THE ANGLE VELOCITY OF EYE MOVEMENTS.

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Until recently the question of the angle velocity of the eye, as the point of regard moves over the field of vision, was a very minor problem of merely physiological interest. So far as the authors can discover, only two experimental answers were published previous to the year 1898. These differed widely in their numerical values and were regarded at best as rather curious but insignificant fragments of knowledge. The problem first assumed psychological importance when it was pointed out by Erdmann and Dodge that the movements of the eye in reading and writing are rhythmically broken by periods of rest which constitute the moments of significant stimulation.

Out of this advance in the physiology of vision has developed a constantly growing group of psychological questions which only a quantitative knowledge of the eye movements can answer. For any adequate analysis of the complex processes involved in reading it became necessary not only to know the number of the alternating periods of movement and rest, but their time values as well. The explanation of the general failure to apprehend the periods of eye movement either as breaks in visual perception or as a fusion of the field of vision demands an accurate knowledge of their duration. Moreover, the problems of the visual perception of motion, binocular coördination, and fatigue of the eye muscles, all presuppose a knowledge of the eye movements which at present is conspicuously lacking.

In view of all this the present paper would present first of all an exact method of recording the movements of the eyes, and secondly, a group of what we may justly claim to be the first accurate measurements of the angle velocity of the eye movements under normal conditions.

Method and Apparatus.

When the problem of the velocity of the eye movements first assumed psychological importance two methods had already been proposed for its measurement. Of these the method of Volkmann[1] was manifestly inaccurate. He reckoned the time of one movement of the eyes by dividing the total time during which the eyes moved rapidly back and forth between two fixation points, by the number of movements. This would obviously include not only the time of movement, but the interval of rest as well.

The other method was devised by Lamansky[1] under the direction of Helmholtz. While it gave results only in large units of measurement, it was unquestionably the better of the methods available, and as modified by Dodge gave more nearly accurate results than had hitherto been obtained. The method in brief was as follows: As the eye moved through a given arc a pencil of light was flashed into it at regular intervals. The number of flashes seen during the movement would be in direct ratio to the time of movement. Besides the error involved in the large unit of measurement, the method showed several other sources of error. Since the flashes appeared elongated in direct proportion to the velocity of the eye, flashes which fused in consequence of the slower movement at the beginning or end of an excursion would give no clue to the number of their constituent elements. Moreover, the experimentation was necessarily limited to monocular vision in a darkened room after adaptation and consequent rest, while it was apparently possible to materially reduce the velocity of movement under slightly modified conditions of the attention. All these facts rendered it doubtful if the results could be applied to the eye movements of normal vision, without correction. Our results show that the defects of the Lamansky method were not over-

[1] Wagner's 'Handwörterbuch,' III., 1, 1846, pp. 275 ff.

[2] 'Ueber die Winkelgeschwindigkeit der Blickbewegung,' *Pflüger's Archiv*, 1869, II., pp. 418 ff.

estimated, while they justify in the main the corrected values used by Erdmann and Dodge[1] in their analysis of the reading processes.

A material advance was made in the technique of the problem when Huey[2] attached a delicate recording apparatus to a Delabarre eye cup and obtained kymographic records demonstrating the number and general character of the eye movements with great distinctness. The measurements of the eye movements during reading, which were obtained from these records, were more satisfactory than any measurements by the earlier methods. However, as was pointed out in the notice of Huey's work in the REVIEW, they could not be regarded as final. In moving the long pointer at short leverage the eye muscles do no inconsiderable amount of extra work. That this should materially delay the eye and fatigue it was *a priori* very probable. A further source of error in the record was the overshoot occurring in the record at the end of every long movement. The method left it quite undetermined what part of the overshoot, if any, belonged to the movement and what part was conditioned by the momentum of the pointer.

The experimental requirements of a satisfactory apparatus for recording the eye movements may be summed up as follows: (1) It must be capable of operating under normal conditions of binocular vision. (2) It must be capable of registering both eyes simultaneously. (3) The unit of measurement must be 1σ or less. (4) The registering medium may have neither momentum nor inertia, while the eye must perform no extra work during registration and be subjected to no unusual conditions. (5) The apparatus should be such as can be used to record the movements of a large number of eyes, without serious inconvenience either during or after the experiments.

None of the methods already used satisfy all these requirements or even the larger part of them. It is indeed doubtful if any attachment to the eye could be devised which would be satisfactory. But the qualities which are demanded of the re-

[1] 'Psychologische Untersuchungen über das Lesen,' pp. 66-67 and 357-360

[2] 'On the Psychology and Physiology of Reading,' *American Journal of Psychology*, Vol. XI., 1900.

cording medium are possessed in an eminent degree by light rays, and a method of registration satisfying all the above mentioned requisites is possible with comparatively simple photographic apparatus.

The general plan of such apparatus is as follows: A sensitive film is moved evenly, in a vertical plane, immediately behind a narrow horizontal slit in the plate holder of a photographic camera. The subject's eye is brought into such a position before the camera that a horizontal plane bisecting the eye through the middle of the pupil bisects the lens of the eye and passes through the horizontal slit. If the eye were held immovable while the sensitive film is exposed behind the slit, the negative would present a series of parallel lines corresponding in cross section at every point to the light and dark parts of an imaginary line drawn horizontally across the eye, bisecting the pupil. A horizontal movement of the eye, while the sensitive film is moving behind the slit, would be marked in the negative by oblique lines. These oblique lines are the records of the eye movements and their time values may be read off from a time record marked on the sensitive film during its movement.

Photography of the eye movements in this simple way is, however, open to some serious objections. An illumination of the eye, capable of affecting the rapidly moving film, through the small slit, must be rather brilliant, and (even though the subjects experienced no discomfort), it was not *a priori* certain that the conditions of vision might not be disturbed sufficiently to affect the eye movements. Still more serious is the character of the records. The lines of demarcation between the pigmented and unpigmented portions of the eye are usually not sharply defined; and although the photographs appeared fairly clear and distinct to the naked eye, it was found impossible to read them with any accuracy when enlarged by the telescope of the cathetometer.

Satisfactory results were first obtained when, after considerable experimentation, we hit upon the plan of utilizing the eccentric surface of the cornea as a reflector. Instead of photographing the eye directly, we photographed the movement of a bright vertical line as it was reflected from the surface of the cornea. Such lines give clean-cut records permitting considerable magnification in reading, while the amount of light needed is comparatively small.

The description of the essential parts of the apparatus used for all the measurements given in this article follows the cuts, Figs. 1 and 2 (Plate I.).

The head rest (*A*) is fitted with an attachment for holding a narrow strip of white cardboard (*k*) which is illuminated by direct sunlight from behind the subject. It is the image of this piece of cardboard reflected from the cornea which makes the records. The ordinary Helmholtz head holder with its mouthpiece of sealing wax was discarded in favor of a simple forehead and chin rest; while a peep sight (*aa′*) enabled the subject to find the right position for his head, irrespective of individual peculiarities.

A horizontal perimeter (*BB*) carries the adjustable fixation points and a holder for printed matter. The perimeter was a horizontal wooden table fastened securely to the head rest, and strong enough to support the camera, which could thus be readily adjusted to the most favorable point of view, without refocusing. The fixation points were bits of white paper attached to knitting needles which could be set vertically into holes in the perimeter table. The knitting needles amply justified their value as fixation objects. In preliminary experiments black cross lines on a white surface were used as fixation objects, but it was found that practically every movement above 15° was a double movement. The first served to bring the eye within 3° or 4° of the cross lines; while the second, occurring after a well-defined pause of about .2″, rectified the faulty fixation. This was clearly inadmissible, since it never permitted us to measure the angular movement desired; and, moreover, burdened the results with a large and varying source of error. It is worth noting in passing that the subject was rarely aware of a broken movement; while the length of time intervening stamps the correction as a time reaction, thus effectually demonstrating that, under ordinary conditions of eye movement the stimulation during the movement does not serve the eye as a guide. Whenever a second or corrective movement was found, the

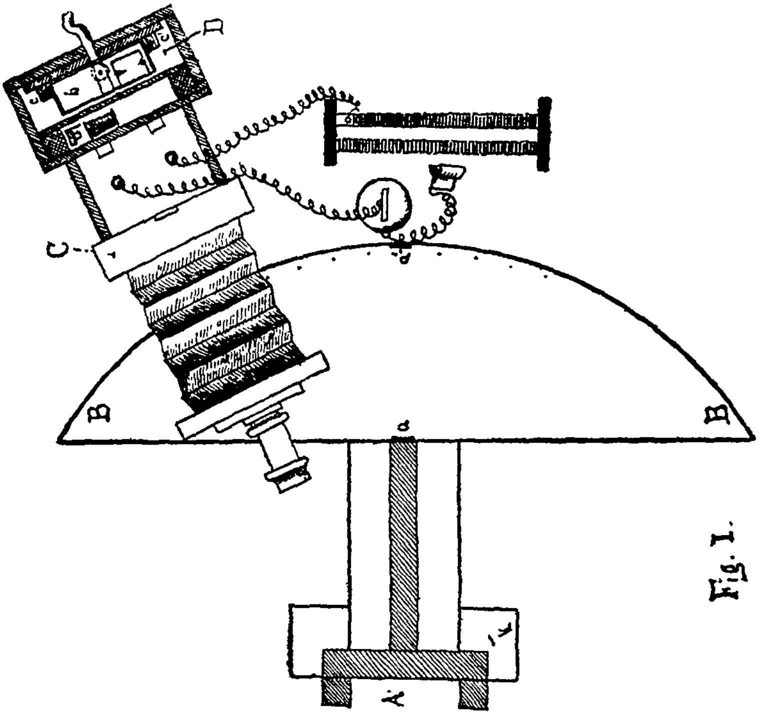

Fig. I.

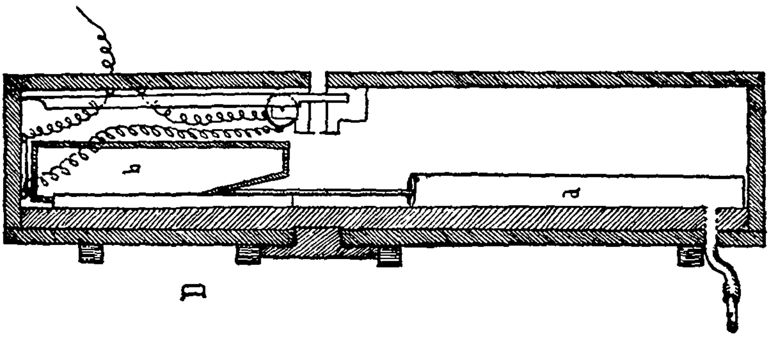

Fig. II.

first movement was regularly too short. The long bright needles, affecting so large a number of retinal elements with a clear-cut stimulus, served so effectually as a stimulus to movement that up to 40° only half a dozen in all were double movements. Of course such movements do not appear in the tabulated results.

The camera (*C*) was an ordinary 5 x 7 bellows camera fitted with a fair lens of 1⅜-in. aperture. An especially constructed lens would be a great improvement in the apparatus, and might possibly permit direct photography of the eye.

The plate-holder (*D*) is the vital part of the apparatus, since it must provide, not only for the regular motion of the sensitive film across the slit, but also for the registration of the time record. Perhaps the best means of moving the film would be to stretch a collodion film over a kymograph cylinder enclosed within a light-tight box. This would permit indefinitely long records and insure an even motion. Lack of the necessary apparatus compelled us to use ordinary plates. The plate is held in a small wooden frame (*b*) guided by two brass rails (*cc'*). Since there must be absolutely no lateral motion of the plate, all play is taken up on one side by a spring pressing the guide on that side against its track. The rapidity of the fall is governed by the escape of air from a cylinder into which the falling plate presses a closely fitting piston. The cylinder (*d*) and piston are an ordinary bicycle pump. A second pump on the outside of the plate-holder (not shown in the drawing) serves to force the plate up to the top of the plate-holder, where it is held by a valve. (In the side elevation of the plate-holder, Fig. 2, the plate is shown at the top of the plate-holder.) The release of the air is provided for by inserting between the valve and the inner air pump, a set of two tightly fitting brass tubes, such as are used for fish pole joints. A set of holes was drilled in the inner tube, and the fall is occasioned and controlled by uncovering one or more of these holes.

It may not be improper to forestall the inevitable criticism of the exceedingly simple and homely means utilized in construction of the apparatus by mentioning the fact that we were compelled to design our apparatus not only to secure the required accuracy of results, but also so that we could construct it ourselves.

The first movement of the plate on the release of the air is subject to considerable variation, and the first ¾ inch of the 5 x 8 plates used is regularly disregarded, but the remainder of the fall is quite regular if the parts are kept well lubricated. Very slight inequalities in the fall are detected with great delicacy by unevenness in the density of the shadows.

The time records are produced by the oscillations of a pendulum within the plate-holder and just in front of the horizontal slit. The light at one end of the slit is intercepted at each oscillation of the pendulum, making a continuous time curve the entire length of the plate. The pendulum is set in motion at the beginning of each exposure by an automatic break in an electric circuit, including a small electric magnet which holds the pendulum motionless as long as the plate remains at the top of the plate-holder.

Fig. 3 is a reproduction of a part of one measurement of the pendulum time record, actual size. The fine curve at the left is the record of the vibrations of a König tuning fork of 100 vibrations per second. The large curve at the right is the pendulum time record. The pendulum was adjusted as closely as possible to .2″. Our measurements show its interval to be 203 σ without any variation which we had the means of detecting.

Fig. 4 is a reproduction of a part of a typical record of reading. While the lines are too delicate to be reproduced satisfactorily, the cuts (Plate II.) indicate their general character.

The reading of the records is a tedious process. It was originally planned to measure the negatives directly, but after considerable experimentation it was found impossible to make the delicate lines on the negatives as distinct as the corresponding lines of a good print.[1] All the results published in this paper are, therefore, obtained from prints which were dried and pressed with great care. They were measured with a cathetometer reading with a vernier to .02 mm. Since .02 mm. had a value of from .4 σ to .8 σ according to the velocity of the sensitive plate, the unit of measurement is well within the required 1 σ.

[1] Since this paper has been made ready for the press a method of preparing the negatives has been devised which permits direct reading as at first planned. This will be used in all future experiments.

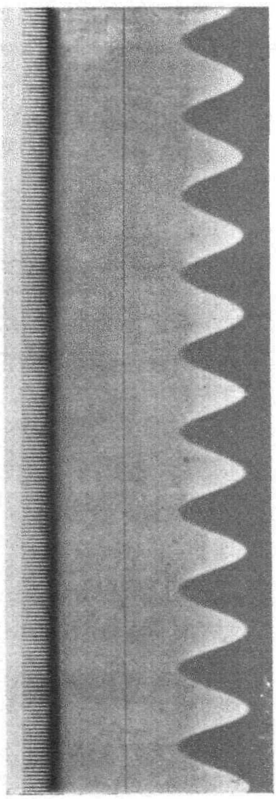

FIG. 3.

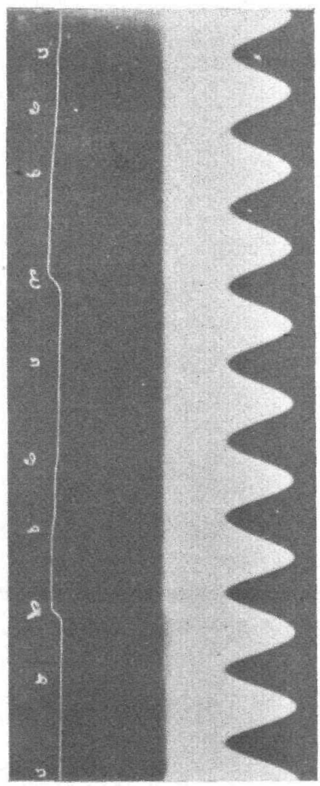

FIG. 4.

Dodge and Cline on the angle velocity of Eye Movements.

The largest error in the readings is due, not to the unit of measurement, but to the character of the eye movement itself. The transition from rest to movement and from movement to rest presents no sharp point on the curve at which the cross line of the reading telescope may be placed. This not only increases the error in the readings, but also increases their difficulty. The problem of placing the central hair line at the beginning and end of the oblique line of movement finally reduced itself to the problem of placing the central hair at that point where the straight lines of rest first showed a deviation from the vertical. The point at which the central hair finally rested for each reading was reached by a series of oscillations in which the amplitude was gradually reduced to zero. The average variation between two consecutive readings each, for 36 consecutive records, was .045 mm., corresponding in the records used to an average difference between the readings of 1.5 σ. Assuming that each reading has equal probability of being the true one, and using the formula $E = 6745\sqrt{\frac{S}{n-1}}$, in which S is the sum of the squares of the differences, we get a probable error of a little less than .5 σ for each reading. In a series of 8 to 10 readings the total error becomes a negligible quantity when the required accuracy is only 1 σ.

Results.

The results of our measurements are presented in the following tables:

Table I.

Velocity of the Eye in Reading.

	Movements toward the right.					Movements toward the left.				
	No.	M.	M.V.	Max.	Min.	No.	M.	M.V.	Max.	Min.
A	12	23.7	3.9	36.5	17.5	5	45.6	3.7	50.1	40 9
B	18	21.9	3.9	29 2	15.0	5	40 1	2.9	43.8	35 0
C	10	23.2	6 1	32.8	14 2	4	37.1	1.9	39 0	33.4
General Av.		22 9					40.9			

Table I. shows the measurements of the movements of the right eye while reading four or five lines of popular scientific matter not familiar to any of the subjects. The three subjects, A, B, and C, were Mr. Cline, Mrs. Dodge, and Professor Dodge respectively. The measurements were made from two records for each subject. The way the records happened to commence and end prevents the relation between the number of movements to the right and those to the left from representing the actual relation in reading. There was an average of a little less than five reading pauses per line, making an average of a little less than four movements to the right for every movement to the left. The designation of the columns is self-explanatory. No. shows the number of movements measured; M., the average; M.V., the mean variation; Max., the maximum value; Min., the minimum value. The *general average* is reckoned from the average for each individual. It may be objected that the number of measurements is too small. The authors discussed this objection; but, in view of the accuracy of the method and the small mean variation, it seemed that the number was sufficient unless we should regroup the results according to the arcs of movement, and this scarcely lay within the limits of the present study.

Estimating the distance from the surface of the cornea to the axis of rotation of the eye as 1 cm., the distance from the center of the printed page to the axis of rotation of the eye measured was 31 cm. The arc represented by each full line of print was 16°. The arcs of the movements to the left varied from 12° to 14°. The arcs of the movements to the right varied from 2° to 7°. The large variation in the arcs of the short forward movements is clearly responsible for the larger comparative variation in the results, as represented in the mean variation and in the maximum and minimum values.

A comparison of our results with the results of Huey shows that the delay occasioned by the extra work of moving the recording pointer amounted to almost as much as the normal duration of the movement for the small angles, and had about the same numerical value for the longer movements to the left. Of course it is possible that individual peculiarities would modify this somewhat. The small differences in the angles measured is also a source of error; but the difference between our results is apparently a very close approximation to the error of the

Huey apparatus, as far as his measurements of the angle velocity of the eyes are concerned.

READING MOVEMENTS.—SUMMARY.

To the right.			To the left.		
Huey average	3°36′	43 9σ	Average	12°12′	57.9σ
Dodge Cline	2°–7°	22.9σ		12°–14°	40.7σ
Difference		21σ	Difference		17.2σ

In this connection it may be noted that the estimate of .02″ each for the reading movements, made on the basis of the Dodge-Lamansky measurements by Erdmann and Dodge in their analysis of the reading processes, is surprisingly close to the true value.

Table II. gives the speed of the eye movements for the same three subjects for the angles 5°, 10°, 15°, 20°, 30° and 40°.

TABLE II.

	A			*B*			*C*			General average.
	M.	M.V.	No.	M.	M.V	No.	M.	M.V.	No.	
5° *5-*	34.5	1.5	8	29.4	2.9	8	22 4	3.3	10	28.8
10° *5-5*	41.8	1.4	9	40 9	3 8	8	33.7	2.1	5	38.8
15° *10-5*	46 7	4.5	8	47 9	2.6	10	49.9	3.1	10	48.2
20° *10-10*	54 5	8 0	8	51.3	3 5	10	58 6	4.1	10	54 8
30° *15-15*	84 3	8.9	7	74.3	9.3	10	82.5	3.8	10	80.4
40° *20-20*	100.4	4 5	7	93 4	7.3	10	106.0	8 0	8	99.9

In Tables I. and II. we have followed the time-honored custom of giving the mean variation of each series. This includes all errors of reading and apparatus; but as these errors can account for only about .75 σ, the remainder must be accounted for from a physiological basis. Two of the factors entering into this physiological variation are clearly indicated in the records. (1) It is partially due to fatigue. The last four movements in a series of ten uniformly average longer than the first four. In view of the enormous number of eye movements during the day's work of a student this evidence of fatigue within a group of ten is surprising and demands further investigation. (2) It will be noticed that the M.V. is considerably larger for larger angles, although the proportion between M. and M.V. holds fairly constant. In all cases where the M.V. is larger than 4.5 σ there is an unequivocal difference between movements of the eye to the right and to the left which is evident even in the small number of records at hand. The data are doubtless too few to permit a quantitative generalization, but we may be permitted to give an illustration. If one follows the records of *B*, it will be seen that while up to 20° the M.V. does not exceed 3.8 σ, the M.V. for 30° is 9.3 σ. Reckoning the mean value of each direction by itself we find the following:

	M.	M V.	
Total 30°	74 3	9 3	
movement to right	83 6	2 1	
movement to left	65 0	4.1	Difference 18.6
Similarly the total for 40° is	93.4	7.3	
movement to right	99 6	5.3	
movement to left	87 1	4 2	Difference 12.5

The same fact is well marked for *A* as low as 20°.

	M.	M.V.	
Total 20°	54.5	8	
movement to right	62.5	2 9	
movement to left	46.5	2.1	Difference 16.

In discussing the eye's inability to see its own movements in a mirror, Dodge[1] called attention to the fact that this did not hold true absolutely except for monocular observation, and he suggested as the probable reason why in binocular observation we occasionally perceive a slight quiver, apparently the beginning or end of a movement, the hypothesis that the eyes do not move absolutely together. This hypothesis seems to be substantiated by the difference just remarked between the duration of eye movements in different directions. A few binocular records of eye movements which we already have show us that the hypothesis is a fact. Apparently the two eyes neither start their movements nor end them at the same instant. This observation suggests that valuable practical as well as theoretical results may be expected from a quantitative study of binocular coördination; it also throws an interesting side light on the facts of the lack of perception during eye movement.

A comparison of Tables I. and II. shows that the *G. A.* for reading movements to the right falls below the *G. A.* for eye

[1] PSYCHOLOGICAL REVIEW, Vol. VII., p. 456.

movements of 5°; while the *G. A.* for reading movements to the left falls between the *G. A.'s* for eye movements of 10° and 15°. This concurrence between the two sets of measurements, not only in their general averages but also in corresponding movements of each individual, amply justifies the conclusion that the character of the eye movements in reading is not materially different, qualitatively or quantitatively, from the eye movements which are made in response to peripheral stimuli as the eye looks back and forth between two fixation points.

Comparison of our results with Dodge's results by the Lamansky method is impossible for angles larger than 15°, since the Lamansky method can measure only the internal movements for larger angles.

C

	Lamansky method.[1]	Photographic method
5°	15 σ	22.4 σ
10°	16–20 σ	33 7 σ
15°	30 σ	49 9 σ

How much of this difference between the results is to be regarded as the result of the previously mentioned sources of errors in the Lamansky method and how much represents the influence of the peculiar conditions it imposes we have no data for determining.

All the measurements in Tables I. and II. were made from records of the right eye under conditions as nearly constant as possible. Each mean value in Table II. is from consecutive records from a single plate; such records only were disregarded as represented, either broken movements, or irregularities in the movement of the plate.

[1] 'Psychologische Untersuchungen über das Lesen,' p. 358