III.—*On the Gradual Production of Luminous Impressions on the Eye : Part II.*
being a description of an Instrument for producing isolated luminous impres-
sions on the eye of extremely short duration, and for measuring their intensity.
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 versity of St Andrews.

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IN 1849 I presented to the Royal Society of Edinburgh a paper “On the Gradual Production of Luminous Impressions on the Eye.” The object of that communication was to investigate the laws of the production of visual impressions. The subject was then new; for although the fact that light requires a certain time to produce its full effect on the eye had been noticed at comparatively early periods, yet no one, so far as I am aware, had attempted to *measure* that time; and the whole subject of the production of visual impressions, regarded as a branch of experimental science, was quite untouched.* I have frequently wished to resume a subject of inquiry which seems to me to merit more attention than it has hitherto received, and which I have not as yet been able to discuss so completely as I could have desired. Various portions of it demand more extended experiments. Among these may be specified, the examination of isolated impressions of shorter duration than my limited instrumental means had enabled me to observe; a more careful determination of the time required for light to produce its complete effect on the eye; and a series of observations on the eyes of various individuals, so that any personal peculiarity of vision, which might affect results derived exclusively from experiments on my own eye, might be eliminated. These, and other subjects of inquiry, I hope sooner or later to overtake; and, indeed, I had anticipated before the end of the present session of the Society to have been able to obtain some experimental results. In this I have been disappointed, owing to the instruments required for my observations having taken a much longer time to make than I had expected.

The observations of impressions of very short duration is attended with much difficulty. The method of observation which I devised in 1848 is to cause a disc, with a sector cut out of it, to revolve with an uniform velocity between the eye and a luminous object. At each revolution a flash of light is perceived as the sector crosses the line of vision,—the time during which each flash acts on the eye depending on the angle of the sector and the velocity of rotation of the disc. The brightness of the resulting visual impression is ascertained by photome-

* See Moigno, “Repertoire d’Optique,” vol. ii., p. 563.

trical arrangements, which are fully described in my paper.* By such means I succeeded in measuring the brightness of luminous impressions caused by light acting on the eye for short intervals of time, varying from a tenth to a thousandth of a second.

There are obvious limits to the applicability of this method of experimenting when it is attempted to examine isolated impressions of excessively short duration. To shorten the impression, we may either diminish the angle of the sector or increase the velocity of the disc, but whichever of these methods we adopt, we very speedily arrive at limits which either cannot be overpassed at all, or can only be so at the cost of great inconvenience. The velocity of the disc is absolutely limited. If we attempt to drive it faster than about 10 revolutions per second, the successive flashes become blended into a single impression, more or less uniform; and as the eye no longer distinguishes them as separate, so we can no longer perceive, or measure, their separate intensities. Again, if we shorten the impressions by diminishing the angle of the sector, we quickly arrive at a practical limit from the smallness of the angle required, even with a disc of considerable diameter. This difficulty may be overcome in theory by increasing the diameter of the disc, while the sector is made of the smallest practicable angle; but a very large disc would obviously be an extremely inconvenient instrument to work with.

I have from time to time thought of various mechanical expedients, more or less feasible, for obviating this difficulty, but I have never been sufficiently satisfied with any of them to attempt their construction. Last autumn, however, I devised an arrangement so simple that I resolved to put it in practice. Suppose a disc with a sector cut in it to revolve between the eye and a light 100 times per second. The eye would in every second receive 100 impressions, and if the sector were $\frac{1}{1000}$ th of the circumference of the disc, each impression would be made in $\frac{1}{100000}$ th of a second; but, from the high velocity of rotation, the observer would be conscious only of an uniform light,—the aggregate of all the nearly instantaneous flashes blended into a single impression. The instrument which I have to describe has for its object to select a *single* impression out of the *hundred*, to convey it to the eye isolated and alone, and to measure its brightness; while the remaining 99 impressions which would have interfered with its effect are intercepted, and excluded from the field of view. From the disc revolving 100 times in a second, the eye will then receive, once a second, a single isolated impression, lasting for the extremely short period of $\frac{1}{100000}$ th of a second. This result admits of being obtained by the very simplest possible means; in fact, I have found it unnecessary to employ any mechanical agent whatever, other than the train of wheels by which motion is communicated to the disc.

* Edinburgh Transactions, vol. xvi., pp. 583–587.

The nature of this arrangement will be understood from fig. 1, Plate I., in which A, B, C, *a*, *b*, *c*, represent a train of toothed wheels and pinions driven by a weight suspended from a line, which is coiled round a drum on the axis of the wheel A, and by which motion is communicated to the disc D. The wheels B, C have each 120 teeth, and the pinions *b*, *c*, 12 teeth; so that if B revolve once in a second, C revolves 10 times, and D, 100 times in a second. Apertures I, K are cut in the wheels, which are otherwise *solid*, and the whole is so arranged, that the apertures I, K, the sector S, and the aperture T in a screen H illuminated by a light F, are in the same straight line; so that an observer at E can see the illuminated aperture I through the holes in the wheels and the sector in the disc. Since the wheels B, C, and disc D revolve respectively once, ten times, and a hundred times in a second, if the apertures are *in line* at the commencement of any one second, they will again come into line at the commencement of each successive second. Suppose the wheel B to be removed, the wheel C and disc D continuing to revolve. By the time the disc D has made a single revolution, the aperture K has moved round so far that when the sector S has returned to its original position, the wheel C intercepts the light; and it is obvious that K will not return to its proper position for transmitting light to the eye until the wheel C has made a complete revolution. The effect of the combination of the wheel C and disc D will therefore be to transmit to the eye a single impression at every revolution of C, or at the end of every $\frac{1}{10}$ th part of a second. Supposing, as before, that the sector D is $\frac{1}{1000}$ th of the circumference, the eye will receive only 10 impressions in a second, each of which has been made in $\frac{1}{100000}$ th part of a second. We may now dismiss the disc D from our consideration, and regard the wheel C as a disc revolving 10 times per second, and having an excessively narrow sector cut in it, occupying $\frac{1}{100000}$ th of its circumference. By repeating precisely the same reasoning for the wheels B and C as has been employed for the wheel C and disc D, it will be seen that the wheel B will transmit to the eye a single impression at each revolution, or once a second, derived from the wheel C. The wheel B will therefore transmit to the eye a single impression in a second, which has acted on the eye for $\frac{1}{100000}$ th of a second, and will thus be equivalent to a disc revolving once a second, and having a sector of only $\frac{1}{100000}$ th part of its circumference. It will be seen also, that as the smallest practicable angle for the sector is obviously the same, whatever be the size of the disc, the effect of the arrangement will be to make a disc of a foot in diameter equivalent in efficiency for observing *short* impressions to one of 100 feet in diameter.

It may, at first sight, be supposed that only a single *screen-wheel*, as it may be called, such as C or B, would be required. Such, however, is not the case. The wheel C alone would be insufficient; for when the disc D was driven with high velocities, C would revolve so fast that its transmitted impressions would

become blended by their persistence on the retina. The wheel B alone would likewise be insufficient, for the disc D revolves so fast compared with B that the sector S would have returned to its position for transmitting light before the hole I had time to get out of the line of vision.

It is obvious that the arrangement might be extended to any number of wheels, the only remaining practical difficulty being that of driving a train of toothed wheels at very high velocities. If this should render it impossible to observe impressions so short as may be desired, there are two methods which may be adopted. The disc itself may be driven directly by a reaction machine, or Barker's mill, the train of wheels then serving merely as *screens* and registers of the number of revolutions made by the disc. Impressions of very short duration might also be obtained by substituting for the disc a small revolving mirror, like Wheatstone's. The mirror attached, with its plane parallel to the axis on which it revolves, receives the light of a flame which has passed through a narrow slit parallel to the axis, and at a considerable distance from it. The light reflected by the mirror falls upon the surface, whose brightness is to be observed, and illuminates each portion of it for a short interval of time, depending on the width of the slit and the velocity of the mirror. Impressions of extremely short duration could thus be obtained, for a small mirror could be driven at a much higher velocity than a disc, which, from its considerable size, experiences great resistance from the air; and the narrow slit would become equivalent to a sector of corresponding width, cut in a very large disc, revolving with twice the angular velocity of the mirror, and having a radius equal to the distance of the slit from the axis of revolution.

I have designed an instrument on the principles now explained, which has been constructed for me by Messrs JAMES MILNE and SON of Edinburgh, and which is represented in fig. 2.

The instrument consists of a solid cast-iron frame A A, carrying a train of wheels B, C, D, E, by which the disc F is driven. Motion is communicated to the wheels by a weight suspended from a cord coiled round the barrel G. Each of these wheels B, C, D, E has 120 teeth; the pinion *b* has 30 teeth, and the remaining three pinions, of which only *d* and *e* are shown in the figure, have each 12 teeth. The wheels B, C, D and the disc F are each 6 inches, and E is 3 inches in diameter.

From the numbers of teeth in the wheels and pinions, it is obvious that for each revolution of the wheel D the wheel E makes 10, and the disc F 100 revolutions; and by means of a train of gas-meter index-wheels H K, to which motion is communicated by the wheel I on the axis of the wheel D,—I and H having the same number of teeth—the number of revolutions made by the disc F is readily ascertained. To facilitate counting the revolutions, the frame carrying the wheels H K turns on a pivot about half-way between H and K, and is pressed by a spring near H

against a stud in the frame A, so as to be kept in gear with the wheel I. A lever L turns an eccentric in contact, near K, with the frame carrying the wheels H, K; and, by moving the lever a little to the right or left, the train of gas-meter wheels is instantly put in or out of connexion with the wheel I. The gas-meter wheels having been adjusted by the hand until their indices read zero, they are put in gear with I, and allowed to remain so for a minute or other definite time. The number of revolutions of the disc F in a second will obviously be 6000 times the number of revolutions of the wheel H registered by the gas-meter train in a minute.

The disc F is an accurately turned plate of brass 0·1 inch in thickness, strengthened by a narrow flange round its circumference, rising 0·1 inch from its plane. An arm of brass M O turns on the axis *e*, independently of the disc. In the disc there is cut an aperture at *h f*, embracing 20° of the circumference; but the effective opening is formed by the knife edges *f g* of the moveable arm M O and *h i* of a fixed piece of brass N *h*. The edge *f g* is carefully filed to radiate from the centre of the disc, and N *h* is screwed to the disc, with its edge *h i* fitting accurately to *f g*, so that when the arm M O is moved away from the piece N *h*, the opening *f g h i* forms a portion of a sector of a circle. The piece M O has its surface in the same plane with the edge of the flange, and accurately fits its inner circumference. An arc of 40° is divided on the edge of the flange, and the arm M O carries a vernier reading minutes. It is obvious that the angle of the sector *f g h i* can be accurately ascertained by taking the difference of the vernier readings when the aperture *f g h i* is open and when it is closed. As the disc F revolves with very great velocity, it is essential, in order to avoid vibration, that it should be quite symmetrical about its axis. In order to effect this, a second aperture is made in the disc, and a piece of brass is attached to it, the same as the aperture and piece of brass at N *g*, and placed, respectively, 180° apart from them, but which are not shown in the figure. No light reaches the eye from this second aperture; for by the time the disc has made a half-revolution, the aperture *k*, which transmitted light from *f h*, has moved out of the line of vision. The second aperture, therefore, simply renders the disc symmetrical without affecting the optical action of the machine.

The apertures in the wheels D and E, through which the light, transmitted by the sector *f g h i*, reaches the eye, are represented at *k*, *m*, and *n*. The wheel E has two apertures, *k*, *l*, 180° degrees apart; and D has four apertures, 90° apart, of which only two are seen in the figure. The aperture *l*, as in the case of the disc, is made simply for the purpose of restoring the symmetry of the wheel E, which would be destroyed if the aperture *k* alone existed; and it will be seen that if the apertures *m*, *k*, and the sector *f h*, be adjusted so as to come together into the same straight line, and to allow light to pass through them to the eye, by the time the wheel E has made a half-revolution, so that the aperture *l* has

taken the place of k , the aperture m will have moved out of the line of vision, and thus no light can reach the eye through l . Of the four apertures in the wheel D we may employ one only, or two 180° apart, or all four, as may be found most convenient, according to the speed with which the train is driven, the apertures not in use being stopped by plugs of cork.

The photometrical arrangement for measuring the brightness of the luminous impressions transmitted by the revolving disc, and its train of wheels, may either be that described in my former paper on the formation of luminous impressions, or the following arrangements may be adopted :—

1st, Let C, D (fig. 3) represent screens having apertures covered with ground-glass, or glass rendered milky-white by arsenic or phosphate of lime, and A, B flames, by which the apertures C, D are illuminated. A piece of transparent parallel glass E is placed so that an observer at F views the aperture C by transmitted, and D by reflected light in apparent contact. The light A remains fixed, while B is moved, until the two apertures appear equally bright. The disc G is now made to revolve, when the aperture C, seen during successive short intervals of time, will appear less bright than before, and the light B must be withdrawn to a greater distance from the screen D, until the equality of the illumination is restored. If the lights emitted by the flames A, B remain constant, the ratio of the brightness of the impression of short duration, transmitted by the revolving disc to that of a complete impression on the eye, will be that of the squares of the distances of the light B from the screen D.

2dly, An arrangement which, from an imperfect trial I have made of it, promises to succeed well for comparing the brightness of the illuminated apertures, may be made by cementing together two equal and similar rectangular glass prisms A B C, B C D, so as to form a parallelopiped, by means of a small portion of Canada balsam, which, when the prisms are pressed together, expands into a circular thin film E. The illuminated apertures C', D' in the screens are placed opposite to the faces A C, C D, and the observer looks through the face B F. The light transmitted through A C, and falling on B C, will be totally reflected, except the portion which falls on the film of Canada balsam at E, which will be nearly all transmitted to the eye of the observer. The light which is transmitted through the face C D will be totally reflected to the eye by the face B C, except what falls on the Canada balsam at E, which will be nearly all transmitted. The spot E will appear of a different brightness from the rest of the surface B C, except when the light totally reflected by B C is equal in intensity to the sum of the lights transmitted and reflected at E. The spot E will then disappear, owing to the whole surface of B C, including the spot, becoming uniformly bright. Assuming that the light partially reflected at E has a constant ratio to that totally reflected by the rest of the surface B C, and to that transmitted by A C, it is obvious that the squares of the distances of the flame from the aperture D

when the spot E disappears will give the ratio of the intensities of the lights transmitted by the aperture C.

3dly, Adopting the arrangement in fig 3, we may compare the illumination of the screens by the following method :—Let the aperture D, whose light is reflected at E, be made larger than the aperture C, or let D be placed so that the distance D E F is considerably less than C E F. Then, by properly adjusting the position of the glass E, the aperture C will be seen projected on the reflected image of D. The distances of the lights A B may then be adjusted, so that the aperture C, seen *through* the reflected image of D, just disappears. The apparent brightness of C will then have a certain ratio to that of D, depending on the power of the observer's eye to discriminate between lights of different intensity : and, as before, the apparent brightnesses of C will be in the ratio of the squares of the distances of the flame B from the screen D when C disappears. From former experience I have found that it requires an almost painful effort of attention to compare the brightness of a surface illuminated by sudden flashes with that of another which is constantly illuminated. The method of observation now described seems to possess the great advantage of substituting mere watching for the disappearance of the flashes in the place of an estimation of equality of brightnesses.

4thly, We may observe the brightness of impressions of short duration by means of a single flame in the following manner :—The disc G transmits flashes from the flame A to the aperture C in a screen, filled with translucent glass. The observer at E looks at C along the edge of another similar piece of translucent glass D. Since illuminated surfaces appear equally bright at all distances and at all inclinations of the visual ray, the ratio of the brightnesses of the aperture at C when the disc revolves, and when it is stationary or removed, will be that of the squares of the distances of the glass D from the flame A, at which the observer estimates C and D as equally bright. By this method of observation, the effect of any want of constancy in the illuminating power of the flame A will be entirely eliminated.

Fig. 2

Fig. 1.

Fig. 3

Fig. 4.

Fig. 5