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METHODS OF RECORDING EYE MOVEMENTS

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THE first attempt to record eye movements systematically was made by Javal⁽¹⁸⁾ in 1878. He observed directly through a telescope the eyes of a subject while reading. The technique of direct observation was improved by Erdmann and Dodge⁽¹⁴⁾, who, in 1898, studied, through a telescope placed behind the subject, the mirror image of his eye movements while reading. Though able to determine the general character of eye movements in reading, and to find approximately the number of movements and fixation pauses, these observers found that the movements were too rapid for it to be possible to measure accurately their duration. Since then direct methods of observation have been used to measure the slower movements of convergence and divergence, and torsion, and also voluntary eye movements; these methods are described in group (c) below. But other methods have been employed for the recording and measurement of the rapid, irregular, jerky or *saccadic** movements of the eyes during normal reading.

These indirect methods may be divided into two groups:

(a) Those which depend upon photography of the eye, of the reflection of light from the apex of the cornea, or of some small object attached to the cornea.

(b) Those which depend upon the attachment of a capsule or recording lever to the cornea or eyelid, the movements of which

* From the French word *saccade* (jerk).

may be recorded by direct tracing on a drum, or else photographically.

(a) **Methods depending upon photography.**

(1) In 1902 G. M. Stratton⁽³¹⁾ recorded photographically the movements made by the eye in following out the lines forming a diagram. As may be seen in Fig. 1, the recording camera C was placed directly in front of the subject. Light from an arc lamp A was reflected by the mirror M_1 on to the subject's cornea, and thence back to the slit of the camera; direct light was kept from falling on the subject by means of the screen S. The diagram to be studied was placed behind the subject; it was tilted down-

FIG. 1.

wards, and reflected to the subject by the upward-tilted mirror M_2 placed just above the camera slit. The experiment took place in darkness. A sensitive plate was exposed in the camera until the eye had followed out all the lines of the diagram.

This method was, of course, only useful for recording the number and path of the eye movements; no measurement of duration was made. Horizontal movements were slightly distorted in the record.

Later⁽³²⁾, the diagram was placed directly in front of the subject, and the camera and arc lamp at an angle of 60° on either side of the line of sight. Camera and lamp could be freely interchanged. There was no distortion of horizontal movements in this position, but a slight distortion of vertical ones.

(2) This method was improved upon by Dodge and Cline⁽⁸⁾ in 1902, for measuring the angle velocity of horizontal eye movements in reading, and also for recording their path. A small piece of white cardboard, K (see Fig. 2), was illuminated by light from a window behind the subject; and the reflected image of K from the cornea, called the "bright spot," fell upon the horizontal slit of a recording camera C which could be moved round a perimeter

PP until focussed in the right position. The subject's head was fixated by means of a wooden chin-rest F; and he was instructed to look through a tube TT. The reading matter R was placed at

FIG. 2.

the centre of the circumference of the perimeter. But previously two knitting needles were stuck vertically into the perimeter at positions corresponding to the beginning and end of the lines of print. The subject was instructed to fixate first one and then the

FIG. 3.

other of these. A record of the reflection of K at these two standard positions of the eye was thus obtained, and subsequent movements could be referred to it.

The recording apparatus consisted of a sensitive plate carried on a framework V which fell vertically between brass grooves *gg* (see Figs. 2 and 3). To the base of the framework was attached the piston of an air pump R. The working of the pump caused

the framework to fall at a constant rate, which could be adjusted by means of suitable stoppages applied to the exit pipe. (In a later modification of this apparatus⁽⁹⁾ an oil pump was substituted for the air pump; the oil, as it was ejected from the bottom, was returned to the top of the barrel by means of a pipe. This arrangement gave smoother working). In order to obtain a time record an electrically controlled pendulum D swung in front of the horizontal slit S; thus at regular intervals of time the light was prevented from falling on the plate and a dark mark appeared on the record.

Dearborn⁽⁶⁾, working with a modification of this method, obtained much valuable information with relation to the reading process.

FIG. 4.

He used as his source of illumination an arc lamp, the rays of which were rendered parallel by intercepting lenses. He stated, however, that his experiments could be carried out as well in daylight as in a darkened room.

(3) J. Piltz⁽²⁹⁾ in 1904 used the photographic method for measuring the convergence and divergence of the pupil. He made his records upon a film rotated by clockwork about a vertical axis.

(4) E. B. Coburn⁽⁵⁾ in 1905 invented a method for recording both the horizontal and vertical components of the eye movements upon moving photographic plates (see Fig. 4). Light from a lamp L fell upon the corneae of both eyes, and was reflected and focussed by the two lenses PP to fall on the photographic plates mounted on two carriers C_1 and C_2 . These moved on smoothly-ground steel wheels along steel wires, C_1 horizontally and C_2 vertically. The wires were so inclined that the carriers did not interfere with one another. Their motion was produced by a clockwork motor M, and was quite regular; they were automatically stopped as soon as they had passed the focal points of the lenses.

In order to separate the records of the two eyes on the horizontally moving plate, two prisms were placed, in a vertical position, side by side at K, with the apex of one pointing upwards, and of the other downwards. Thus light from the left eye l was deflected upwards, and from the right eye r downwards on to the

plate at C_1 . Before records were made the corneal images were focussed by manipulation of the lenses on to ground-glass screens placed in the carriers. The screens were then removed and replaced by the photographic plates.

This method appears to be more useful for recording the number and path of eye movements, for instance in pathological cases, than in reading, since, presumably, only the movements in reading a few lines of print could be recorded on one plate. It is possible that the duration of the movements could be measured by using a suitable time marker.

(5) In 1905, Judd, McAllister, and Steele⁽¹⁹⁾ modified the method of Dodge and Cline by photographing the movements of a small flake of Chinese white paint, specially prepared, and attached to the cornea slightly below and on the nasal side of the pupil. They claimed that it was quite easily applied by holding the lower lid down, and then manipulating it to get the flake into the right position. If the flake was lost under the lid, it was dissolved and caused no harm; but once in position, it was not removed by ordinary winking. The movements of this white flake were said to represent more accurately the movements of the eye as a whole than the movements of the "bright spot," in the method of Dodge and Cline (but see ⁽¹⁰⁾ and ⁽¹¹⁾).

Direct or reflected sunlight, graduated by several thicknesses of blue glass to a comfortable intensity, was used as the source of illumination. The movements were recorded by means of a kymatographic camera driven, first by hand, later⁽²⁰⁾ by a motor. The film was drawn before the shutter of the camera in jerks, by means of a sprocket wheel the teeth of which fitted into the series of holes in the film. A semicircular rotating shutter moved between the lens of the camera and the film, and exposed to the light each section of the film as it came into place in front of the lens. A hard rubber wheel attached to the driving handle carried on its circumference a number of metal strips; during rotation they were brought into electric contact with two brass brushes, and the current thus made passed through a marker which traced on a kymograph. These contacts were synchronized with the film exposures; and the duration of the latter was measured by means of a time-marker also tracing on the kymograph. A double camera was afterwards constructed with two films; the exposure of one coincided with the closure of the other, and *vice versa*. Thus a continuous record was obtained. The camera was placed directly in front of the subject.

The head was fixed as far as possible by means of suitable head and teeth grips; but, as was found by other observers, head movements were not eliminated in this way. They were recorded by the reflection from small, brightly polished steel balls, or from

small concave mirrors, fastened to a wire spectacle frame. Later, a fixed point of reference independent of the head or the camera was always photographed; to this head movements could be related.

The determination of the path of the eye movements from the photographic record was an elaborate and lengthy process. For each section of the film separately the position of the eyes had to be referred to the points of reference on the spectacle frame, and their distance from them measured and recorded on a chart. This method was used extensively by these observers for measuring intra-fixation movements, movements made in viewing optical illusions, and movements of convergence and divergence. The

FIG. 5.

recording process, however, is too laborious for use without modification in connection with eye movements in reading.

(6) In 1907, Dodge⁽¹¹⁾ issued an account of a comparison of the accuracy of his method with that of Judd. Instead of a flake of white paint, however, he attached to the cornea a minute silver hemisphere mounted on a fragment of black tissue paper soaked in paraffin. As his source of illumination he substituted for daylight an alternating current arc lamp. This produced a series of discrete flashes, and hence obviated the use of Judd's kinematographic shutter, and also of a time signal, since the time of each exposure was known from the rate of alternation of the current. However, this rate did not remain altogether constant; a direct current lamp with a tuning-fork interrupter would probably be more accurate (see C. T. Gray's method).

The arrangement of the apparatus is shown in Fig. 5. Part of the beam from the lamp A was reflected from the side of the silver bead B to the camera C; the remainder was reflected from the partially silvered mirror M to the centre of the cornea, and then back to the camera. Thus a direct comparison of the records obtained by the two methods was possible. Dodge found that the movements of the bead were slightly larger in the record than those of the "bright spot," but they were more distorted, because the bead had of necessity to be placed to one side of the pupil that it might not impair vision. It was important, however, to ensure

that the light striking on the cornea and the light reflected from it should make equal angles with the sagittal plane; and that the "bright spot" should be confined to the central third of the cornea. In this work Dodge made use of a head and tooth rest similar to those used by Judd; and also of spectacles carrying small concave mirrors for recording head movements.

In recording vertical movements he employed Stratton's fixed plate method (this was, of course, possible with an alternating arc lamp in a darkened room).

(7) Another modification of Dodge's method was made by E. Koch⁽²¹⁾ in 1908, for measuring the angle velocity of voluntary eye movements. Light from a Nernst lamp N (see Fig. 6) was reflected from the cornea through tubes TT, after having been

FIG. 6.

focussed by lenses LL, to a camera C, with shutter H, containing a film O which could be drawn vertically upwards by means of a kymograph between grooves *gg*. Light passing through a slit S was reflected by a totally reflecting prism K, fixed in an aperture of the tube, on to the film; a pendulum P, screened from the subject, swung in front of the slit, thus giving a time record on the film. The subject's head was fixated by means of a tooth rest. Two fixation marks were reflected to him by the small mirror M; he was required to sweep his eyes from one to the other. To record vertical eye movements, the camera was laid on its side, and the film moved horizontally.

(8) Another variant of this method was designed by O. Weiss⁽³⁶⁾ in 1911 for recording the blinking and rolling movements of the eyes and eyelids. In this case the eyes and lids were themselves photographed. The film was drawn from a roller B on to a roller A passing behind a slit S in a screen through which the image of the eye was focussed by means of a lens L (see Fig. 7). In front of the slit rotated a disc D in which were two openings in the shape of sectors. When one of these sectors coincided with the slit the movement of the film was stopped by one of the rollers R, moving about on axis C, which pressed against it. The movement of these

rollers was automatically synchronized with the rotation of the disc. Thus a series of sharp, almost instantaneous, photographs was obtained.

(9) The movements of the eye in reading were recorded in a similar way by C. T. Gray⁽¹⁶⁾ in 1917, and G. T. Buswell⁽⁴⁾ in 1920. A beam of light generated from a 400-watt. nitrogen-filled bulb,

FIG. 7.

which gave a constant illumination, was rendered parallel by a double convex lens and reflected by two silvered glass mirrors on to the cornea, and thence to a camera containing a vertically moving film. The beam was interrupted by an electrically driven tuning-fork, vibrating at a rate of 50 or 25 per second; so that the film recorded the movements and fixation pauses of the eyes in a series of dots, each representing a duration of $1/50$ th or $1/25$ th

FIG. 8.

of a second. The camera was placed immediately in front of the subject; and the reading matter was projected, by means of a lantern and mirror, on to a plaster-of-Paris surface placed above the camera. Before beginning to read, the subject fixated successively two spots above the first and last letters of the line of print. These acted as points of reference on the record.

(10) In 1921, Dodge⁽¹²⁾ invented a method of studying the compensatory movements of the eyes when the lids were closed. This method could also, however, be used for unocular reading. He devised a species of spectacle frame (see Figs 8 and 9) of thin tubular steel with an adjustable hard rubber nose-piece N and two ear-pieces TT which could slide in and out of

the tubular supports SS to give correct adjustment. HH were hard rubber blocks which could be fixed by screws C_1 , C_1 , to fit closely to the subject's temples. Two arms LL could also slide in and out and be fixed by screws C_2 , C_2 . These arms bore adjustable blocks of hard rubber BB to which were attached small cone bearings that carried light steel arms AA. These arms were forked at their further ends; and small concave mirrors

FIG. 9.

M_1 , M_2 swivelled about vertical axes, made of steel needles, which were carried by the forks.

This framework could be so adjusted to the subject's head that the mirrors M_1 and M_2 rested upon the closed eyelids, and were rotated by the rotation of the apices of the corneae beneath. If it was desired to record the movements of one eye only while the subject read with the other, one of the mirrors could be removed. Without careful calibration, however, it would be difficult to determine the exact relationship between the eye movements and the movements of the beam of light recorded by the camera.

In order to record head movements a small mirror M_3 was attached to the nose-piece N, and adjusted so that the reflected beam from it also fell on the recording apparatus. But in 1923 Dodge⁽¹³⁾ invented a method by means of which the effects of head movements were almost entirely eliminated. (Dodge gives no diagram of his apparatus; for the sake of clearness I have, however, attempted to construct one (Fig. 9) from his description*).

* His description is far from lucid; I hope I have understood and reproduced it correctly.

A Dodge-Cline falling plate camera C was fastened to a rigid support above the subject's head so that the vertical axis of rotation of the head passed through the centre of the horizontal slit F. A projection P, also coinciding with this axis, worked in a socket K attached to the top of the subject's head by means of a broad elastic band. By this means the head movements were confined to rotations about the vertical axis. The source of illumination, A, a 100-watt, nitrogen-filled incandescent lamp with horseshoe filament, was situated just above and in front of the camera slit. A light framework was supported by two rods R_1 and R_2 , one of which was gripped between the subject's teeth, and the other secured to a point just above the camera slit, so that it could

FIG. 10.

rotate in a horizontal plane about the vertical axis of rotation of the head. This framework carried two plane mirrors M_4 and M_5 ; the beam from the arc lamp was directed to M_4 , reflected to the mirrors M_1 and M_2 , back to M_4 and M_5 , and thence to the camera slit, as shown in Fig. 9. Now, since the mirrors M_4 and M_5 could rotate with the rotation of the head, the beam of light would also rotate with the head, and the eye movements be recorded relatively to the movements of the head, *i.e.*, the effects of these movements upon the record would to all intents and purposes be eliminated. It was found that a record taken by reflection from the head mirror M_3 was virtually a straight line; showing that the desired results had been attained.

(11) A further modification of C. T. Gray's method was made by Miles and Shen⁽²⁵⁾ in 1925, in their work on recording the eye movements in the reading of Chinese. Light was supplied by a carbon arc lamp A (see Fig. 10) in front of which rotated a toothed wheel W at the rate of one revolution in five seconds; thus illumination took place in a series of discrete flashes of known duration, through the gaps between the teeth of the wheel. (One gap was stopped up; thus every five seconds there was a longer period of darkness, which made measurement from the record more easy). The beam of light then passed through a double lens LL, to render the rays parallel; its intensity

was suitably reduced by a blue glass screen and cooling cell G, and marginal light was cut off by a diaphragm D. The beam was then reflected obliquely on to the centre of the subject's cornea by two small mirrors M_1 and M_2 , and thence to the recording camera C. The mirrors were slightly to one side of the subject, and therefore did not interfere with his view of the reading matter R in front of him. The latter was illuminated by means of an ordinary reading lamp to the left of and behind the subject. The print was covered by a piece of paper upon which were fixation marks corresponding to the beginning and end of the lines; this cover was secured by a rubber band which, when pulled towards himself by the subject with the string S, allowed the cover to fall and expose the print.

A long-barrelled camera projecting towards the subject was used for recording. A paper roll upon which were pasted strips of film 60 inches long and $2\frac{1}{2}$ inches wide was drawn vertically across the slit of the camera by a revolving drum which had special adjustments for starting and stopping it rapidly and altering its speed. The film could be moved horizontally for vertical eye movements.

The subject read with binocular vision; but only movements of the right eye were recorded. The head was fixated by means of an adjustable head and tooth rest; and head movements were recorded by reflection from a metal bead fastened to a spectacle-frame worn by the subject.

(b) Methods requiring the attachment of a capsule or recording lever to the eyes

(1) Lamare,⁽²²⁾ following up the work of Javal, attempted to measure eye movements by causing the movement of the lid to break the circuit of an electric current and give rise to sounds through a microphone, which he counted. He was unable, however, to obtain accurate results in this way.

(2) Ahrens⁽¹⁾ in 1891 attempted to record eye movements by attaching to the cornea a light ivory cup, to the apex of which was fastened a bristle that traced on a smoked drum. This method was not very successful either.

(3) In 1898, however, Delabarre⁽⁷⁾ adapted this method. He made a plaster cast of an artificial eye, and trimmed it to the shape of the subject's cornea. The eyelids were propped open with a special framework, the cornea anaesthetized with cocaine, and the plaster cast fitted over it. A hole had been drilled in the centre of the cast through which the subject could see. A piece of wire was embedded in the plaster with one end projecting; this was connected by a thread to a lever tracing on a smoked drum. Delabarre also

used a cast with a small mirror embedded in it, reflecting light to a recording camera.

He did not experiment himself with this method. But in the same year E. B. Huey⁽¹⁷⁾ made use of virtually the same method. The plaster cast was connected by a light tubular lever of celloidin and glass to a light thin aluminium pointer tracing on a smoked drum. A "spark" time recorder was used; an electric current from an induction coil, interrupted at regular intervals by a tuning-fork, passed through the pointer, and at each interruption the spark caused a spot of soot to fly off the drum. Huey claimed that no harm was done to the eye by this method provided that due precautions were observed; and that an accurate record of eye movements was obtained by it. He acknowledged, however, that the eye felt strained for some time after the plaster cast had been removed.

(4) In 1899 a further modification was invented by J. Orchansky⁽²⁸⁾. He used a capsule made of glass or light metal. Above and below the central aperture for the pupil were flaps on which the eyelids could rest; and to one side was a slot in which could be inserted a fine rod tracing on a rotating drum, or another short rod bearing a vertical mirror parallel to the sagittal plane. Orchansky does not appear to have done much experimental work using this method.

(5) The method remained in abeyance till 1911, when Marx and Trendelenburg⁽²⁴⁾ employed it, using a very light aluminium capsule, of the same curvature as the cornea, adjusting it to the right size by pressing it on a suitable brass hemisphere. At the edge of the capsule was a lateral flap which fitted to the sclera when the capsule was applied to the cocainized cornea. The capsule had a central opening for the pupil, and a small mirror fixed just to one side of it. For horizontal eye movements the image of a vertical slit illuminated by an arc lamp was focussed on the mirror by means of a convex lens, and reflected from thence through a horizontal slit on a clockwork kymograph covered with bromide paper. The fixation mark was a small black point on a piece of paper fastened to an adjustable framework. The subject could move this framework until his eye, when fixating the mark, also reflected the image of the illuminated slit on to the slit of the camera. For recording vertical movements a horizontal illuminated slit and a vertical camera slit were used.

Head movements were recorded by the reflection of the illuminated slit by a mirror fixed with a spring clip to the bridge of the nose. The head was fixated as far as possible by means of a head rest with forehead band, side clamps and tooth rest.

This method gave a delicate and accurate method of recording the minute tremors of the eye during voluntary fixations. An

angle of eye movement of $1'$ gave a displacement of approximately 1 mm. on the record. The observers did not allow a fixation to last for more than half-a-minute; it is not certain if the capsule would have remained in place for any length of time, or if it would have been displaced by the flow of tears. Thus it is doubtful if this method could be used for recording eye movements in reading.

FIG. 11.

(6) A simple piece of apparatus was described by A. Schackwitz⁽³⁰⁾ in 1913, which was used to measure the number and duration of eye movements in reading, but would be of doubtful accuracy in recording their extent. It consisted essentially of a small distended rubber capsule R (see Fig. 11) mounted on an adjustable spectacle frame in such a manner that it rested on the upper eyelid. It was connected by means of a thin brass tube T_1 , and a rubber tube T_2 , either to a Marey tambour or to a Marbe

FIG. 12.

flame. The latter is an acetylene gas flame, also connected to a gas reservoir; when the capsule is compressed, the gas is driven out faster, and the increased flame forms a smoke ring on a strip of paper drawn through it by means of a rotating kymograph.

It is, of course, inevitable by this method that lid movements and eye movements should sometimes be confused. It is just possible that the capsule might be made to lie on the cornea without damaging it or obstructing the eye movements, so that this inaccuracy would be removed.

(7) For registering eye movements and lid movements J. Ohm⁽²⁶⁾ in 1916 made use of quite a different piece of apparatus, which is shown in Fig. 12. A light lever A B C swivelled about a point O;

one end C could pass freely through a slot N. This end was either fixed to the eyelid by means of court plaster; or a little stick of glass with a round head was fastened to it, and rested against the side of the cocainized cornea. The movements, greatly magnified, were recorded by the pointer on a kymograph. It is doubtful if this method would provide a very accurate or delicate method of recording eye movements in reading.

(8) J. L. Struycken⁽³³⁾ in 1918 is reported⁽³⁴⁾ to have photographed a minute sphere mounted on three legs attached by hooks to the cornea. A total reflection prism in front of the lens separated the beam of light and permitted the simultaneous recording of the vertical and horizontal components of the eye movement.

(c) Methods of direct observation

(1) Direct observation of the torsional movements of the eyes was made by B. Barnes⁽³⁾ in 1905 and by M. Loring⁽²³⁾ in 1915, by very similar methods. The subject was asked to fixate the eyepiece of a telescope mounted facing him on a horizontal perimeter;

FIG. 13.

the cross wires of the telescope were then focussed on one of the striae of the iris. The telescope was then rotated to another position, the subject's eyes following the objective. The cross wires were again set on the same stria, and the angle of rotation of the eye-piece of the telescope gave the angle of torsion of the eye.

(2) A more delicate modification of this method was designed by Dr. Barany and described in 1911⁽²⁾; his apparatus is shown in Fig. 13. The eye was illuminated by a lamp L while fixating a point P, and observed by means of a telescope T the cross wires

of which could be rotated, and the angle measured on the vernier scale V_1 . The subject's head was fixed to the telescope-stand by means of a mouth-piece M , and a screw fitting into a forehead band at F . The stand could be adjusted in three planes by the screws S_1 , S_2 , and S_3 , and could be rotated about a horizontal axis parallel to the subject's line of regard by a screw S_4 , the angle of rotation being measured on the vernier scale V_2 . Also, by rotating the mouth-piece M , the subject's head could be rotated about its vertical axis. One of the striae of the iris was fixated on the cross wires of the telescope; the head was rotated in the desired direction, and the cross wires again fixated by rotating the vernier scale V_1 .

(3) H. Ohrwäll⁽²⁷⁾ in 1912 and C. G. Sündberg⁽³⁵⁾ in 1917 observed both intra- and inter-fixation movements by means of a Blix's ophthalmometer. The image of the illuminated diaphragm of one of the microscopes of the ophthalmometer was reflected from the cornea to the other microscope, the eye-piece of which was fitted with a micrometer scale. The position of one of the striae of the iris, or of one of the blood-vessels of the conjunctiva, was noted on the micrometer scale; movements of this point were then measured directly on the scale. The voluntary movements of the eye from one fixation point to another could thus be observed and measured.

(4) In 1923, George, Toren and Lowell⁽¹⁵⁾ measured the movements of the vertex of the cornea by the method of direct observation. The eye was fixated upon a needle fixed in the illuminated diaphragm at the further end of a tube. This tube could be swivelled around a horizontal arc, and could be adjusted in the vertical and in both horizontal planes; it was always placed so that it pointed towards the vertex of the cornea. The cornea was observed through a microscope adjusted to be at right angles to the tube when the latter was in its central position. The micrometer scale of the microscope was focussed upon the vertex of the cornea; and movements of the latter could be measured on the scale as the eye followed the rotating tube from one position to another. This method was used chiefly to demonstrate the horizontal movements of the cornea parallel to the sagittal plane.

Discussion of methods

Several points emerge from the foregoing description of methods of recording eye movements.

In the first place, with regard to photographic methods, nearly all investigators have used artificial light as their source of illumination. Dodge began by using daylight; but found an arc

lamp more convenient, because it was possible to obtain intermittent illumination with it. Judd, McAllister, and Steele made use of daylight, and employed an intermittent recording apparatus. It was pointed out, however, that measurement of the number, distance, and duration of eye movements from these records was very laborious. Those observers whose methods were devised primarily for the reading process, *i.e.*, Dearborn, Dodge, C. T. Gray, and Miles and Shen, have all used discontinuous artificial illumination; and it is because it is difficult to regulate and to render discontinuous that daylight is not very satisfactory for this purpose. The series of white dots forming a continuous line on a dark background is probably the most convenient and easily interpreted form of record to obtain. The duration of the movements or pauses is calculated by counting the dots. It has been found advisable to calibrate the direction of the movements by including in the record a few voluntary movements, the direction of which is controlled by providing suitable beginning and end fixation points. It may be pointed out that the use of an artificial source of illumination has not necessitated that the experiment should take place in a completely darkened room; Dearborn and C. T. Gray found that they were able to carry on their experiments in the daylight. If, however, daylight was not desired, the reading matter was illuminated by means of a suitably placed lamp, as in the method of Miles and Shen.

It should be noted that a great improvement was effected by Dodge in eliminating the effects of head movements, which apparently it is impossible entirely to prevent. It might be possible to substitute for the Dodge-Cline falling plate camera a moving film camera which would record more conveniently and accurately.

The advantages of the methods in which some capsule or recording lever is attached to the eye over those of photography of the "bright spot" are that they require less elaborate and expensive apparatus. A device such as that of Schackwitz or Ohm can be cheaply and easily fitted up. Their disadvantages are:

- (1) They may cause some permanent injury to the eye.
- (2) The anaesthetization of the eye, especially if cocaine* is used, and the weight of the capsule or lever resting on the eye may interfere with the natural movements of the eye, rendering them slower and of longer duration.
- (3) On the mechanical side, these methods, with the possible exception of that of Marx and Trendelenburg, are of doubtful accuracy.

*Holocaine is said to interfere less with the normal movements of the eye.

It is very improbable that anything more than the approximate number and the general character of the fixation pauses and eye movements in reading can be observed directly, even through a telescope. The pauses last on the average only about 0.2 seconds and the movements 0.04 seconds each. Possibly very unusually long pauses and regressive movements might be noted in this way, even if they could not be measured.

In conclusion, then, it appears that the photographic method, as used by Dodge, C. T. Gray, and Miles and Shen, has proved the most completely satisfactory, though it is probably difficult to manipulate, and requires expensive apparatus. The rubber capsule used by Schackwitz, or the method of direct observation through a telescope, has been of use for preliminary or less detailed work.

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The source of the figures is given in the text and references.

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THE MOVEMENTS OF THE EYES IN READING

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It was thought, at one time that in reading the eyes move backwards and forwards smoothly and continuously, and perception of the words takes place during the movement. One is not conscious during reading of anything but a smooth and regular motion of the eyes. But in 1878, and the following years, Javal⁽¹⁶⁾ and others working with him observed the movements of a subject's eye while he was reading, and found that this was not the case. Movement takes place in a series of jerks, with a pause after each movement during which the eyes are relatively at rest. Only during the backward sweep of the eyes from the end of one line to the beginning of the next is movement smooth and regular. It was observed that the short jerky, or saccadic, forward movements are very rapid; and that the durations of the pauses during which the eyes are fixated upon the print are much greater. The number and duration of the pauses vary considerably for different subjects and different types of reading matter.

Erdmann and Dodge⁽⁷⁾ in 1898 and Huey⁽¹⁴⁾ in 1900 made a number of observations on eye movements and fixation pauses, and a more extensive research was made by Dearborn⁽⁴⁾ and published in 1906. At a later period C. T. Gray,⁽⁹⁾ W. A. Schmidt⁽²³⁾, and G. T. Buswell^(2, 3) made similar determinations. The results of these and of other observers are summarized in Tables I and III.