It was also observed in this research that the amount of electrical variation produced by light of various intensities corresponded pretty closely to the results expressed by Fechner's law, which regulates the relation between the stimulus and the sensational effect in sensory impressions. This law is, that the sensational effect does not increase proportionally to the stimulus, but as the logarithm of the stimulus. Thus, supposing the stimulus to be 10, 100, or 1000 times increased, the sensational effect will not be 10, 100, or 1000 times, but only 1, 2, and 3 times greater. This law, then, applies to the phenomena happening in the terminal organ, and not, as generally supposed, exclusively to those occurring in the brain.

Such electrical phenomena probably result either from thermal or chemical changes in the retina. Recent researches of Boll and Kühne have shown that light produces chemical changes in the retina. If an animal be killed in the dark, and if its retina be exposed only to *yellow* rays, the retina has a peculiar purple colour, which is at once destroyed by exposure to ordinary light. The purple matter apparently is decomposed by light. Kühne has also shown that an image may actually be *fixed* on the retina by plunging it into a solution of alum immediately after death. Thus it would appear that light affects the purple-matter of the retina, and the result of this chemical change is to stimulate the optic filaments; if the action be arrested, we may have a picture on the retina, but if it be not arrested, the picture is evanescent; the purple-matter is used up, and new matter of a similar kind is formed to take its place. The retina might, therefore, be compared to a sensitive plate having the sensitive matter quickly removed and replaced by chemical changes; and it is probable that the electrical expression of these changes is what has been above described.

(*a*) *Phosgenes.*—Luminous impressions may also be produced by pressure on the eyeball. Such impressions, termed *phosgenes*, usually appear as a luminous centre surrounded by coloured or dark rings. Sometimes they seem to be small bright scintillations of various forms. Similar appearances may be observed at the moments of opening or of closing a strong electrical current transmitted through the eyeball.

(*b*) *The Retina's Proper Light.*—The visual field, even when the eyelids are closed in a dark room, is not absolutely dark. There is a sensation of faint luminosity which may at one moment be brighter than at another. This is often termed the *proper light of the retina*, and it indicates a certain condition of molecular activity, even in darkness.

(*c*) *The Excitability of the Retina.*—The retina is not equally excitable in all its parts. At the entrance of the optic nerve, as was shown by Mariotte in 1668, there is no sensibility to light. Hence, this part of the retina is called the *blind spot*. If we shut the left eye, fix the right eye on the cross seen in fig. 15, and move the book towards and away from the eye, a position will be found when the round spot disappears, that is when its image falls on the entrance of the optic nerve. There is also complete insensibility to colours at that spot. The diameter of the optic papilla is about 1·8 mm., giving an angle of 6 degrees; this angle determines the apparent size of the blind spot in the visual field, and it is sufficiently large to cause a human figure to disappear at a distance of two metres (Beaunis).

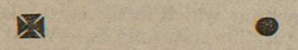

FIG. 15.—Diagram for the study of the *Blind Spot*.

The *yellow spot* in the centre of the retina is the most sensitive to light, and it is chiefly employed in direct vision. Thus, if we fix the eye on a word in the centre of this line, it is distinctly and sharply seen, but the words towards each end of the line are vague. If we wish to see each word distinctly, we "run the eye" along the line,—that is, we bring each successive word on the yellow spot. This spot has a horizontal diameter of 2 mm., and a vertical diameter of ·8 mm.; and it corresponds in the visual field to an angle of from 2 to 4 degrees. It is believed that the fossa in the spot, where there are almost no retinal elements except Jacob's membrane, consisting here entirely of cones (2000 in number), is the area of most acute sensibility. This fossa has a diameter of only ·2 mm., which makes the angle ten times smaller. Thus the field of distinct vision is extremely limited, and at the same moment we see only a very small portion of the visual field. Images of external objects are brought successively on this minute sensitive area, and the different sensations seem to be fused together, so that we are conscious of the object as a whole.

Towards the anterior margin of the retina sensitiveness to light becomes diminished; but the diminution is not uniform, and it varies in different persons.

(*d*) *Duration and Persistence of Retinal Impressions.*—To excite the retina, a feeble stimulus must act for a certain time; when the retina is excited, the impression lasts after the cessation of the stimulus; but if the stimulus be strong, it may be of very short duration. Thus the duration of an electrical spark is extremely short, but the impression on the retina is so powerful, and remains so long, as to make the spark visible. If we rotate a disc having white and black sectors we see continuous dark bands. Even if we paint on the face of the disc a single large round red *spot*, and rotate rapidly, a continuous red *band* may be observed. Here the impressions of red on the same area of retina succeed each other so rapidly that before one disappears another is superadded, the result being a fusion of the successive impressions into one continuous sensation. This phenomenon is called the *persistence of retinal impressions*. It has been ascertained that an impression lasts on the retina from $\frac{1}{50}$ to $\frac{1}{30}$ of a second. If we look steadily at a bright light for a few seconds and then quickly close the eyes or gaze into a dark room, a luminous image of the light will be visible for a short time. Such an appearance is called a *positive accidental image*, or a consecutive image. It may also be observed in this experiment that the intensity of the retinal excitation is not uniform. It increases quickly at its commencement, and after it has reached a maximum it slowly declines. Many familiar toys, such as the thaumatrope, or wheel of life, stroboscopic discs, and the phenakistoscope, produce curious effects due to persistence of retinal impressions.

(*e*) *The Phenomena of Irradiation.*—If we look at fig. 16, the white square in the black field appears to be larger than the black square in the white field, although both are of precisely the same size. This is due to *irradiation*, a phenomenon explained by Helmholtz, by stating that the borders of clear surfaces advance in the visual field and encroach on obscure surfaces. Probably, even with the most exact accommodation, diffusion images form round the image of a white surface on a black ground, forming a kind of penumbra, thus causing it to appear larger than it really is.

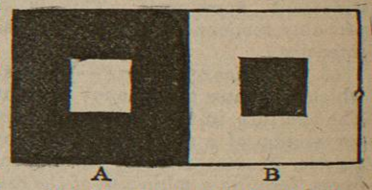

FIG. 16.—Illustrating the effect of irradiation.

(*f*) *Intensity of Light required to excite the Retina.*—Light must have a certain intensity to produce a luminous impression. It is impossible to fix the minimum intensit necessary, as the effect will depend, not only on the intensity of the stimulus, but on the degree of retinal excitability at the time. Thus, after the retina has been for some time in the dark, its excitability is increased; on the other hand, it is much diminished by fatigue. Aubert has stated that the minimum intensity is about 300 times less than that of the full moon. The sensibility of the eye to light is measured by *photometers*, instruments which will be described under the article LIGHT.

(*g*) *Consecutive Retinal Images.*—Images which persist on the retina are either positive or negative. They are termed *positive* when the bright and obscure parts of the image are the same as the bright and obscure parts of the object; and *negative*, when the bright parts of the object are dark in the image, and *vice versa*. Positive images are strong and sharply marked when an intense light has acted for not less than $\frac{1}{3}$ of a second. If the excitation be continued much longer, a negative and not a positive image will be seen. If, when the positive image is still visible, we look on a very brilliantly illuminated surface, a negative image appears. Negative images are seen with greatest intensity after a strong light has acted for a considerable time. These phenomena may be best studied when the retina is very excitable, as in the morning after a sound sleep. On awakening, if we look steadily *for an instant* at the window and then close the eyes, a *positive* image of the window will appear; if we then gaze fixedly at the window for one or two minutes, close the eyes two or three times, and then look at a dark part of the room, a *negative* image will be seen floating before us. The positive image is due to excitation of the retina, and the negative to fatigue. If we fatigue a small area of the retina with white light, and then allow a less intense light to fall on it, the fatigued area responds feebly, and consequently the object, such as the window pane, appears to be dark. Many curious experiments may be made to illustrate the laws of consecutive images. Thus, if we look at a black figure on a white ground for, say, one minute, and then gaze into a dark part of the room, a gigantic *white* figure, of corresponding shape, may make its appearance. A white figure on a black ground will produce a black image, a green figure will produce a red, and a red a green,—the reproduced colour being always complementary to that of the figure.

4. SENSATIONS OF COLOUR.

(1.) *General Statement.*—Colour is a special sensation excited by the action on the retina of rays of light of a definite wave length. Thus we have a sensation of red when a certain number of waves of light impinge on the retina in a unit of time, and with about twice the number of waves in the same time the sensation will not be of red but of violet. When we examine a spectrum, we see a series of colours merging by insensible gradations the one into the other, thus:—red, orange, yellow, green, blue, and violet. These are termed *simple* colours. If two or more coloured rays of the spectrum act simultaneously on the same spot of the retina, they may give rise to sensations of *mixed colours*. These mixed colours are of two kinds:—(1) those which do not correspond to any colour in the spectrum, such as purple and white, and (2) those which do exist in the spectrum. White may be produced by a mixture of two simple colours, which are then said to be *complementary*. Thus, red and greenish-blue, orange and cyanic-blue, yellow and indigo-blue, and greenish-yellow and violet all produce white. Purple is produced by a mixture of red and violet, or red and bluish-violet. When white light falls on a surface, the surface may absorb all the rays except the red. If the red rays are alone reflected, then the object will be red; if the green rays are reflected, then the object will appear to be green. Again, if we look through red glass, all the rays are absorbed except red, and consequently the world beyond appears to be red. So with regard to the other transparent coloured media. The following table by Helmholtz shows the compound colours produced by mixing other colours:—

	Violet	Indigo-blue	Cyanic-blue	Greenish-blue	Green	Yellowish-green	Yellow
Red	Purple	Deep-rose	White-rose	*White*	Whitish yellow	Golden yellow	Orange
Orange	Deep-rose	White rose	*White*	Whitish-yellow	Yellow	Yellow	
Yellow	White rose	*White*	Whitish-green	Whitish-green	Yellowish-green		
Yellowish-green	*White*	Green	Green	Green			
Green	Blue	Water-blue	Greenish-blue				
Greenish-blue	Water-blue	Water-blue					
Cyanic blue	Indigo-blue						

This table shows that if we mix two simple colours, not so far separated in the spectrum as the complementary colours, the mixed colour contains more white as the interval between the colours employed is greater, and that if we mix two colours further distant in the spectrum than the complementary colours, the mixture is whiter as the interval is smaller. By mixing more than two simple colours, no new colours are produced, but only different *shades* of colour.

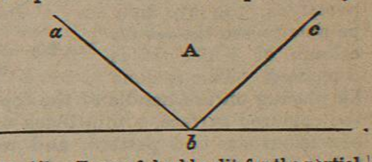

FIG. 17.—Form of double slit for the partial superposition of two spectra.

(2.) *Modes of Mixing Colour-Sensations.*—Various methods have been adopted for studying the effect of mixing colours.

(*a*) *By Superposing two Spectra* (Helmholtz and Clerk Maxwell).—This may be done in a simple way by having a slit in the form of the letter V (see fig. 17), of which the two portions *a b* and *b c* form a right angle; behind this slit is placed a vertical prism, and two spectra are obtained, as seen in fig. 18, in which *b f e a* is the spectrum of the slit *a b*, and *c e f d* that of the slit *b c*; the coloured spectra are contained in the triangle *g e f*, and, by arrangement, the effects of mixture of any two simple colours may be observed.

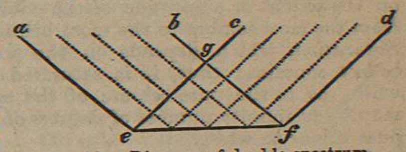

FIG. 18.—Diagram of double spectrum partially superposed.

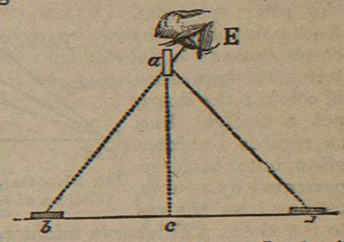

FIG. 19.—Diagram showing Lambert's method of mixing sensations of colour.

(*b*) *By Lambert's Method of Reflection.*—Place a red wafer on *b*, in fig. 19, and a blue wafer on *d*, and so angle a small glass plate *a* as to transmit to the eye a reflection of the blue wafer on *d* in the same line as the rays transmitted from the red wafer on *b*. The sensation will be that of purple; and by using wafers of different colours, many experiments may thus be performed.

(*c*) *By the Use of Rotating Discs which quickly superpose on the same Area of Retina different Impressions of Colour.*—Such discs may be constructed of cardboard, on which coloured sectors are painted, as shown in fig. 20, representing diagrammatically the arrangement of Sir Isaac

Newton. The angles of the sectors were thus given by him:—

Red	60° 45·5′	Green	60° 45·5′
Orange	34° 10·5′	Blue	54° 41′
Yellow	54° 41′	Indigo	34° 10·5′
Violet	60° 45·5′		

With sectors of such a size, *white* will be produced on rotating the disc rapidly. This method has been carried out with great efficiency by the colour-top of Clerk Maxwell. It is simply a flat top, on the surface of which discs of various colours may be placed. Dancer has added to it a method by which, even while the top is rotating rapidly, and the sensation of a mixed colour is strongly perceived, the eye may be able to see the *simple* colours of which it is composed. This is done by placing on the handle of the top, a short distance above the coloured surface, a thin black disc, perforated by holes of various size and pattern, and weighted a little on one side. This disc vibrates to and fro rapidly, and breaks the continuity of the colour-impression; and thus the constituent colours are readily seen.

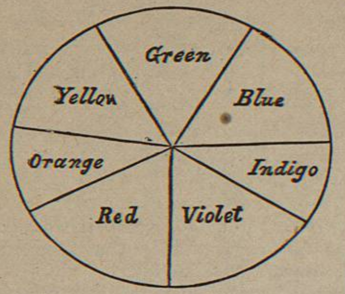

FIG. 20.—Diagram of the Colour Disc of Sir Isaac Newton.

(3.) *Physiological Characters of Colours.*—All colours have three special characters:—(1) *Tone*, depending on the number of vibrations per second; (2) *Intensity*, depending on the extent or amplitude of the vibrations, and passing from the most sombre to the most brilliant shades; and (3) *Saturation*, which depends on the amount of *white* the colour contains; thus, it is saturated when there is no white, as in the pure colours of the spectrum, and there may be an infinite number of degrees of saturation from the pure colour to white.

(4.) *The Geometric Representation of Colours.*—Colours may be arranged in a linear series, as in the solar spectrum. Each point of the line corresponds to a determinate impression of colour; the line is not a straight line, as regards luminous effect, but is better represented by a curve, passing from the red to the violet. This curve might be represented as a circle in the circumference of which the various colours might be placed, in which case the complementary colours would be at the extremities of the same diameter. Newton arranged the colours in the form of a triangle, as shown in fig. 21. If we place three of the spectral colours at three angles, thus,—green, violet, and red,—the sides of the triangle include the intermediate colours of the spectrum, except purple.

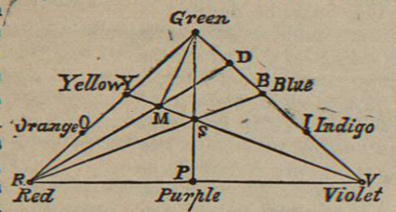

FIG. 21.—Geometrical representation of the relations of colours as shown by Newton.

The point S corresponds to white, consequently, from the intersection of the lines which join the complementary colours, the straight lines from green to S, R S, and V S, represent the amount of green, red, and violet necessary to form white; the same holds good for the complementary colours; for example, for blue and red, the line S B = the amount of blue, and the line S R = the amount of red required to form white. Again, any point, say M, on the surface of the triangle, will represent a mixed colour, the composition of which may be obtained by mixing the three fundamental colours in the proportions represented by the length of the lines M to green, M V, and M R. But the line V M passes on to the yellow Y; we may then replace the red and green by the yellow, in the proportion of the length of the line M Y, and mix it with violet in the proportion of S V. The same colour would also be formed by mixing the amount M Y of yellow with M S of white, or by the amount R M of red with the amount M D of greenish blue.

(5.) *The Theory of Colour-Perception.*—The theory generally accepted was first proposed by Thomas Young and afterwards revived by Helmholtz. It is based on the assumption that three kinds of nerve fibres exist in the retina, the excitation of which give respectively sensations of red, green, and violet. These may be regarded as fundamental sensations. Homogeneous light excites all three, but with different intensities according to the length of the wave. Thus long waves will excite most strongly fibres sensitive to red, medium waves those sensitive to green, and short waves those sensitive to violet. Fig. 22 shows graphically the irritability of the three sets of fibres. Helmholtz thus applies the theory:—

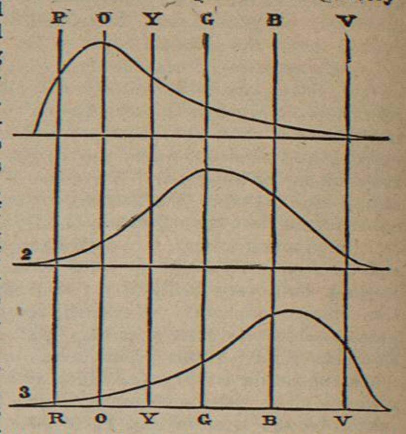

FIG. 22.—Diagram showing the irritability of the three kinds of retinal elements.
1. Red; 2. Green; 3. Violet. R, O, Y, G, B, V, initial letters of colours

"1. Red excites strongly the fibres sensitive to red and feebly the other two—sensation: *Red.*
2. Yellow excites moderately the fibres sensitive to red and green, feebly the violet—sensation: *Yellow.*
3. Green excites strongly the green, feebly the other two—sensation: *Green.*
4. Blue excites moderately the fibres sensitive to green and violet, and feebly the red—sensation: *Blue.*
5. Violet excites strongly the fibres sensitive to violet, and feebly the other two—sensation: *Violet.*
6. When the excitation is nearly equal for the three kinds of fibres, then the sensation is *White.*"

This theory explains some of the phenomena of what is called *colour blindness* or *Daltonism.* All individuals appear to have some kind of colour-sensation; in some, however, there may be no sensation for particular colours. The most common defect is insensibility to *red* (Daltonism properly so called). The spectrum to such an eye is deficient in red, and the sensation corresponding to all compound colours containing red is that of the complementary colour only. Thus, white is bluish-green, and intense red appears green, so that red poppies in a green cornfield do not appear of a different hue from the green by which they are surrounded. If we suppose in such cases an absence or paralysis of the red-fibres, the phenomena are accounted for. Blindness to green and violet is rare.

Young's theory also explains the appearance of the consecutive coloured images already referred to.

Suppose, for example, that we look at a red object for a considerable time; the retinal elements sensitive to red become fatigued. Then (1) if the eye be kept in *darkness*, the fibres affected by red being fatigued do not act so as to give a sensation of red; those of green and of violet have been less excited, and this excitation is sufficient to give the sensation of pale greenish blue; (2) if the eye be fixed on a *white* surface, the red fibres, being fatigued, are not excited by the red rays contained in the white light; on the contrary, the green and violet fibres are strongly excited, and the consequence is that we have an intense complementary image; (3) if we look at a *bluish-green* surface, the complementary of red, the effect will be to excite still more strongly the green and violet fibres, and consequently to have a still more intense complementary image; (4) if we regard a *red* surface, the primitive colour, the red fibres are little affected in consequence of being fatigued, the green and violet fibres will be only feebly excited, and therefore only a very feeble complementary image will be seen; and, (5) if we look at a surface of a *different* colour altogether, this colour may combine with that of the consecutive image, and produce a mixed colour; thus, on a yellow surface, we will see an image of an orange colour.

(6.) *The Contrast of Colours.*—If we look at a small white, grey, or black object on a coloured ground, the object appears to have the colour complementary to the ground. Thus a circle of grey paper on a *red* ground appears to be of a greenish-blue colour, whilst on a blue ground it will appear pink. This effect is heightened if we place over the paper a thin sheet of tissue paper; but it disappears at once if we place a black ring or border round the grey paper. Again, if we place two complementary colours side by side, both appear to be increased in intensity. Various theories have been advanced to explain these facts. Helmholtz is of opinion that the phenomena consist more in modifications in judgment than in modifications of sensation; Plateau, on the other hand, attempts to explain them by the theory of consecutive images.

5. THE MOVEMENTS OF THE EYE.

(1.) *General Statement.*—The globe of the eye has a *centre of rotation*, which is not exactly in the centre of the optic axis, but a little behind it. On this centre it may move round *axes of rotation*, of which there are three,—an antero-posterior, a vertical, and a transverse. In normal vision, the two eyes are always placed in such a manner as to be fixed on one point, called the *fixed point* or the *point of regard.* A line passing from the centre of rotation to the point of regard is called the *line of regard.* The two lines of regard form an angle at the point of regard, and the base is formed by a line passing from the one centre of rotation to the other. A plane passing through both lines of regard is called the *plane of regard.* With these definitions, we can now describe the movements of the eyeball, which are of three kinds. (1) *First position.*—The head is erect, and the line of regard is directed towards the distant horizon. (2) *Second position.*—This indicates all the movements round the transverse and horizontal axes. When the eye rotates round the first, the line of regard is displaced above or below, and makes with a line indicating its former position an angle termed by Helmholtz the angle of vertical displacement, or the *ascensional angle;* and when it rotates round the vertical axis, the line of regard is displaced from side to side, forming with the median plane of the eye an angle called the *angle of lateral displacement.* (3) *Third order of positions.*—This includes all those which the globe may assume in performing a rotatory movement along with lateral or vertical displacements. This movement of rotation is measured by the angle which the plane of regard makes with the transverse plane, an angle termed the *angle of rotation* or of *torsion.*

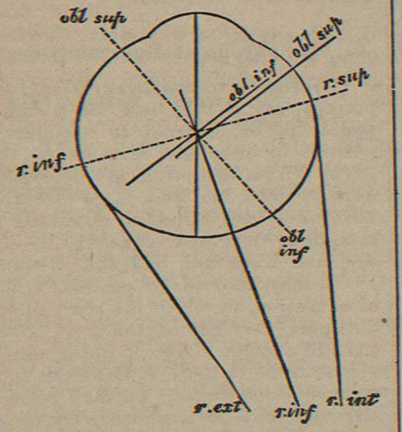

FIG. 23.—Diagram of the attachments of the muscles of the eye and of their axes of rotation, the latter being shown by dotted lines. (Fick.)

The axis of rotation of the rectus internus and externus being vertical, that is, perpendicular to the plane of the paper, cannot be shown.

The two eyes move together as a system, so that we direct the two lines of regard to the same point in space.

The eyeball is moved by six muscles, which are described in the article ANATOMY, vol. i., p. 891. The relative attachments and the axes of rotation are shown in fig. 23. The following table, given by Beaunis, summarizes their action:—

Number of Muscles in activity.	Direction of Line of Regard.	Muscles acting.
One	Inwards	Internal rectus.
	Outwards	External rectus.
Two	Upwards	Superior rectus. Inferior oblique.
	Downwards	Inferior rectus. Superior oblique.
Three	Inwards and upwards	Internal rectus. Superior rectus. Inferior oblique.
	Inwards and downwards	Internal rectus. Inferior rectus. Superior oblique.
	Outwards and upwards	External rectus. Superior rectus. Inferior oblique.
	Outwards and downwards	External rectus. Inferior rectus. Superior oblique.

The term *visual field* is given to the area intercepted by the extreme visual lines which pass through the centre of the pupil, the amount of dilatation of which determines its size. It follows the movements of the eye, and is displaced with it. Each point in the visual field has a corresponding point on the retina, but the portion, as already explained, which secures our attention is that falling on the yellow spot.

(2.) *Simple Vision with Two Eyes.*—When we look at an object with both eyes, having the optic axes parallel, its image falls upon the two yellow spots, and it is seen as one object. If, however, we displace one eyeball by pressing it with the finger, then the image in the displaced eye does not fall on the yellow spot, and we see two objects, one of them being less distinct than the other. It is not necessary, however, in order to see a single object with two eyes that the two images fall on the two yellow spots; an object is always single if its image fall on *corresponding points* in the two eyes. Thus, in the experiment above described, after having seen two images by displacing one eyeball, we may be able again to see only one image by pressing on the other eyeball. There are then corresponding points in the two retinæ, so that if they were superposed the two yellow spots would coincide; the upper and lower parts of the left retina would touch the upper and lower parts of the right retina; the nasal side of the left retina would correspond to the temporal side of the right retina, and the reverse would also hold good. The relation of the two retinæ to each other in the field of vision may be illustrated by the diagram in fig. 24. When an image falls on non-corresponding points of the retina, it is seen double.

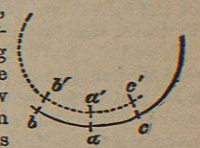

FIG. 24.—Diagram to illustrate the physiological relations of the two retinæ.

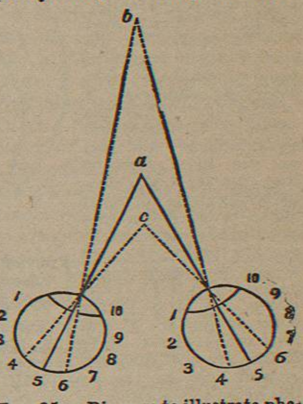

FIG. 25.—Diagram to illustrate phenomena of double vision. (Müller.)