nearer the intensity of the stimulus is to the threshold of the dark-adapted fovea the nearer is the spot to the fovea: the feebler the light the more eccentric is fixation. With a given sub-minimal foveal stimulus Simon found that he fixed 2° from the fovea after 10 minutes dark adaptation, $1\frac{1}{2}$° after 20 minutes, and 1° after an hour. The direction is constant for the same eye and varies with different eyes—Simon's right eye up and out, left eye up—and depends upon muscular balance and refraction rather than on the specific sensibility of the parts of the parafoveal region (Simon).

Although the fovea is night-blind relative to the periphery it is capable of a slight degree of dark adaptation, but the small rise in sensitiveness of the fovea is only appreciable after previous very strong light adaptation, such as looking at the clear sky.

The peripheral rise in retinal sensibility in dark adaptation is rapid from 1° to 4° around the fovea, then slower to a maximum between 10° and 20° (Breuer and Pertz), beyond which it falls.

The alterations in sensibility differ according to the size of the area stimulated, and the relations between sensibility and the area stimulated are different in the light- and dark-adapted eye, and also in the foveal region and the periphery. For foveal vision the sensibility is proportional to the area stimulated (Riccò, Loeser). In the dark-adapted periphery the stimulus is proportional to the square root of the area stimulated (Piper), but only for composite-white light and objects subtending a visual angle of 1° to 10°. Above 10° the sensibility rises more slowly. The rise is still less even for smaller angles with red light. The rise of the curve of sensibility in dark adaptation therefore varies with the size of the area of retina stimulated and with the nature of the light. In the light-adapted eye there is no definite relationship between the rise of sensibility and the size of the visual angle.

In dark-adapted eyes binocular summation of stimuli occurs, so that the sensibility is about twice as great with both eyes open as with only one (Piper), though individual variations occur. In light-adapted eyes no such binocular summation occurs (Fechner, v. Helmholtz), but care must be taken that there is good light adaptation, and one eye must be covered for only a very short period, otherwise partial dark adaptation occurs. In this respect there is a noteworthy analogy to the effects of the size of the area of retina stimulated: with complete light adaptation the stimuli to different parts of the retina are not summated, given that the visual angle exceeds a certain (small) size, nor are the stimuli to the two eyes summated, whereas in the condition of dark adaptation both summations occur.

It will be readily appreciated that complete dark adaptation rarely occurs under normal conditions of life. Scotopia or Dämmerungssehen is the condition of vision in which there is a high degree of dark adaptation accompanied by a small residuum of light adaptation. It will be best to consider the conditions of vision after prolonged stay in a feebly lighted room. If now coloured objects are viewed under feeble illumination the colours cannot be distinguished, but all appear to be of various shades of grey. The eye is totally colour-blind. A spectrum of low intensity appears as a colourless bright streak, varying, however, in brightness in different parts. The striking feature is that the brightest part, instead of being in the neighbourhood of the D line (yellow), is moved farther towards the violet end—about 530 $\mu\mu$ instead of about 580 $\mu\mu$. The luminosity curve falls slowly towards the violet end, sharply towards the red, and the red end is shortened. The same results are obtained with normal and abnormal trichromates, protanopes (red-blind), deuteranopes (green-blind), and totally colour-blind people.

To the totally colour-blind the spectrum appears monochromatic under all conditions of adaptation, and their luminosity curve is practically identical with the normal scotopic luminosity curve. Still more remarkable is the identity of the curve with that obtained from the bleaching values of different monochromatic lights for (frog's) visual purple (Trendelenburg).

It is instructive to compare the differences in the appearances of coloured objects by daylight vision or photopia and by scotopia. In the dispersion spectrum of gas light the red (670 $\mu\mu$) appears about 10 times as bright as the blue (480 $\mu\mu$). On the other hand the scotopic value of the red is less than one-sixteenth that of the blue. Hence with failing light the brightness of differently coloured objects alters, the colours towards the red end of the spectrum becoming relatively darker, those towards the violet end brighter, so that finally the reds appear almost black and the blues bright. This fact was first investigated by Purkinje and is known as *Purkinje's phenomenon.* Hering drew attention to the fact that the brightness of the blues increases much more rapidly than that of the reds diminishes. The alterations are not limited to the ends of the spectrum. Colours which under ordinary circumstances appear equally bright become dissimilar in scotopia. Ebbinghaus and Christine Ladd-Franklin almost simultaneously observed that three whites made by mixture of red and blue-green, yellow and blue, and greenish-yellow and violet darken unequally with proportionally diminishing luminosity—the first least, the second more, and the third most. Yellow made by mixture of red and green under scotopia appears paler and brighter than its photopic spectral (homogeneous) yellow match. Similar, but much greater differences occur in colour-blind people, more in deuteranopes than in protanopes. They also occur in peripheral retinal stimulation: colours which, when viewed by peripheral parts of the retina, match in luminosity with high intensities of light adaptation cease to match in scotopia.

Purkinje's phenomenon does not occur at the macula. If a circle, half red, half blue, of equal luminosities, on a black background, is looked at and the light diminished, as soon as the eye is dark adapted the blue appears brighter. If the circle is made so small that it subtends a visual angle of less than 2° no change in brightness is observed by direct fixation. By eccentric fixation the change at once becomes apparent. The fovea is therefore scotanopic.

This fact is more easily demonstrated in the colour-blind, especially deuteranopes, than in the normally colour-sensitive. In the former a greenish-yellow light has a scotopic luminosity value a hundred or more times as great as its photopic red luminosity match, whereas in the latter the maximum ratio is 1 : 6. The scotanopic foveal area subtends a visual angle of about 1·5° (Nagel).

The fovea is therefore an area of pure photopic vision, with no admixture of scotopic vision, a condition only obtained in the periphery by the extremest possible light adaptation.

From what has already been said we see that there are two thresholds of vision—an *absolute threshold*, the minimal stimulus producing the sensation of light; and a *specific or colour threshold*, the minimal stimulus producing the sensation of colour. The interval between them is known as the *colourless interval*. It depends upon the scotopic visibility of the given light below the threshold of photopic vision, and varies with the condition of retinal adaptation and the nature of the light stimulus. The colourless interval increases with increasing dark adaptation, and this is due to lowering of the absolute threshold, the specific threshold remaining almost or quite constant. As regards the nature of the light stimulus the colourless interval is greatest for light of short wave-length and least for light of long wave-length. In the orange it is small even with good dark adaptation. In the red of more than 670 $\mu\mu$ it is almost completely abolished. In fact even with very good dark adaptation such a red light excites the red sensation, and the only evidence of a colourless interval is the alteration in the character of the sensation as dark adaptation becomes more complete, the red becoming paler and brighter. A minimal colourless interval can, however, be elicited under suitable conditions—degree of dark adaptation, size of field, para-central or peripheral stimulation (Charpentier).

These facts explain some of the peculiarities observed in distinguishing bright coloured points of light at night with the dark-adapted eye. If the light is white it may be invisible to the night-blind fovea, whilst it is clearly visible to the parafoveal or peripheral regions of the retina. Such a faint white point of light is readily "picked up" by the wandering eye, but becomes less obvious, or even disappears, when it is directly fixed.

If the light is green it will be "picked up" in a similar manner, and when first observed by the wandering eye will appear very bright with only a tinge of green, or no green at all. When it is fixed by direct vision it may disappear entirely, as with the white light, but if sufficiently saturated and sufficiently bright to simulate foveal vision it will appear definitely green.

If the light is red it will be "picked up" with difficulty, because it will be invisible to the peripheral retina, but if it is sufficiently bright to stimulate the central region of the retina (8°–10°) it will be unmistakably red, and will not exhibit any of the white dazzle which characterises the green light.

It has been pointed out that scotopia is in every way allied to total colour-blindness. Now the extreme periphery of the photopic field of vision is also totally colour-blind, this zone being separated from the macular region by a zone of dichromatism. The question arises whether the photopic zone of total colour-blindness possesses the same properties as the scotopic retina. To determine this point it is necessary to enquire more nearly into the properties of the photopic field of vision.

As already mentioned, only the foveal region gives the unadulterated photopic reactions, unless the eye is very fully adapted to light, so that all traces of scotopia are eliminated from the peripheral field. Ordinary observations with the perimeter do not afford accurate details for comparison. If light adaptation is rendered as complete as possible by exposure to bright sunlight many points of interest are elicited. Under these circumstances it appears—within the limits of experimental error—that colour matches, spectral or composite, which hold good for the fovea remain good matches when viewed eccentrically, but though the matches remain matches the values alter, the colours changing in the mid-peripheral region, and becoming colourless in the extreme periphery. It may therefore be concluded that peripheral vision differs from central vision only in the direction of a *reduction* of sensation, and not of a change in character of sensation.

Further, all colour mixtures which appear colourless by central vision remain colourless by peripheral vision. Allowance must, however, be made for macular pigmentation; the deduction is therefore more accurate if paracentral and peripheral regions are compared. Care must be taken that light adaptation is complete and has been induced by colourless light, and that long exposure to coloured lights is avoided.

The limits of the photopic colour fields vary with the intensity of the light, the saturation of the colour, and, above all, the size of the object. If these are sufficiently great colours may be recognised, almost, if not quite, at the extreme periphery.

Hess has shown that colour pairs can be selected which lose their colour simultaneously and form a grey match when viewed peripherally, *e.g.*, green (495 $\mu\mu$) and red mixed with a moderate amount of blue, and yellow (574·5 $\mu\mu$) and blue (471 $\mu\mu$). These colours are complementary. All colours of greater wave-length than 495 $\mu\mu$ appear yellow, all of less wave-length blue, in peripheral vision. Hence, there are only four colours which gradually become paler without altering their colour tone, ultimately becoming colourless, as one passes from central to peripheral vision. Hess calls these colours *invariable* red, yellow, green and blue. The zone in which these changes occur is dichromatic. As to its limits they vary with conditions already mentioned, but the limits for invariable red and green are the same, as also for invariable yellow and blue.

Beyond this zone there is an extreme peripheral zone which is monochromatic or totally colour-blind. It is best demonstrated in the nasal and upper and lower portions of the field, only with very small test objects in the peripheral portion. If the luminosity curve for different colours is worked out for this zone it is found to be quite different from the scotopic luminosity curve. The peripheral luminosity curve is highest at about 608 $\mu\mu$ instead of 544 $\mu\mu$, thus nearly approximating the luminosity curve for the fovea. We have here a further proof that peripheral vision is a reduction of central vision, whereas scotopia is a different form of vision; the former is a quantitative variation, the latter qualitative.

It is of interest to note that the photopic luminosity curves of the normal and deuteranope are the same, whereas the protanopic curve is displaced towards the violet.

In the previous remarks care has been taken to set forth reasonably established facts without reference to any theory of visual sensations. The differences exhibited by photopia and scotopia are so great as to render it improbable that they are carried out by the same retinal mechanism. It is natural, therefore, to enquire whether the anatomy of the retina provides any evidence of two dissimilar end apparatus, and the rods and cones suggest the possibility that they supply the necessary requirements. This view is not new, but the evidence which has accumulated in its favour is so overwhelming that v. Kries puts it forward as a definite theory—the duplicity theory (Duplizitätstheorie). According to this theory the rods are the organ of scotopic vision, the cones of photopic vision. The rods are susceptible of very marked alterations of adaptation, whereby all effective stimuli excite colour-free sensations of light, which vary in intensity in accordance with the scotopic luminosity curve. The cones, on the other hand, are susceptible of only slight alterations in adaptation; they are colour-sensitive, and react with an intensity which varies according to the photopic luminosity curve, being relatively more excitable to the rays of long wave-length than the cones.

The absence of rods in the foveal region led von Helmholtz to consider the cones the light-sensitive elements of the retina, and he thought that it was improbable that the rods were also sensitive to light. Later he adopted the view of H. Müller and Kölliker that they were also sensitive, but played a different *rôle* from the cones. Max Schultze, in 1866, propounded the hypothesis that the rods subserve impressions of simple light without discrimination of colours, and that the cones are the organ of colour perception. The chief arguments in favour of Schultze's theory were the diminution of colour sensation towards the periphery correlated with the increase in the number of rods, and comparative anatomical observations. The latter, the absence of cones in night animals and the absence of rods in day animals, are now known to be faulty; complete absence occurs in neither case. The difference consists less in number than in the length of the rods and the amount of visual purple they contain. The independent researches of Parinaud and von Kries have done most to support, extend and modify Max Schultze's theory. Apart from the obvious arguments deduced from foveal vision and the absence of rods in this region, and so on, the strongest argument in favour of the theory is probably the fact that the visual purple is limited to the rods and that the curve of chemical sensitiveness of this substance coincides with the scotopic luminosity curve.

The existence of four "invariable" colours strongly supports the Hering theory of colour vision, and many of the phenomena described above find an easy explanation on that theory. The phenomenon least easy to explain by it is the difference between the scotopic and the peripheral luminosity curves.

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A Clinical Lecture

ON

THE DIAGNOSTIC VALUE OF THE VISUAL ACUITY

Delivered at the Royal London (Moorfields) Ophthalmic Hospital on November 20, 1907

BY

J. HERBERT PARSONS, D.Sc. Lond.,
F.R.C.S. Eng.

ASSISTANT SURGEON TO THE HOSPITAL; ASSISTANT OPHTHALMIC SURGEON, UNIVERSITY COLLEGE HOSPITAL.

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A Clinical Lecture

ON

THE DIAGNOSTIC VALUE OF THE VISUAL ACUITY.

GENTLEMEN,—I propose to speak to-day upon the diagnostic value of accurate records of the visual acuity, laying particular stress upon those diseases in which ambiguity is likely to arise. I shall not consider defects of visual acuity due to errors of refraction, though it is scarcely necessary to emphasise their importance and their elimination in the process of investigation. I have elsewhere [1] discussed this aspect of the subject in part. Nor shall I treat of defects of central vision due to the more easily recognised forms of disease, such as opacities in the lens, &c. I shall concern myself chiefly with the following groups of cases: (1) those in which central visual acuity is normal or approximately normal, whilst ophthalmoscopic investigation reveals serious changes in the fundus oculi; (2) those in which central visual acuity is depressed, whilst ophthalmoscopic investigation reveals no abnormality in the fundus; and (3) those in which central visual acuity and the fundus are both normal, whilst there are yet serious disease and impairment of vision.

Before entering upon the examination of these groups of cases I wish to emphasise the importance of systematic orderly investigation of visual acuity in all cases. The distant vision should first be taken, then the presence or absence of manifest hypermetropia, then the near vision; finally, the pupil reactions should be examined and all the results carefully recorded. It may seem waste of time to

[1] The Visual Efficiency of the Uncorrected Myope, THE LANCET, Feb. 2nd, 1907, p. 286.

state these elementary facts, but experience unfortunately proves that this is not the case. Students fail to realise what an immense amount of valuable information is derived from this systematic examination and how much time is wasted by neglecting it. One repeatedly sees cases in which the distant vision has been taken and the accommodation promptly paralysed by atropine or homatropine. Further investigation may, perhaps, show that the pupil reactions are of fundamental importance as a factor in the diagnosis. Since they have not already been recorded a further visit of the patient becomes essential, much to his annoyance and possibly detriment. The neglect to test the near vision may in similar circumstances entirely frustrate accurate diagnosis, as, for example, in a case of post-diphtheritic paralysis of accommodation.

It is a truism to say that if the visual capacity is not normal it is the surgeon's duty to find out the reason of the defect. The second and third groups of cases will illustrate some of the difficulties which are met with in this attempt. What is more often forgotten is that even when the visual acuity is normal the fundus should in all cases be examined by the ophthalmoscope, not perfunctorily, but accurately and thoroughly. Take a presbyope, for example, whose vision is readily corrected by the ordinary rules and appears to be quite satisfactory. It is often tedious to examine every such case in the out-patient department with the ophthalmoscope, but if it is not done systematically mistakes will certainly be made. That this is an undeniable fact is shown by the cases belonging to the first group to which we may now turn our attention.

Headache is one of the commonest symptoms which come under the notice of the physician. The origin of the complaint is often obscure, but physicians are now aware that headaches are frequently due to errors of refraction or muscle balance. Consequently they freely avail themselves of the ophthalmic department and it must be admitted that some of the cases have not been very carefully investigated before they are passed on to the ophthalmic surgeon. That fact, however, does not relieve the surgeon of responsibility. Such cases as the following occur. A patient is sent complaining of headache. There has been no trouble with vision, but careful questioning may elicit the information that there has recently been transient mistiness from time to time. Examination of the visual acuity may show that it is normal both for distance and near. Ophthalmoscopic examination may reveal a choked disc in each eye. Perfect central vision therefore is not inconsistent with the occurrence of choked discs associated with grave intracranial disease. It follows clearly that every case of headache sent for investigation of the refraction should be thoroughly investigated with the ophthalmoscope.

In most cases of papillitis other than those due to intracranial pressure central visual acuity is early depressed, so that the risk of missing the disease is less likely, and this is particularly the case when there is also extensive retinitis. In albuminuric neuro-retinitis, for example, the macular region is quickly if not simultaneously involved with the optic nerve head and failure of central vision may be the symptom which leads the patient to consult an ophthalmic surgeon. As is well known the visual defect may be the first sign of sufficient prominence to excite apprehension, though the nephritis is already far advanced.

Another disease in which central vision may remain intact for a very long period is retinitis pigmentosa. This disease, which is congenital in origin, has often a notoriously prolonged course. During its progress central vision may be normal until the almost inevitable posterior cortical cataract makes its appearance. It is true that there are serious defects in the field of vision, usually of the nature of a ring scotoma, which broadens out in each direction until there is simply extreme contraction of the field. The field may be contracted down to close to the fixation point yet central vision may remain normal. In this condition there is no likelihood of the visual defect passing unnoticed, for such patients have the greatest difficulty in getting about. They see only the thing actually looked at, so that they grope about wildly amongst surrounding objects which normal people appreciate by means of their peripheral vision. A similar field, or rather absence of field, is not infrequently obtained in hysterical patients but their behaviour in walking about at once reveals the fallacy of the subjective test, and it must never be forgotten that perimetric observations are purely subjective tests, but that is another story.

In early cases of primary optic atrophy central vision may be intact, and these are liable to be overlooked unless the fundus is carefully examined and the field investigated; the latter will usually show definite uniform contraction. Allied to these cases and dependent upon a similar cause are the early cases of primary glaucoma. The tension may be quite normal at the time of examination, the fundus may be normal, or there may be arterial pulsation or even deep excavation of the disc ; the field will usually show contraction on the nasal side. The history of the disease, the condition of the other eye, and as a last resource investigation of the central field by Bjerrum's method, may serve to distinguish between these two types of early atrophy.

The diseases in which the central visual acuity is depressed in spite of the absence of refractive error or its correction and in spite of the absence of gross disease, whether in the fundus or other parts of the eye, belong for the most part to two groups—viz., those which are commonly gathered together under the general heading "retrobulbar neuritis" and those in which there is disease of the higher visual nervous centres or tracts. Owing to the similarity in the clinical symptoms and signs the toxic amblyopias, of which alcohol and tobacco amblyopia is the form most frequently seen, are usually included in the class of retrobulbar neuritis. The pathogenesis of the various forms of toxic amblyopia is obscure, but anatomical evidence and experimental investigation tend to show that it is diverse in different forms. Thus alcohol and tobacco amblyopia is probably due to primary degeneration of the ganglion cells of the retina. On account of the greater vulnerability of the cells of the macular region the papillo-macular bundle of nerve fibres first succumbs, thus causing symptoms which are indistinguishable from those caused by primary destruction of the papillo-macular fibres themselves behind the globe, as in true retrobulbar neuritis. Quinine amblyopia, on the other hand, is primarily due to disorder of the vascular system manifesting itself locally in the eye by extreme passive constriction of the retinal blood-vessels with consequent anæmia and consecutive degeneration in the retinal. Hence in this form general amaurosis or extreme contraction of the field of vision ushers in partial or complete optic atrophy and there is no resemblance clinically to retrobulbar neuritis. You have had the opportunity of seeing recently in my clinic a case of poisoning by extract of filix mas. The patient, a young man, took a drachm of the extract three times a day for ten days. The result was a toxic amblyopia showing some resemblance both to quinine amblyopia and to the optic atrophy of lead poisoning. One eye showed finally normal central vision with slight constriction of the field and temporal pallor of the disc, whilst the other showed complete blindness with total optic atrophy. Some of you may also have seen a case of toxic amblyopia in a patient suffering from diabetes who was a non-smoker; the clinical picture nearly resembled that of tobacco amblyopia.

For examples of true retrobulbar neuritis I need only refer you to the admirable clinical lecture delivered here eight years ago by Mr. E. Nettleship and published in the Hospital Reports. The feature which stands out most prominently in these cases is the greater vulnerability of the papillo-macular fibres, which explains the obscuration of the central portion of the field of vision, as shown by the development of a relative or even absolute central scotoma. The field of vision, however, is usually one of the last subjects which receives attention in the clinical investigation of a case. Ophthalmoscopic examination may show no abnormality in the fundus or it may show doubtful increased pallor in the temporal portion of the disc, slight blurring of the edges of the disc, or rarely pronounced papillitis; in the later stages partial or complete optic atrophy may be present. In the slighter cases there is one objective sign which outweighs the many subjective symptoms which are so often ambiguous and open to doubt. The retro-ocular affection not only interposes a partial block to the transmission of afferent visual impulses but acts in the same manner upon the afferent pupillary impulses. Hence, careful examination of the reaction of the pupil to light will show that although the pupil contracts more or less normally the contraction is not maintained under the continued incidence of the light. Instead of remaining constricted the pupil slowly dilates, though the light is still directed upon the retina. It would appear that the preliminary stimulus of light suffices to establish an impulse which overcomes the block upon the afferent pupillary system but that the succeeding stimuli, being of less intensity, fail to create sufficiently powerful impulses to sustain the reaction. One could scarcely adduce a stronger example of the necessity for careful and methodical examination of the pupil reactions at an early stage of the investigation of a case (*vide supra*).

These remarks on the pupil reaction of retrobulbar neuritis lead one naturally next to refer to those cases of retrobulbar affection occurring in disseminated sclerosis. This disease, unlike tabes, rarely appears first in the ophthalmic clinic, yet when one realises that it is often extremely difficult to diagnose between it and functional disorder and that about half the cases of disseminated sclerosis have ocular symptoms its importance to the ophthalmic surgeon will be readily appreciated. The partial blockage of afferent tracts which has been exemplified in the pupillary reaction is characteristic of multiple sclerosis. Sir William Gowers, with his usual acumen, has laid stress upon the defective "insulation" which occurs in this disease. Anatomical investigation strikingly bears out the point. Whereas in tabetic atrophy the primary lesion is probably situated in the ganglion cells of the retina, resulting in rapid degeneration of the optic nerve fibres with relatively slow and incomplete degeneration of the medullary sheaths, in multiple sclerosis the sheaths degenerate rapidly and completely whilst the axis-cylinders may show little or no change. Upon this fact depends the relatively good prognosis for vision in the latter disease.

The group of diseases with good central vision and no fundus changes dependent upon disease of the higher visual tracts or centres differs clinically from the retrobulbar cases in the persistence of normal pupil reactions. Blockage of the visual impulses in the optic radiations or destruction of the cortex of the occipital lobe—i.e., any lesion of the visual tracts above the external geniculate body, superior colliculus, and pulvinar of the optic thalamus—will produce the characteristic visual defects. Central vision escapes except in the very rare bilateral lesions on account of the bilateral representation of the fovea in the occipital lobes. The pupillary reactions are normal owing to the escape of the whole of the pupillary reflex arcs. Help in diagnosis here is obtained from the hemianopic pupillary reaction of Wernicke, which is characteristic of blockage of one optic tract. The visual lesion is usually a homonymous hemianopia. It is true that some of these cases may show changes in the fundus. Such are those due to intracranial tumour involving the occipital lobes or pressing upon the higher visual tracts, when the presence of choked discs may be anticipated. The amaurosis of uræmia is probably due to an unknown toxic product of metabolism acting upon the higher visual centres, since in most of these cases the pupil reactions are intact, as has been specially pointed out by Schmidt-Rimpler.

The subject of this discourse might easily have been further elaborated, but sufficient has been said to emphasise the importance of systematic examination and careful attention to detail in the examination of the visual acuity and of the pupil reactions.

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NIGHT BLINDNESS.[1]

BY J. HERBERT PARSONS, D.SC. LOND, F.R.C.S. ENG.,

ASSISTANT SURGEON TO THE HOSPITAL; ASSISTANT OPHTHALMIC SURGEON TO UNIVERSITY COLLEGE HOSPITAL; OPHTHALMIC SURGEON TO THE HOSPITAL FOR SICK CHILDREN, GREAT ORMOND-STREET, LONDON, W.C.

WHEN a patient comes to us complaining of inability to see in the dusk or in foggy weather we at once think of the disease commonly known as retinitis pigmentosa. If we were practising in India we should be much more familiar with patients complaining of this symptom and should be less likely to attach the same importance to it. There have recently been several excellent examples of retinitis pigmentosa in my clinic and you have had the opportunity of making yourselves fully acquainted with its peculiarities. It is only necessary for me, therefore, to review very briefly its principal features. The routine examination of the patient shows that there is comparatively little disturbance of central vision, though there are exceptions to this rule. Examination of the fundus shows in the early stages in young patients a zone of characteristic retinal pigmentation in the neighbourhood of the equator; both peripheral and central to this zone the retina looks almost or quite normal. I need not dwell upon the striking characters of the pigmentation—the spots shaped like bone corpuscles and the aggregations along the perivascular sheaths of the retinal vessels. At this stage we may expect to find a ring scotoma on examination of the field of vision. My senior clinical assistant, Mr. M. L. Hepburn, has recently devoted much attention to the nature of this scotoma and has shown amongst other points that it is seldom complete, but is dotted over with

[1] From a clinical lecture delivered at the Royal London (Moorfields) Ophthalmic Hospital on Feb. 1st, 1908.

areas in which vision is only partially lost. Probably these areas are closely related to the distribution of the vessels, but for an exhaustive discussion of the subject I must refer you to Mr. Hepburn's admirable paper in the last number of the Hospital Reports. At a later stage the zone of pigmentation has extended both peripherally and centrally, and the field now shows uniform contraction, the peripheral area of vision having become abolished. The progress is usually very slow and central vision is seldom lost by the extension of the choroido-retinal disease to the macular area. Before this occurs a posterior cortical opacity appears in the lens, which, however, has much the same effect upon the visual acuity. This so-called idiopathic retinitis pigmentosa is a progressive form of chronic night blindness. It is an obscure disease in which heredity and the consanguinity of parents play some considerable part. In reality the chorio-capillaris of the choroid seems to be first attacked, the retinal degeneration being secondary. As you are aware the outer layers of the retina are nourished by the chorio-capillaris and in retinitis pigmentosa the inner layers show comparatively little change. These facts help us to a reasonable conjecture as to the exact causation of the night blindness.

You will remember that in birds which seek their prey at night, such as the owl, the retina contains only rods; there are no cones in the neuro-epithelial layer. You will also remember that the visual purple is associated with the rods only, so that in animals possessing a fovea, where the rods are absent, there the visual purple is also absent. I may further remind you that with low illumination in man there is much more rapid depreciation of central than of peripheral vision, so that we may reasonably conclude that vision in these circumstances is chiefly carried out through the agency of the rods. Form sense, dependent upon the cones, quickly diminishes in passing from the point of fixation towards the periphery, but at night acute appreciation of variations of light and shade is much more important than accurate delineation of objects. These considerations may afford some explanation of the night blindness in retinitis pigmentosa, as well as of the partial nature of the annular scotoma and the comparative perfection of central vision. Of course, it is not suggested that the cones escape destruction in the affected zonular area, but their loss is discounted by their relatively unimportant functions in this situation.

There is another chronic form of night blindness which we occasionally meet with, differing from retinitis pigmentosa in the fact that it is stationary. This form is always hereditary and shows no gross changes in the fundus. It is a rare disease except in the families afflicted with it, when as has been recently shown in a very striking manner a large proportion of the members are attacked. Thus Mr. E. Nettleship has continued the work of Cunier on a certain family in the south of France and has discovered no less than 135 subjects of congenital night blindness amongst 2121 members of 10 generations, the first member of which, a male, himself night blind, was born in 1637. Unfortunately, no case of this disease has been examined anatomically ; it may possibly be found that the retina is deficient in rods or visual purple.

A group of cases of chronic night blindness in some respects intermediate between idiopathic retinitis pigmentosa and congenital night blindness is that of syphilitic pigmentary retinitis. It does not show the same uniformity either of symptoms or of objective signs that are characteristic of idiopathic retinitis pigmentosa. The night blindness is progressive during the active stage of the disease but may then remain stationary for an indefinite period. Fundamentally, however, the night blindness must be regarded as due to the same pathological proces-es. Besides these chronic forms of disease manifesting this symptom there are also acute forms. Though these show a great variety of clinical types there is nearly always one feature common to all—namely, malnutrition. They are probably much less frequently seen in England now than formerly owing to the improvement in the conditions of the poor. We generally meet with them in badly nourished children and a large proportion of them have xerosis of the conjunctiva. The combination of these symptoms is not so invariable as is sometimes thought. Many cases of xerosis without night blindness and *vice versâ* occur. In some cases the cornea becomes ulcerated and in the worst there is keratomalacia ; in many of these the age of the patient or the severity of the attendant symptoms prevents the demonstration of night blindness. One fact which may be definitely deduced is that there is no inherent relationship between the xerosis and the night blindness other than a common cause.

Acute night blindness was at one time common among sailors, soldiers, and the inmates of prisons and workhouses. In Russia it was, and probably still is, common during the Lenten fast. Uhthoff, amongst 500 cases of severe alcoholism, found 5 per cent. suffering from xerosis, night blindness, or both together. Less frequently night blindness has been found associated with scurvy, malaria, nephritis, the puerperium, vegetarianism, and so on. Most of these patients have reflex blepharospasm ("photophobia") in bright sunlight. That in many, most likely all, the lesion is peripheral is shown by Mr. Nettleship's interesting observation that if a sailor afflicted with the disease covers up one eye during the daytime that eye has sufficiently good vision at night for the man to carry out the duties of the watch. It would appear, therefore, that malnutrition acts by lowering the vitality of the retina in such a manner that the process of repair is delayed. Probably the visual purple is restored more slowly than normal—that is, the anabolic processes are defective. To call the condition torpor retinæ and to regard this as an explanation is futile; it is simply describing the condition by another name.

Another group of cases of night blindness, allied to those last mentioned but deserving separate treatment, are those associated with jaundice. The symptom is not very uncommon in severe cases of jaundice. In some pigmentary changes of slight degree have been found in the retina and the condition has been dignified with the name ophthalmia hepatica: in most the ophthalmoscopic signs are negative. It is noteworthy in this connexion to recall the fact that bile salts are a solvent of the visual purple, as was shown by Kühne. Night blindness is common in India among badly-nourished natives, especially during the periodic famines. It has been found that the symptom disappears when the patients are fed on liver, a fact difficult to correlate with the cases occurring with jaundice. The mode of treatment is of extreme antiquity, being advocated in the Ebers papyrus (B.C. 1500).