PILOT STUDY IN ELECTRO-OCULOGRAPHY*†

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THE eyes are a major communication channel through which information passes into the human being. The pattern of successive fixations and eye movements may well indicate the progress of the dynamic perceptual process of searching for and absorbing visual information. Interest has therefore increased recently in the various methods of recording eye position and eye movement. A method which has shown much promise but which has not yet been developed to the full is electro-oculography (EOG). The basis of EOG is a standing potential difference between the front and back of the eyeball; as the eye rotates, electrodes suitably placed on the skin surface near the eye socket will detect the resulting change in DC potential (Fig.1).

FIG. 1.—Basis of electro-oculography.

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The most extensive application of this technique so far has been to the study of reading (Carmichael and Dearborn, 1948); the development of EOG has been comprehensively reviewed by Marg (1951), who discussed also some of the requirements to establish it firmly as a routine recording technique.

In the course of studies to improve the accuracy and reliability of EOG it was considered necessary to investigate certain factors with a large number of subjects. Also EOG potential level (the definition of this and some other terms is given in the Appendix) is an interesting psycho-physiological variable by itself, and it was desired to make an exploratory study of this level and its possible relationship to other population variables. Therefore the investigation described in this report had the two-fold purpose of learning more about some of the parameters of EOG as a measuring instrument and of exploring for any factors which might be related to the EOG potential level.

The questions which it was hoped would be answered by the investigation were:

- (1) What are the statistics of the distribution of the EOG potential level in the population studied?
- (2) Is the relationship between the EOG potential and the eyeball rotation (up to 30°) reasonably linear for practical purposes?
- (3) Which is the "best-fitting" relationship between EOG potential and angle of eyeball rotation, the linear or the sine relationship?
- (4) Are age, height, weight, and rate of change of height or weight correlated in any way with the EOG potential level?
- (5) Are any other variables, which could be measured, correlated with the EOG potential level?
- (6) Because the full preparatory technique with skin-drilling is not to be used, what are the statistics of the distribution of zero level drifts thereby obtained and how do they compare with the minimal drifts attainable with the full technique?

Further, it was planned to retest the same group of subjects after 9 to 12 months so that a test-retest correlation of the EOG potential level might be obtained and correlations of the EOG potential level with other variables re-examined.

These questions form a series of relatively isolated problems, although the required EOG data were all gathered from one 5-minute session with each subject. Therefore the apparatus and method will be described first, and then each particular section of the investigation, with its appropriate rationale results, and discussion, will be treated separately.

Subjects.—The subjects were 129 Juniors, all male, age range 15 years 1 month to 17 years 6 months, of No. 103 recruitment at the Naval Training Establishment,

H.M.S. Ganges. The subjects were tested on December 5, 6, and 7, 1956. Data on body height, body weight, and selection-test scores were made available from records. A retest of body height and weight was made in March, 1957.

Apparatus.—A portable version of the electronic system which has been developed for measuring eye movements (Shackel, Sloan, and Warr, 1958) was used for amplifying and recording, for subsequent analysis, the EOG potentials in the horizontal plane. Six separate pairs of the electrodes which have been developed for EOG applications (Shackel, 1958) were used in rotation.

A target was used with suitable spot marks so that, with the eyes at a fixed distance 30" from the target, eye rotations to positions from 5° to 40° (in 5° steps) to left and right of centre zero could be made. The height of the target could be adjusted to one of three fixed positions so as to be approximately at the subject's eye level. A wooden spatula suitably mounted as a biting bar ensured adequate head positioning and, it is thought, avoidance of head movements for the short duration of the test.

The electronic apparatus, target, and biting bar are shown in Fig. 2.

FIG. 2.—Target, biting bar, and recording apparatus.

Method.—Eye movements in the horizontal plane only were recorded from each subject. To save time the skin drill (Shackel, 1959) was not used, because it was expected that a reasonable percentage of results would be obtained without excessive drift potentials from the skin in the short duration of recording required. To minimize electrode drifts, the six pairs of electrodes were used in rotation and were kept soaking in separate beakers of 1 per cent. saline, with leads shorted, between uses. The same electrode was used for earth throughout the test because the earth electrode has little effect on zero stability.

The subjects were familiarized in the waiting room with the general procedure and the specific eye movements for which they would be asked. In the testing room each was allowed to see his predecessor being tested. The skin near the external canthi of each eye and behind the right ear, for the earth electrode, was

cleaned with acetone. The electrodes were charged with pure 1 per cent. saline jelly and applied. The siting of the electrodes is shown in Fig. 3. The subject was seated and the wooden biting bar adjusted to a comfortable height. The height and distance of the target were checked and adjusted if necessary. The appropriate target points and sequence of movements were again explained.

With the subject fixing zero and moving to the left 30° and right 30° points on request the gain of the apparatus was adjusted. Three separate series of eye rotations were then recorded, with the subject looking to the various positions as enumerated below (*L* and *R*=left and right; degree symbols omitted for simplicity).

- (1) Zero, L30, zero, R30, zero
- (2) Zero—L5, 10, 15, 20, 25, 30, 35, 40—
Zero—L40, 35, 30, 25, 20, 15, 10, 5—
Zero—R5, 10, 15, 20, 25, 30, 35, 40—
Zero—R40, 35, 30, 25, 20, 15, 10, 5—zero
- (3) Zero, L30, zero, R30—
Zero, L35, zero, R35—
Zero, L40, zero, R40—zero

FIG. 3.—Positions of electrodes.

FIG. 4.—Section of pen record.

The record was then calibrated with a known input voltage, the electrodes were removed and replaced to soak in saline, and the subject's skin was cleaned. A fresh wooden spatula was placed ready for the next subject. The total time required to prepare, test, and finish with each subject was between 5 and 7 min.

A typical section of record is shown in Fig 4. The two sides of the recording paper, here seen as top and bottom, were used entirely separately. The record is read from left to right. The top part shows Subject 107 from the start to the end of his second series of eye rotations; the bottom part shows Subject 122 from the middle of his second series of rotations to the end of his record. The fixations are typically steady; the movements are well controlled, with the usual, small, corrective saccades for overshoot or undershoot, after a number of the large excursions, and with an occasional mistake in direction.

Results

(1) EOG Potential Level

The statistics of the distribution of the EOG potential level are required both as basic knowledge and as the parameters of the signal level which may be expected when EOG is used as a practical method for recording eye movements. Only two similar studies have been reported, one in the U.S.A. (Miles, 1939b) on 69 subjects, mostly female, in various age groups, the other in Germany (Mackensen and Harder, 1954) on 45 subjects of unspecified age and sex. Table I gives the readings from these studies, to which the results of the present study are most nearly comparable.

TABLE I
EOG POTENTIAL LEVELS FOR 30° LATERAL EYE ROTATIONS

Authors	Date	No. of Subjects	Age (yrs)	Sex	EOG Potential (μ V)
Miles	1939b	20	10-12	F	Mean 1,170 S.D. 320
		20	17-19	F	Mean 1,370 S.D. 290
		15	41-65	F	Mean 1,100 S.D. 210
		14	21-37	3F 11M	Mean 1,070 S.D. 290
Mackensen and Harder	1954	45	—	—	Mean 980 S.D. 370

Results.—One subject was absent and the recordings from two subjects were completely unusable because of excessive drift; the mean potential

level for each subject is based on four readings per subject for sixteen subjects and eight readings per subject for 110 subjects. The statistics of the population are given in Table II and a histogram of the distribution in Fig. 5.

TABLE II
EOG POTENTIAL LEVEL FROM H.M.S. *GANGES* TEST FOR 30°
LATERAL EYE ROTATIONS

No. of Subjects	Age (yrs)	Sex	EOG Potential (μ V)
126	15-17½	M	Mean 580 S.D. 146 Median 560

FIG. 5.—Histogram of EOG potential levels of 126 men aged 15 to 17½ years.

Discussion.—The most notable feature of these results is the large difference in mean EOG potential level. There are three possible explanations of this difference: first there may have been a significant difference between the testing conditions; secondly there may be a true difference in corneo-retinal standing potential between the populations; thirdly both the above factors may have been operating.

There were inevitably a number of differences in testing conditions. The input impedance of the amplifier used by Miles (1939a) was 5 megohms, ours was 1 megohm. However, the electrode skin resistance of 37 of our subjects was checked; none was more than 10 kilohms and the average was 4.4 kilohms. Even had the average resistance of our subjects been 100 kilohms, the differences in amplifier input impedance would still only have accounted for 10 per cent. of the difference in results. Mackensen and Harder (1954) used a mirror galvanometer of 5,400 ohms resistance without a high input impedance amplifier; they measured the subject's skin and electrode resistance and allowed for it in calculating the EOG potential level. This resistance may vary indeterminately, and, although they measure it frequently during their recording, it is probably the cause of the somewhat higher standard deviation of their results; however, their mean EOG potential levels were probably not affected. It seems unlikely, therefore, that this

difference of input impedance between the three studies is the operative factor.

Another difference between testing conditions, namely in electrode position, probably does cause most of the difference in results. From his photograph, Miles (1939b) seems to have placed his metal foil electrodes as close to the eyes as possible; the centres of the relevant pair (Miles' Lead 3) appear to be about 0.5 to 0.75 cm. from the external canthi. The centres of our electrodes were about 1.5 to 2.25 cm. from the external canthi. This difference will obviously have affected the results considerably. Mackensen and Harder report, from a test on twelve subjects, that, with the electrode pick-up points between the "temporal lid-corner and the rim of the orbit", the mean EOG potential level is 950 microvolts (S.D. 400), with the electrodes 1 cm. "temporal from the bony rim of the orbit" the level is 480 microvolts (S.D. 170), and with the electrodes 2 cm. temporal it is 340 microvolts (S.D. 150). However, interpolating the various results for comparison cannot be accurate; simultaneous recording from a number of electrodes in the positions used by the three studies is the only complete solution. A brief preliminary test on a few subjects has suggested that the differences in electrode position do not entirely account for the whole of the difference in results; a full experiment will be necessary to determine precisely the answer to this problem.

If electrode distance from the eye should not account for all the difference, then two or more factors may be operating, one of which may be a true difference between the subject populations in corneo-retinal standing potential. If this is so, it will be interesting to investigate whether sexual, racial, or environmental differences are significant and why.

(2) EOG Potential : Eye Rotation — Practical Linearity

Several workers have plotted graphs of EOG potential against eyeball rotation and have shown an apparent sine relationship between the two variables (e.g. Fenn and Hursh, 1937); but Leksell (1939), with graphs of results from three subjects, drew attention to the effective linearity of the relationship for practical purposes. Mackensen and Harder (1954), using the data from excursions of 10°, 20°, 30°, and 40° to left and right by nineteen subjects, found that the deviations from a linear plot were not significant. Their graph indicates a standard deviation of about 1° to 1.5° for excursions up to 30°; their calibration accuracy, as defined below, was therefore about $\pm 2^\circ$ to $\pm 3^\circ$.

To determine the eye movements and eye positions by the EOG method, it is necessary first to record the potential from the subject for some known excursion angle; then the potentials recorded during the test can be converted to excursion angles *via* this calibration. The accuracy of the EOG technique is tested by analysing the errors between the actual potentials for a series

of known excursions and fixations and the expected potentials derived from the calibration. Accuracy determined in this way will be more meaningful and useful than accuracy quoted in terms of the residual error about the best-filling linear plot (by a least-squares criterion), because this latter way of finding the appropriate calibration for each subject is too lengthy for routine practical use.

The data of eyeball rotations in 5° steps was therefore analysed in two ways. First, for left and right rotations separately from each subject, the variance was calculated of the residual errors of the 5°, 10°, 15°, and 20° fixations about a linear calibration line based on the 20° excursions only; the root mean sum of the variances of all subjects was then calculated to give the standard error of fit of the calibration lines to the actual data; calibration accuracy can thus be quoted as ± 2 standard errors, the limits within which lie 95 per cent. of all the actual readings. Secondly, a similar analysis was made of the movements up to 30° either side of zero about a linear calibration line from the 25° excursions (because if the relationship is truly sinusoidal, then a linear plot through the 25° point will be a better fit than one through either the 20° or the 30° point).

Results.—The data from 97 subjects was used in these analyses; excessive or non-linear drift of the zero level made the scores from the remainder obviously unreliable. The results are given in Table III.

TABLE III
FIT OF SINGLE-POINT LINEAR CALIBRATION TO EYE ROTATION DATA

Data	0 to 20° (<i>N</i> =1,552)	0 to 30° (<i>N</i> =2,328)
Calibration Point	20°	25°
Standard Error of Fit	0.60°	0.67°
Accuracy (± 2 S.E.)	$\pm 1.20^\circ$	$\pm 1.34^\circ$

The variances of the errors of fit at the various excursion angles were compared to see if there is any significant tendency towards increased error with large excursions; a slight trend was apparent, but the variance ratios were barely or not significant at $P=0.05$.

Inspection of the error distribution at various excursion angles shows them to be fairly normal. In a few cases the mean of the error distribution is significantly different from zero, *i.e.* from the appropriate point on the calibration plot. However, these differences are only between 0.08° and 0.25°, and are almost certainly caused in two cases by the tendency to a true sine relationship between the data, and in the remainder by slight non-linearities in the pen recorder; this latter effect, small and evident only with large data samples, has been found before with the type of pen recorder used in the experiment (Shackel, 1954).

Discussion.—It is clear that interpreting eye rotations, up to 30° left and right of zero separately, in terms of a simple linear calibration from one excursion angle, 25° to left and right, gives practical results with an average error of not more than 0.25° and with an accuracy of $\pm 1.35^\circ$ (*i.e.* 95 per cent. of individual readings are accurate to better than these limits).

The accuracy scores are biased, correctly, against showing favour to the technique. The error variance almost certainly contains errors from three separate sources only one of which is the “true” error source we wish to sample. First, the subject may fail to fixate precisely the point requested or may use different parts of his fovea for fixation during different parts of the trial; these are true eye movements, but would appear as system errors during the accuracy analysis, because he is assumed to be fixating precisely the excursion points given. Secondly, the zero drifts, although fairly small and fairly linear, were still much larger than when the full preparatory technique is used (see Section 6 below for comparisons); despite the interpolation of zero lines between the points at which zero was fixated, residual uncorrected zero drifts will have increased the variability of all measurements. Thirdly, the remaining errors are probably compounded from small random changes of the actual eyeball potential and within the recording apparatus, minor head movements, and so on.

The third source of errors is the “true” calibration error variance for the EOG technique but estimates of the other two sources cannot be made from the present data. Nevertheless it is clear that horizontal eye movements can be determined by this technique, using a simple linear calibration, with reasonable accuracy.

(3) EOG Potential : Eye Rotation — True Relationship Linear or Sine

The source of EOG potential seems to be a negatively polarized area in the retina with respect to anterior parts and the cornea (Mowrer, Ruch, and Miller, 1936; Brindley, 1956), the eyeball thus apparently forming a rotatable dipole. Assuming a reasonably homogeneous conducting medium, the potential difference between two points, one on either side and about equidistant from such a dipole, will vary with the sine of the angle of rotation of the dipole (Fig. 6, overleaf) (Coulson, 1951). Graphs of EOG potential against the sine of the angle of rotation show an apparently good fit (Fenn and Hursh, 1937; Mackensen and Harder, 1954). However, Leksell (1939) pointed out that linear plots of potentials against the actual angle of rotation yield an equally good fit, and Mackensen and Harder (1954) found that, with the excursions of nineteen subjects to fixation points 10° , 20° , 30° , and 40° , the deviations of their data from a linear plot were not statistically significant. Graphical methods are obviously not precise enough to determine which is the true relationship and thus test the theory of the eyeball as a rotating dipole in a relatively homogeneous conducting medium.

FIG. 6.—Potential difference ef varies with $\text{Sine } \alpha^\circ$.

Results.—The experiment was designed to gather the necessary data for a full statistical analysis. Successive rotations in steps of 5° up to 40° to left and right of centre were recorded, and also single rotations from zero to the left and right 30° , 35° , and 40° points separately. The latter records were taken for a supplementary analysis, in case the primary one should be inconclusive.

The successive 5° rotations were analysed by calculating the residual error of the best fitting linear and sine function to each subject's left and right data separately. If both left and right residual errors for the sine function were less than for the linear, or vice versa, that subject was counted as one in favour of the sine relationship, or vice versa; if the left and right comparisons were not consistent, the subject was assigned to the doubtful group. The results are given in Table IV.

TABLE IV
SUBJECT'S DATA FAVOURING SINE OR LINEAR FUNCTION

Function						No. of Subjects
Sine = Best fit	..	..	..	..	..	35
Linear = Best fit	..	..	..	..	..	34
Doubtful	..	..	..	..	..	28

The residual error of estimate of the best fitting straight line to a sine function (Fig. 6) is such that ± 2 standard errors of fit = $\pm 0.94^\circ$. The residual errors of estimate of the best fitting linear functions to the data of 5° rotations up to 40° from all the subjects is such that ± 2 standard errors of fit = $\pm 1.36^\circ$. The inconclusive result is therefore probably due to the sampling error variance of the data.

The separate single rotations to the 30° , 35° , and 40° points were analysed by a similar but less rigorous method; data from more subjects were available because less had to be rejected for excessive zero drift. From the potential for the 30° rotation the expected potential from the 35° and 40° rotations, on a linear and on a sine function passing through zero, were calculated for the left and right excursions of each subject separately. The differences for each subject between the actual and the predicted levels were converted to degrees of equivalent eye movement by the appropriate 30° /EOG potential calibration. The frequency distributions of these differences were then examined.

If all the means of the linear extrapolation difference distributions are not significantly different from zero but the means of the sine extrapolation difference distributions are significantly positive of zero, then the data support the hypothesis of a linear relationship between EOG potential and eye rotation. If, on the other hand, the sine distribution means are not significantly different from zero but the linear distribution means are significantly negative of zero, then the data support the hypothesis of a sine relationship between EOG potential and eye rotation.

The statistics of the difference distributions are given in Table V. The precision of the data is reasonable. The difference between the linear and sine functions, when the linear function is extrapolated from the 30° point,

TABLE V
STATISTICS OF LINEAR AND SINE EXTRAPOLATION DIFFERENCES ($^\circ$)
(*N* for each mean = 124)

Side		Left		Right	
		35°	40°	35°	40°
Linear	Mean Difference from Zero	-0.81	-1.72	-0.50	-0.98
	S.D. of Differences about Zero	1.5	2.3	1.4	1.9
	<i>t</i>	6.10*	8.35*	3.97*	5.65*
Sine	Mean Difference from Zero	-0.08	-0.11	+0.18	+0.67
	S.D. of Differences about Zero	1.3	1.6	1.3	1.8
	<i>t</i>	0.70	0.75	1.55	4.12*

* Significant at $P = < 0.001$ on a one-tailed test ($n = 120$; $P = 0.001$; $t = 3.16$)

is 0.58° at the 35° level and 1.43° at the 40° level, while the confidence limits (± 2 standard errors of the mean) on the 35° means of this analysis are not worse than $\pm 0.27^\circ$ and on the 40° means not worse than $\pm 0.42^\circ$.

Seven of the eight results in Table V support the hypothesis of a sine relationship. The discrepant result, indicating that the actual data of the right 40° excursions are not satisfactorily fitted by a sine function extrapolation, appears no less valid than the other results.

Discussion.—The data from this experiment may be taken to give some support to the hypothesis that the true relationship between EOG potential and eyeball rotation is a sine function. Thus the theory of the eyeball as a rotating dipole in a relatively homogeneous conducting medium also receives some support. However, the results are not conclusive and a further experiment would be desirable. The discrepant results may for instance be caused by a significant unbalance or lack of homogeneity in the conducting medium; the tissues and structures between eyeball and electrodes are certainly not uniform.

Leksell (1939) concluded that, from a practical point of view, the EOG potential could be regarded as directly proportional to the angular deviation for horizontal eye movements up to 45° from the centre. The more detailed results available from this survey enable assessment of the possible errors if, for practical convenience, a linear relationship is assumed. For excursions up to 40° , if a simple linear calibration from the 30° point is used, mean errors up to more than 1.50° and scatter of 95 per cent. of results up to $\pm 3.62^\circ$ from the linear calibration plot are possible; if however the best fitting linear calibration is calculated, average errors will be smaller and the scatter of 95 per cent. of the results will be within $\pm 1.36^\circ$ of the linear plot. For rotations up to 30° on the other hand, even with the simpler linear calibration from the 25° point the mean errors are never more than 0.25° and the scatter of 95 per cent. of the results is within $\pm 1.34^\circ$ of the linear plot. Therefore the assumption of linearity for practical purposes would seem only to be justifiable for excursions up to 30° ; however the assessment of what is practical here must depend upon how much error can be tolerated in any experiment or whether the more complex task of calculating the best fitting linear calibration for each subject can be accepted.

(4) Age, Height, and Weight Correlations

Interest has of course been directed by several workers towards finding any factors significantly associated with the EOG potential level. Fenn and Hursh (1937) were not able to correlate the potential levels of 21 subjects with age, sex, or any other characteristics. Miles (1939b) had three groups of female subjects, twenty aged 10 to 12, twenty aged 17 to 19, and fifteen

aged 41 to 65; by comparing the group means he concluded that there is a tendency towards a curvi-linear relationship between chronological age and eye potential, with indications of an early small positive and a late small negative correlation with age, but he pointed out that his results were not conclusive. Miles (1939c) has also drawn attention to the tendency of the eye potential to conform to the pattern for blood pressure, metabolism, and other functions which decrease with relaxation and inactivity; similarly, if the subject is afraid and tense, the eye potential tends to increase.

For the subjects studied in this survey, age, height, and weight measures were readily available and were therefore compared by product-moment correlation with the subject's mean EOG potential levels. The heights and weights were measured again 3 months after the initial experiment to enable correlations of potential level with changes in height and weight; rate of change might be expected to be a useful measure with these subjects, a fair proportion of whom were passing through the puberal phase.

Results.—The product moment correlation with age was calculated for all 126 subjects (age range 15 to 17½ years) for whom mean EOG potential levels were measured; height and weight measures were not available for ten subjects. The results are given in Table VI.

TABLE VI
CORRELATIONS WITH EOG POTENTIAL LEVEL

Correlations					<i>r</i>	<i>N</i>	<i>P</i>
Age ..	..	..	..	..	0.33	126	0.001 Regressions linear
Height ..	..	..	..	..	0.22	116	0.02 One regression not linear
Weight ..	..	..	..	..	0.19	116	0.05 One regression not linear

The correlations with height and weight may only be regarded as suggestive and not conclusive; it is the regression of height or weight onto potential level which is significantly non-linear in each case.

The differences between the first and second measures of height and of weight were correlated with EOG potential level and also the height and weight differences were correlated with each other. All the correlations were low and none was significantly different from zero. It is thought that the changes in height and weight over the 3-month period were probably not large enough, in comparison with the inevitable sampling errors, to yield reliable measures of the differences. The same measures were taken as part of the second survey on the same subjects 10 months later (in October, 1957) and a similar analysis will be made.

Discussion.—It is interesting that a moderate but significant negative correlation with chronological age should have been found over such a small age range between 15 and 17½ years (with only three subjects over 17

years). It is thought that the result may well be associated in some way with the fact that this age range covers the middle and end of puberty for males. Whether the change in potential level reflects a true change in potential at the eyeball or a change in the surrounding tissues cannot yet be determined.

Miles (1939b) has shown a tendency for the mean eye potential of a group of females aged 17 to 19 to be larger than for a similar group aged 10 to 12 years, but he has not given any data of correlations within each age group. The results reported here are not incompatible with his findings. The mean potential level may well reach a peak at say 14 to 15 years of age and decrease slowly thereafter. On the other hand there may perhaps be a true sex difference in this aspect of the EOG potential level.

There is little reason to believe that chronological age as such has any direct effect on eyeball potential, and it is assumed that age, height, and weight are all correlated with and acting as somewhat imprecise measures of some variable which does directly affect the potential. Perhaps this variable is the general metabolic state of the body at the time, or the local metabolic state of the retina. What evidence there is so far favours this hypothesis (tendency of both eyeball potential and metabolism to increase with tension, decrease with relaxation and with age). A proper experiment to test the hypothesis is very desirable, because many possibilities would be opened up if it were confirmed.

(5) Other Exploratory Analyses

There is one other piece of evidence suggesting an association of EOG potential level with metabolic state. Kris (1957), from serial time studies on a number of subjects over periods up to 36 hours, has reported that there is a diurnal variation in the potential level, similar in characteristics to the broad diurnal variations in metabolic rate, with a maximum at between 12 noon and 4 p.m. Because the testing for the survey reported here was spread over two and a half days, an attempt was made to confirm this finding by comparing the results from subjects tested in the middle of the day with those from subjects tested at the beginning or end of the working day; the difference was not significant. The variability between subjects is too large and obscures any time difference.

The results of these subjects on SP Tests R and T2 were available, both being composite tests of intelligence and level of education. Product moment correlations were therefore calculated between EOG potential level and performance scores separately from the two tests. As was expected, no significant correlation was found.

(6) Zero Drift

For convenience and speed of testing, the skill drill, which has been shown to diminish considerably unwanted skin potentials (Shackel, 1959) was not

used. It was accepted that a certain percentage of results would have to be rejected as unusable and it was expected that a useful comparison between the two techniques, with and without the skin drill, would be possible.

The electrodes, which are the other possible source of zero drift in the situation, were kept soaking in saline, with their leads shorted, when not in use. Six pairs were used in rotation, so that each pair successively was in use for about 5 minutes and then was stabilized in saline for about 25 minutes; their performance cannot have been as good as when treated with normal care in laboratory tests, but it is thought that they cannot have contributed the major part of the zero drift results.

The drift distribution was compiled by sampling at fixed intervals on the record of the 5° rotations from each subject. Successive fixations of the zero point permit the interpolations of zero drift lines, and at 5, 10, and 15" from the start the drift rate was measured in microvolts per second; three samples per subject yielding a population of 366 was considered adequate.

Results.—The 5° rotations from six subjects were not recorded or were completely unusable because of excessive zero drift. The distribution from the remainder gives a mean zero drift of $9.67 \mu\text{V}/\text{sec.}$ equivalent to $580 \mu\text{V}/\text{min.}$

By contrast, when using the skin drill, the drift is so small that it can only be recorded reliably in terms of total excursion in one minute intervals. From 22 pairs of electrodes on eleven subjects (Shackel, 1958), the total of 430 one-minute samples was found to have a mean zero drift rate of $47 \mu\text{V}/\text{min.}$, equivalent to $0.78 \mu\text{V}/\text{sec.}$

To show these results more clearly the percentage ogives of the two distributions are given in Fig. 7 (overleaf). To put the two graphs into similar terms, although with a different scale expansion, the microvolt-per-minute points have been divided by 60 to convert them to microvolts per second.

Discussion.—These results show that there is an improvement in zero drift of the order of at least ten to one when the full technique with skin drill is used to prepare the subject. They also enable estimates to be made of the rejection rate and the accuracy of data obtained by the mass survey method without skin drill.

Six in 128 or about 5 per cent. of recordings have to be rejected completely. The remaining 95 per cent. can be used reliably, provided the excursions do not last more than about 2 sec. and are measured from a zero line interpolated from zero checks immediately before and after (thus typically excursions of the 0° - 30° - 0° type, see Fig. 4, are reliably recorded). Potentials recorded under these conditions can be measured with an accuracy of certainly not worse than ± 50 microvolts (from Section 3 sine plot 35° excursions, where errors known not to be due to zero drift are minimum, $\pm 2 \text{ S.D.} = \pm 2.6^\circ$

FIG. 7.—Percentage of zero drifts less than a certain drift rate.

and average calibration = $580 \mu\text{V}$ for $30^\circ = 19.33 \mu\text{V/deg.}$). 31 in 128 or about 25 per cent. of recordings have to be rejected for excessive or obviously non-linear drift if excursions lasting more than about two seconds are to be measured. The remaining 75 per cent. can be used reliably (typically for the 5° rotations) provided that the intervals between zero checks are not longer than about 10 sec.; potentials recorded under these conditions can be measured with an accuracy of certainly not worse than ± 26 microvolts (from Section 2, $\pm 2 \text{ S.E.} = \pm 1.34^\circ$ and average calibration = $19.33 \mu\text{V/deg.}$). The accuracy figures assessed here are pessimistic and may therefore be relied on, because, as discussed in Section 2, they probably contain also an error variance due to any fixation inaccuracies by the subjects.

These estimates show, by comparison with the zero drift distribution, a better accuracy than might be expected. This is because, as is obvious from inspection of the records, the zero drifts are not entirely random with a rapid periodicity, but progress fairly linearly for perhaps 5 or 10 sec. on average. It has not been possible, however, to compile a distribution of time intervals during which the drift remains truly linear, because the

fixations on zero were intermittent during the task and the recording was continuous only for about 20 to 30 sec. The assessments given above, based on linear interpolations between zero check points, are therefore the best estimates at present of zero drifts and of the accuracy which can be achieved, without using the full preparatory techniques including the skin drill, under various test durations and conditions. Use of the skin drill is thus not essential, particularly for clinical applications, but it is very helpful if maximum zero accuracy is required.

(7) Clinical Observation

In the course of this survey an interesting clinical observation was made which, so far as the search has gone at the present, does not seem to have been reported previously.

While doing the task of fixing on demand the successive points set at 50° intervals almost every subject from the very start has no difficulty in fixing steadily each point until asked to move on to the next. The result, on the record, is a series of clear, even "steps", of which typical examples can be seen in Fig. 4. However, during the first survey, Subject 40 was found to be markedly unsteady in his fixations. When asked to move to the 5° point, he might well move rapidly to the 5°, 10°, and 15° points, and then settle his fixation back on the 10° point until told to move back one step to the 5° point; then, when asked to move to the 10° point, he might move to the 10° point and rapidly on to the 15° point and hold his fixation there until told to move back; again, when asked to hold steadily on zero, he would often move rapidly to points either side, fix zero for a short while, and then move off to one side again. At the time this behaviour was thought to be caused possibly by anxiety, lack of understanding, or deliberately poor co-operation, and a usable, though still irregular, record was obtained eventually, with an assistant pointing to the fixation spots. However, when the results were analysed, it was obvious that this response pattern was not just the worst example from a population of patterns but was instead an entirely different type of response.

This subject was marked down, along with others whose "step" records had not been taken because of excessive drift, for special study during the re-test survey 10 months later. During this second survey Subject 40 was not available, but one of those whose "steps" had been omitted previously, Subject 50, was found to have, to a lesser degree, this same labile pattern of movement and fixation. In discussion, Subject 50 said that he was aware of his inability to maintain a steady fixation for long, that as far as he could remember he had always had it, that he did not think it interfered with his normal activities or with reading, that it had never previously been mentioned in any ophthalmic examinations, that he had no complaints about this vision, and that the only activity he found difficult was rifle-shooting, in

FIG. 8.—Subject 40 attempting 0° to 30° left in 5° steps.

which the target became blurred when fixed with the right eye, so that he always shot “left-handed” using the left eye.

An opportunity arose subsequently for a fuller test of Subject 40, during which the phenomenon was unchanged despite the subject’s full understanding of the task, good motivation, and apparent freedom from anxiety; this subject has now been tested on three separate occasions and has stated himself that he understands clearly, is trying hard, and is not worried. Part of a record of his horizontal eye movements on the 5° steps task, along with the exact timing and words of the experimenter’s instructions, taken from a tape-recorder, is shown in Fig. 8. During these latter tests this subject has also been found to have an unusual response pattern when asked to fix and follow a moving target. The “normal” response in this situation, with a target speed in the range of 30°/sec. to about 1°/sec., is one saccadic movement to “lock on” to the target and then a smooth rotation of the eyeballs at the same speed as the target, with in some cases small saccadic movements of not more than about 2° (Dodge, 1903; Westheimer, 1954).

An example of the typical response is given in Fig. 9 (opposite), where the pursuit eye movement at a mean speed of 3°/sec. follows the target as it moves across the horizontal frontal plane from 33° left to 33° right at constant speed. Subject 40, however, tends to develop the correct velocity of smooth eyeball rotation, but intersperses it with large saccadic movements, some as much as 20° in extent, to points in advance of the present target position. An example of his following a target moving horizontally at about 6°/sec. (at which he was a little better than at slower speeds) is shown in Fig. 10 (opposite).

FIG. 9.—Average subject following a target at 3°/sec.

FIG. 10.—Subject 40 attempting to follow a target at 6°/sec.

The timing marks indicate when the target was at successive 5° points in the visual field.

In a full discussion the subject said that he was not aware of this phenomenon and thought, for instance, that he was fixing the moving target all the time. He had no complaints about his vision; his rifle-shooting performance had been poor, but he could not remember whether he kept looking away from the target.

Neither of these two subjects had any items in their medical history which might suggest an explanation or correlation. Subject 50 at about 3 years of age had had his adenoids removed in hospital. Apart from this neither had ever been in hospital, had ever had severe head injuries or nerve diseases such as meningitis, or had even been knocked unconscious (as far as they were aware). The mental and educational development of both appears to have been within the normal range, and neither was unduly near the bottom level in the T2 selection test (their scores were 79 and 84; the range of this recruitment was from 56 to 121).

An ophthalmic report was obtained on both subjects. Subject 50 has uncorrected visual acuity 6/9 in both eyes separately, slight astigmatism and refractive error, Maddox wing exophoria 7°, and left hyperphoria 1°

to 2° . However this imbalance is well compensated, and, although both eyes show some alternate suppression, there is moderately good fusion and stereopsis. The left is the master eye and the right the constant deviator; this latter point would seem to explain the subject's change to "left-handed" rifle-shooting. However, in view of the relatively good compensation, fusion, and stereopsis, it is by no means certain that the ophthalmic defects are the cause of this subject's unusual eye-movement and fixation pattern; but the possibility cannot be excluded.

Subject 40, on the other hand, whose records are shown in Figs 8 and 10, has uncorrected visual acuity 6/6 both eyes, Maddox wing exophoria 4° , right hyperphoria 0.5° , both well compensated; slight convergence deficiency and some central suppression on left eye, otherwise binocular vision satisfactory. It does not appear that the ophthalmic defects can be the cause of this subject's markedly unusual eye-movement and fixation patterns.

These symptoms do not appear to match any of the many types of nystagmus, as classified by Duke-Elder (1932), except possibly the category of "pseudo-nystagmus", which would appear to be a broad designation covering the remaining nystagmoid patterns with no clearly established aetiology. It is tempting to speculate about possible causes, perhaps in terms of some minor neurological fault, but more evidence is needed.

(8) Integrated Data on the Technique of Electro-Oculography

Statements of the accuracy of the EOG technique have varied between not better than 5° (Jung, 1939) to $\pm 1^\circ$ (Halstead, 1938). However no statistical data have in fact been published to establish its accuracy as a method of recording eye movements, and Marg (1951) has pointed out the need for such a study.

Moreover it is important to distinguish between the various types of accuracy which can be quoted. First there is the sensitivity of the technique, in terms of the smallest eye movement which can be detected. Secondly, there is the zero accuracy in terms of the maximum amount by which eye movement results may be in error, within a certain period of time, because of drifts of the zero point from which all measurements must be made. Thirdly, there is the calibration accuracy, in terms of ± 2 standard deviations of the error distribution of the results, recorded and interpreted in the usual way, when a series of known eye movements is repeated several times by a reasonable sample of subjects.

From the data on EOG potential level, practical linearity and zero drift (using the full preparatory technique), reported in Sections 1, 2, and 6 above, statistical assessments can be made of these various accuracy terms. The results of course apply to horizontal eye movements when recorded with electrodes across the two eyes in series; the same type of analysis will apply to other methods of recording but the numerical results will be different.

The data on sensitivity and calibration accuracy will apply whether AC or DC recording methods are used, but the data on zero accuracy are relevant only to DC recording of the eyeball position with respect to a fixed zero point; AC recorders are of course used to nullify drifts of the zero level.

Sensitivity.—The smallest eye movement which can be detected depends upon the potential per degree of eye movement from the electrode positions used and upon the peak-to-peak noise level of the recording system. Zero drifts may, for practical purposes, be ignored when recording for only a second or two, provided the full preparatory technique is used. Moreover when it is desired merely to record whether or not an eye movement has occurred, for instance as a control on the maintenance of a given fixation during perception experiments, then an AC amplifier with a long time constant, for instance an EEG amplifier, can safely be used, without loss of relevant information, to eliminate any residual zero drifts.

Suitable amplifiers are available with peak-to-peak noise levels of less than $3 \mu\text{V}$. Taking a conservative view, and requiring a signal to be nearly twice the noise level to be classified as reliably detectable, we may conclude that an eye movement can certainly be detected if it results in a change of potential of $5 \mu\text{V}$ at the electrodes. The exact amplitude of the smallest detectable eye movement will therefore vary between subjects according to their EOG potential level and the electrode positions.

With the electrode positions used in this survey, it is clear from the EOG potential distribution of Section 1 that horizontal eye movements from 30 min. down to 10 min. of arc can be detected. With special electrodes placed close to the external canthi, the higher potentials obtained may enable eye movements as small as 5 min. of arc or less to be detected with suitable subjects.

Zero Accuracy.—The assessment of zero accuracy depends upon the potential per degree of eye movement from the subject and upon the distribution of zero drifts which occur over the time periods which are of interest. The residual noise level and drift of a good recording system may, for practical purposes, be ignored.

Thus to determine the maximum amount by which eye movement results may be in error, within a certain period of time, it is necessary to combine the data from two distributions, that of the EOG potential levels of different subjects and that of the amplitudes of zero drift. This has been done, and from Fig. 11 (overleaf) it can be deduced what percentage of subjects will have what maximum error (in degrees of eye movement) for what percentage of one-minute recording spells. It should be remembered that the results given here are specific to the full preparatory technique with skin drill, and to horizontal eye movements and the electrode positions used in these experiments.

FIG. 11.—Zero accuracy of present EOG technique.

However the results are considered to be very conservative estimates of the zero accuracy attainable. The maximum error figures assume that all movements would be measured, in each one-minute recording spell, from the same arbitrary zero level; but because there is a general tendency for the zero drifts to progress fairly linearly for several minutes at a time, it is possible, by interpolating a zero line between the two levels at start and finish, from which to make all measurements, to improve considerably the accuracy of analysis. Again, by placing the electrodes nearer the external canthi larger EOG potentials can be obtained, thus improving the ratio of the signal to the drift error. Moreover the longer the electrodes are in position the smaller the zero drifts tend to become (mean drift rate for first half of zero drift test periods = $56 \mu\text{V}/\text{min.}$, for second half = $44 \mu\text{V}/\text{min.}$; 20 per cent. improvement significant at $P = < 0.01$. Shackel, 1958).

Thus Fig. 11 is probably a reliable guide to the worst error results which should now be attainable with the technique of electro-oculography, but does not fairly represent the best which can be achieved.

Calibration Accuracy.—Ideally, the assessment of calibration accuracy should be uncontaminated by an error term from zero drifts. In practice this is not possible; the zero error can only be diminished as far as possible (by interpolating a zero level between the zero checks at start and finish). Therefore the measures of calibration error obtained from this survey really provide assessments of the total error of the EOG technique for various angular excursions in the horizontal plane.

The subjects were fixing a series of known points, their results were interpreted into degrees of eye movement in the usual way, and the distributions

of the differences between the actual and the recorded excursion were computed. From these analyses it is clear that the technique may be regarded as accurate to $\pm 1.2^\circ$ for excursions up to 20° and to $\pm 1.35^\circ$ for excursions up to 30° . Results of this accuracy are obtainable when using only a simple linear calibration from one excursion point. The calculation of best-fitting linear calibration plots to the data of each subject is not regarded as practical for routine use; there are indications, therefore, that care must be exercised in the method of calibration when using the technique to investigate accurately excursions of more than 30° from the centre (see Section 3 for details).

It should be emphasized that, as discussed in Section 2, these assessments of accuracy are considered pessimistic and therefore reliable. The technique of electro-oculography thus seems capable of providing accurate, objective, eye-movement records both for research and for routine clinical use, as has been emphasized by, for instance, Cohn (1957), Dieterlé and von Berger (1954), and McLay, Madigan, and Ormerod (1958).

Conclusion

It is believed that the survey has adequately fulfilled its purpose of exploring empirically some parts of the field of electro-oculography. That it has raised more problems than it has solved is regarded as a measure of its value.

Three main sections can be distinguished. Some statistical evidence has been gained on EOG as a technique for recording eye movements; some more precise tests are needed to determine its ultimate accuracy. Some evidence has been gained about the EOG potential itself as a psycho-physiological variable, adding slightly to the evidence already available which suggests that some significant relationship with body metabolism may be found; it is hoped to study this problem further in a number of ways. An individual difference in eye-movement behaviour of two subjects is reported; further investigation is needed.

A second survey on the same group of subjects has already been made as a continuation from this study. The results will be reported in due course.

Summary

126 subjects, making a series of simple eye movements and fixations in the horizontal plane, were studied by means of the electrical technique for recording eye movements known as electro-oculography (EOG) in order to learn more about the underlying principles of the technique and about the eyeball potential itself. The test took less than 10 min. on each subject. The following main evidence was obtained:

- (1) In the population tested and with the method used the mean EOG potential for a 30° horizontal excursion is $580 \mu\text{V}$, with a range of about 300 to $1,000 \mu\text{V}$.

- (2) The relationship between EOG potential and eyeball rotation may be regarded as linear for excursions up to 30° either side of centre; the accuracy of recording eye movements in this range, by linear conversion from single calibration points at 25° , is not worse than $\pm 1.35^\circ$.
- (3) Some supporting but not conclusive evidence was found for the hypothesis that the true relationship between EOG potential and eyeball rotation is a sine function.
- (4) A correlation for EOG potential level with age of $r = -0.33$ was found.
- (5) No other significant and reliable correlations with EOG potential level were found.
- (6) The zero accuracy of the technique without using the "skin drill" was found to be more than ten times worse than when preparing subjects fully with the "skin drill" as well.
- (7) Two subjects were found to have an unusual and, it is believed, hitherto unreported type of eye-movement and fixation response-pattern for apparently "normal" persons doing a simple visual task.

Some implications and deductions from the results are presented.

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APPENDIX

SOME SUGGESTED DEFINITIONS IN ELECTRO-OCULOGRAPHY (EOG)

CORNEO-RETINAL STANDING POTENTIAL.—The actual potential difference between cornea and foveal sclera as measured by electrodes placed in contrast with those structures. It is thus normally exactly measurable only on freshly-excised eyes.

EOG POTENTIAL.—The corneo-retinal standing potential as measured in an EOG situation by means of peri-orbital electrodes suitably placed to record a potential difference when the eyeball position in the plane of the electrode departs from the mean zero point (at which cornea and central retina are approximately equidistant from the electrodes.)

EOG POTENTIAL LEVEL OF A GIVEN SUBJECT.—A measure of the corneo-retinal standing potential level for that subject, because it is the EOG potential recorded under standard conditions.

UNIOCLAR EOG POTENTIAL LEVEL.—This is measured in the horizontal plane across one eye.

BINOCULAR EOG POTENTIAL LEVEL.—This is measured horizontally across both eyes with an electrode placed near the external canthus of each.

Note: For exact measurement the electrodes must be placed precisely on the horizontal plane through the cornea.

EOG POTENTIAL LEVEL.—The mean potential recorded at any time for a 30° excursion. It is the mean of at least one excursion each side of centre to 30° left and 30° right; it may be expressed simply in millivolts or microvolts, the standard conditions being assumed, or may be divided by 30 and expressed in microvolts per degree ($\mu\text{V}/\text{deg.}$). Unless stated to be unioclar, it is assumed that any EOG potential level is a binocular level (because Lead 3, as defined by Miles, horizontally across both eyes gives more reliable results; Miles, 1939b).

Note: It is known that EOG potential varies with the distance of the electrodes from the eye, but the exact relationship is not known. Therefore at present the EOG potential level of one subject cannot be directly compared with that of another subject unless the electrode positions be known to be identical on both. Also one distribution of EOG potential levels cannot be directly compared statistically with another unless it be known that the electrode positions were substantially the same for the two surveys from which the distributions were obtained. Two distributions obtained by the same experimenter are probably comparable, provided he has used the same electrodes and technique, because he will have placed the electrodes in much the same position on people with similar facial structure; provided the sampling populations are reasonably large and of broadly similar age and racial groups, the differences due to different facial structures (which therefore cause different distances between the electrode and the eye) will add a random sampling error but will not bias the data.