EYE-MOVEMENTS IN A TWO-DIMENSIONAL PLANE: A METHOD FOR CALIBRATION AND ANALYSIS USING THE VERTICAL AND HORIZONTAL EOG *

J.C. WOESTENBURG **, M.N. VERBATEN and J.L. SLANGEN

Department of Psychophysiology, University of Utrecht, 3511 BZ Utrecht, The Netherlands

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A method for calibration, orthogonalization and standardization of eye movements is described. The method is based on linear transformation of the horizontal and vertical EOG. With this method it is possible to measure the locus of eye fixation on a TV screen and its associated fixation time. Because of the used time constant (TC) of 36 sec, subjects must look at the centre of the TV screen or at random places on the screen during the interstimulus intervals (ISIs). For the EOG registration pre-amplifiers with a long TC were used to cut off slow changes in polarization caused by the electrode-electrolyte combination. In the calibration procedure only four orthogonal stimulus points were used. In an experiment to evaluate this method, subjects had to fixate letters on a TV screen in 12 different pre-determined positions. The distance between the measured locus of fixation and the coordinates of the stimulus was measured. The mean horizontal errors ranged from 1.4–2.2 degrees of arc and the mean vertical errors from 2.4–3.8 degrees of arc across subjects. It was concluded that accuracy was within acceptable limits, despite the fact that eye movement behaviour during the ISI was free. It was shown that the method is insensitive to non-orthogonality of the vertical and horizontal EOG. Calibration and transformation can be done by any real time computer system. The method is suitable for measuring, e.g. the visual orienting reaction (VOR), and it can also be applied in event related potential (ERP) studies where ocular fixation is used.

1. Introduction

Of the several low cost methods of measuring eye movements, electro-oculography (EOG) is one that gives the least hindrance to the subject. The problems involved in EOG recording are summarized by Shackel (1967) and Tursky (1974). However, progress in the preparation of low-drift Ag-AgCl electrodes and the availability of high-input impedance pre-amplifiers have made these problems surmountable (Young and Sheena, 1975). Most im-

* This is a revised version of the method described in Woestenburger (1978).

** Send reprint requests to: J.C. Woestenburger, Department of Psychophysiology, Varkenmarkt 2, University of Utrecht, 3511 BZ Utrecht, The Netherlands.

portantly, the EOG supplies us with a voltage signal which allows direct input into a mini-computer for analogue-digital (A/D) conversion and on line processing, which makes eye-movement analysis practicable without additional equipment. By the method proposed here it is possible to determine the locus of eye fixation on a TV screen and the associated fixation time using the vertical and horizontal EOG. As mini-computers are becoming standard equipment in psychological laboratories, this technique is within the reach of many investigators and requires little additional investment.

The horizontal EOG is usually measured from electrode positions at the outer canthus of each eye, while for the vertical EOG the electrodes are placed under and above one of the eye sockets. Usually it is necessary to locate these two pairs of electrodes in exactly orthogonal positions, because failure to do so results in an inaccurate determination of the locus of eye fixation. However, it is difficult to reach this exact orthogonality. It is possible to correct to some extent for the non-orthogonality of the electrodes by replacing them, using a trial-and-error procedure, but this method is far from perfect (Shackel, 1967). Firstly it is time consuming, and secondly two other factors may lead to non-orthogonality and thus to 'crosstalk' of the vertical and horizontal EOG. One is the lack of homogeneity in the distribution of the potential field of the eyes, and the other is the diversion from parallelism between the plane formed by the subject's eyes and the plane in which the stimulus material is presented.

The eye movement calibration procedure presented here has the advantage of being fast, and the method for eye movement analysis is insensitive to the non-orthogonality of the vertical and horizontal EOG.

In contrast to eye-trackers using the cornea-reflex method (Harris, Hainline and Abramov, 1981), only 4 calibration points are sufficient. Within the range of about 30 degrees of arc both horizontal and vertical eye movement potentials are linearly related to the angle of eye rotation (Shackel, 1967; Bicas, 1972). Calibration with cornea-reflex methods usually is more complicated, because the cornea and the rest of the eye have different radii of curvature (Hainline, 1981).

2. Method

The method is based on the assumption that there is a linear relation between EOG voltage changes and angle of eye rotation, at least for eye movements up to 30 degrees of arc from the centre. Because of the used time constant (TC) of 36 sec (see paragraph 2.2.1), subjects must look at the centre of the TV screen or at random places on the screen during the interstimulus intervals (ISIs). To determine the locus of eye fixation on a TV screen, the non-orthogonal A/D coordinates of the measured EOG must be expressed in orthogonal coordinates which can be related to the coordinates of the TV

Fig. 1. The TV coordinates of the calibration stimuli.

Fig. 2. The actually measured A/D coordinates of the eye fixations of 3 subjects, corresponding to the TV coordinates of fig. 1.

screen. The solution to this problem is to transform the A/D coordinates to a new standardized system of coordinates. The TV coordinates are also expressed to the latter system of coordinates. For this purpose a computer program was written based on the following theoretical considerations.

When orthogonal calibration stimuli – stimuli in each corner of the TV screen – are used (fig. 1), the measured A/D coordinates of fixation to these stimuli are usually non-orthogonal. The EOG coordinates yield visual fields, e.g. as presented in fig. 2.

A stimulus presented on the TV screen with coordinates M (horizontal) and V (vertical) and which concurs with the locus of eye fixation on the TV screen can be related to the EOG coordinates as follows:

$$HOR = a_1 MV + a_2 M + a_3 V + a_4, \quad (1)$$

$$VER = b_1 MV + b_2 M + b_3 V + b_4, \quad (2)$$

in which HOR is the horizontal EOG coordinate, VER the vertical EOG coordinate, and a_1 to a_4 are constants which are derived from EOG values determined during the calibration procedure (the calibration stimuli: (a, b) , (c, d) , (e, f) and (g, h) , see also paragraph 2.3.1 and appendix A). The constants are:

$$a_1 = (e - g - c + a)/N^2, \quad b_1 = (f - h - d + b)/N^2,$$

$$a_2 = (c - a)/N, \quad b_2 = (d - b)/N,$$

$$a_3 = (g - a)/N, \quad b_3 = (h - b)/N,$$

$$a_4 = a, \quad b_4 = b.$$

The formulae (1) and (2) are linear and have a linear interaction which accounts for the 'cross-talk'.

With $N = 100$, the orthogonal coordinate system has a resolution of less than half a degree using integers.

Only M and V are unknown. They indicate the values in the $N * N$ coordinate system which concur with the locus of eye fixation on the TV screen. Because of the linear interaction ($M * V$ in formulae 1 and 2) M must be determined by a quadratic solution of the form: $XM^2 + YM + Z = 0$ (see appendix A). This results in two solutions of M . The M value closest to the middle of the visual field (coordinates 50, 50) is considered to be the correct M . V is found by an inverse transformation of (1) (see appendix A).

The proposed method is applied in the experiment to be described. Its possibilities are demonstrated by presenting stimuli in 12 different locations on the TV screen and measuring the distance between the measured locus of eye fixation and the TV coordinates of the stimulus.

2.1. Subjects

Subjects were three males and two females. The mean age was 21 years, S.D. 2.3. Subjects who wear glasses kept them on during the experiment.

2.2. Apparatus

2.2.1. Electro-oculogram (EOG)

Ag-AgCl electrodes in plastic cups were used¹. They were attached by means of adhesive rings. For the horizontal EOG the electrodes were placed at the outer canthus of each eye and for the vertical EOG infra-orbital and supra-orbital electrodes were placed in line with the pupil of the left eye. Hellige EEG paste was used because of its low polarization in combination with the Ag-AgCl electrodes. Resistance of the electrodes was never higher than 2 K Ω . The signals from the electrodes were amplified and filtered by high-input impedance pre-amplifiers with a TC of 36 sec and a low-pass frequency of 15 Hz. The long TC was chosen to cut off slow changes caused by the polarization of the electrode-electrolyte combination. The pre-amplifier output was first sent through a 50 Hz notch filter and a 45 Hz low-pass filter to cut off 50 Hz main frequency and its harmonics (mainly the third harmonic) and then sent to the analogue inputs of a PDP 11/40 computer for A/D conversion and on line processing. Sampling during calibration and experimental stimuli started at stimulus onset and lasted 2 sec. The sample rate was 40 Hz.

2.2.2. Stimulus conditions

During the experiment subjects lay on an examination table in an acoustically and electrically shielded room. The upper portion of the examination table was adjustable so that the subjects head could be adjusted to a position roughly parallel to a TV monitor (black-white, 26 inch screen) which was positioned above and in front of the subject at a distance of 60 cm from the subject's eyes. The subject's head was positioned so that the centre of the TV screen was in the centre of the subject's visual field. Clamps were used to fix the head in order to limit horizontal head movements. Eye movements from the centre to each of the four corners of the TV screen were 28 degrees of arc.

2.2.3. Stimuli

Stimuli presented during the eye movement calibration were the letters O and X. They appeared on the TV screen in an alternating sequence. The O was presented for 3 sec in the centre of the TV screen, followed by an X in one of the corners (see fig. 1). The X was presented for 2 sec in alternating corners.

During the experiment letters were presented in 12 different positions on the TV screen. The ISI was 7 sec. During calibration and experiment the letters subtended 1.1 degrees of arc for the vertical dimension and 1.0 degree of arc for the horizontal dimension.

¹ Silver electrodes were chlorized in a 5% NaCl solution with a constant current source of 10 μ A during 5 min. These electrodes were only used in one experiment. Afterwards they were dechlorized and the silver area cleaned so that the above procedure could be repeated.

Eye movements as well as the marks of stimulus onset and offset were displayed as ink-records on a mingograph 80 polygraph. Horizontal and vertical EOG's were also displayed on an X-Y oscilloscope for purposes of checking. Presentation of stimuli, instructions, and the sampling procedure were controlled by PDP 11/40 programs.

2.3. Procedure

On arrival the subject was familiarized with the procedure and put at ease regarding the methods employed and his/her part in the experiment. The head was fixed in the desired position (see 2.2.2) and the subject was informed that instructions would follow on the TV screen. The experiment started with a 5 min adaptation period after which the calibration period began.

2.3.1. Eye movement calibration

The subject was asked to fixate the calibration stimuli as accurately as possible. A calibration trial consisted of three runs around the four corners of the TV screen (see 2.2.3). The first run was used to familiarize the subject with the calibration procedure. During the second and third run, horizontal and vertical EOGs were sampled and the A/D coordinates which concurred with the locus of eye fixation during presentation of the X were determined. In order to do so, the EOGs were analysed on line by a computer program. After this program detected an eye movement towards the X, it determined fixations. A fixation was defined as a period of longer than 300 msec in which there was less than 50 A/D units of change compared to the previous sample. The criterion of 50 A/D units was about 2.5% of the distance of the A/D coordinates measured between two Xs in the same dimension. This criterion was used to account for effects caused by the TC. Subsequently, the longest fixation period was determined, and from the associated horizontal and vertical EOG the first samples were taken as the A/D coordinates describing the locus of eye fixation during presentation of the X. Because data were collected over two runs around the four corners of the screen, two A/D coordinates were determined for each of the X positions. The difference between these two values was not allowed to be larger than 10% (horizontally) and 15% (vertically) of the mean distance between the A/D coordinates of two different stimuli in the same dimension.

If necessary, the calibration procedure was repeated until this criterion was met. All three subjects reached the criterion in one or two calibration trials. When the criterion was met, the computer constructed a two-dimensional representation of the four different positions of the letter X as perceived by the subject (see fig. 2).

2.3.2. Experimental letter stimuli

After the calibration procedure, the subject was instructed that a number of letters would be presented at different places on the TV screen. He or she was

instructed to fixate these letters accurately. Then the letter H was presented in 12 different positions (see table 1 and fig. 3) and horizontal and vertical EOGs were sampled during the stimulus presentations. Eye movement behaviour of the subjects during the ISI was free.

2.4. Scoring of the locus of eye fixation

The TV coordinates and the A/D coordinates (eye movement coordinates) belonging to a certain letter position were transformed to the 100*100 system of coordinates. Eye movement analysis was done on line in this 100*100 system. After the program detected an eye movement towards the stimulus, fixations were determined. A fixation near the stimulus was defined as a period of longer than 300 msec in which the change in the 100*100 units was less than or equal to 2% compared to the previous sample. The 2% criterion, corresponding to 0.84 degrees of arc, was used to account for effects caused by the TC. Subsequently, the fixation closest to the locus of the stimulus on the TV screen was determined and the first samples were scored from the associated horizontal and vertical $N*N$ coordinates as the locus of fixation of the stimulus.

3. Results

The locus of fixation as measured by the described method was compared to the actual position of the stimulus. The results show that they were close together. The distances between the locus of the stimulus and the measured locus of fixation are summarized in table 1 for the 3 subjects.

As table 1 shows, the accuracy of the transformed coordinates, averaged over trials, ranged from 1.36–2.16 degrees of arc for the horizontal coordinates and from 2.4–3.8 degrees of arc for the vertical coordinates. For the 12 stimuli presented, the measured loci of fixation are represented in degrees of arc in fig. 3 for the 5 subjects. The heavy lines indicate the deviation of the locus of gaze from the locus of the stimulus.

4. Discussion

The original non-orthogonal vertical and horizontal EOG (see fig. 2) does not indicate the position of the eyes less accurately than the transformed coordinates, but it is difficult to relate the original EOG data to any point on the TV screen. This is the main reason why the non-orthogonality of the EOG presents a problem in the determination of the locus of eye fixation.

The results of the orthogonalization method shown in table 1 illustrate that the accuracy of the transformed coordinates ranged from 1.36–2.16 degrees of

arc for the horizontal measurements and from 2.4–3.8 degrees of arc for the vertical measurements. These values are well below the calibration error criterion and near the range as summarized by Young and Sheena (1975). The less accurate vertical coordinates (see also fig. 3) must also be considered in relation to the less accurate calibration criterion used for the vertical EOG. The latter EOG lead is less stable due to, e.g. eyebrow displacements, which affect potentials recorded on the electrode above the eye.

It should be noted that looking behaviour during the ISIs was free. Despite this fact the accuracy was within acceptable limits. Free looking behaviour was chosen for two reasons. Firstly, in many psychophysiological experiments free looking behaviour is needed or desirable. Secondly, it offered the opportunity for the most rigorous test of the proposed method, because under this condition the TC of 36 sec can have negative effects on the method's accuracy. The method would not hold if during the ISI a subject should look for several seconds at a systematically preferred place more than 10 degrees of arc away from the centre of the TV screen. Such looking behaviour would cause a shift away from the eye movement calibration values because the TC of 36 sec would determine a new 'centre' for the next eye movements. One should

Table 1

TV coordinates of the stimulus and distances between the measured locus of fixation and the TV coordinates for 3 subjects, expressed in the 100×100 coordinate system. Mean distances over 12 stimuli and S.D. in terms of 100×100 coordinates and degrees of arc.

TV coordinates (100×100)		Distances between TV coordinates and locus of eye fixation					
HOR	VER	Subject 1		Subject 2		Subject 3	
		HOR	VER	HOR	VER	HOR	VER
25	25	2	15	8	28	7	8
50	100	14	11	1	2	4	1
100	50	2	19	0	14	0	19
50	50	1	5	8	16	7	11
100	0	4	4	13	11	5	13
25	75	4	4	10	7	13	0
50	0	3	16	7	11	7	1
75	75	0	1	1	4	6	6
0	100	5	5	1	1	2	7
75	25	1	8	1	25	6	2
0	50	4	2	10	0	2	3
100	100	1	2	0	9	6	9
Mean distance in the 100×100 system		3.4	7.6	5.0	10.6	5.4	6.7
Mean distance in degrees of arc		1.36	2.7	2.0	3.8	2.16	2.4
S.D. in the 100×100 system		3.67	6.12	4.76	9.98	3.31	5.74
S.D. degrees of arc		1.47	2.2	1.9	3.23	1.3	2.06

Fig. 3. Distances between the TV coordinates of the stimulus and the corresponding measured locus of fixation (in degrees of arc) of 5 subjects for each of the 12 letter positions.

remember that the EOG voltage describing a fixation at a certain eccentric point is already reduced by 30% in 4 sec when a TC of only 36 sec is used. However, if the experimental situation does not provoke it, subjects generally do not look in such a way, not even with longer ISIs than in this experiment. This property of eye movement behaviour makes it possible to use a TC of 36 sec to cut off slow changes caused by polarization of the electrode-electrolyte combination. This change of polarization makes DC recording impossible, because the EOG signal would drift out of the dynamic range of the final amplifier and A/D converter. However, if TCs much longer than 36 sec were to be used, the accuracy of the method might be enhanced. In that case, the

method can also be used in experimental situations where its prerequisites are not met.

It can also be expected that the accuracy may be increased when subjects are given the centre of the TV screen as a continuous reference point during the ISI. Such reference point can also be used in research on event related potentials (ERPs) if ocular fixation is applied to avoid the eye movement artifact. In such studies the method proposed here can be used to determine if the subject is looking at the preset point. If necessary, stimulus presentation can then be postponed until the present point is fixated (Woestenburg, Verbaten and Slangen, 1981; Woestenburg, Verbaten and Slangen, 1983). The method might be applied in visual half-field studies to control the locus of eye fixation before stimulus presentation. For applications of the method to determine the visual orienting reaction (VOR), see Verbaten, Woestenburg and Sjouw, 1979; Verbaten, 1981.

Appendix A

Background of the transformation

If the eyes fixate a point on the line $(a, b) - (c, d)$ of fig. 1 and 2, the fixation can be linearly described by:

$$X1 = (M(c - a)/N) + a \quad (3)$$

$$Y1 = (M(d - b)/N) + b, \quad (4)$$

in which M is the new horizontal coordinate, N is the subdivisor, and $X1$ and $Y1$ are the measured A/D coordinates.

The same can be done for line $(g, h) - (e, f)$:

$$X2 = (M(e - g)/N) + g \quad (5)$$

$$Y2 = (M(f - h)/N) + h. \quad (6)$$

A fixation on any point on any vertical line $(X1, Y1) - (X2, Y2)$ holding M constant can be obtained by substituting the above formulae in:

$$HOR = (V(X2 - X1)/N) + X1 \quad (7)$$

$$VER = (V(Y2 - Y1)/N) + Y1, \quad (8)$$

in which V is the new vertical coordinate and which results in formulae (1) and (2) in paragraph 2.

After changing the equations (1) and (2) we get:

$$V = \frac{HOR - a2M - a4}{a1M + a3} \quad (9)$$

and

$$V = \frac{VER - b2M - b4}{b1M + b3} \quad (10)$$

(9) subtracted from (10) gives:

$$\frac{HOR - a2M - a4}{a1M + a3} - \frac{VER - b2M - b4}{b1M + b3} = 0, \quad (11)$$

or

$$(a1b2 - a2b1)M^2 + (HOR b1 - VER a1 + b4a1 - a4b1 + b2a3 - a2b3)M + (b4a3 - a4b3 + b3HOR - a3VER) = 0. \quad (12)$$

The general form of (12) is $XM^2 + YM + Q = 0$.

The solution of M is obtained by:

$$M(1, 2) = -P \pm \sqrt{P^2 - Q} \quad (13)$$

in which,

$$P = \frac{HoR b1 - VER a1 + b4a1 - a4b1 + b1 + b2a3 - a2b3}{2(a1b2 - a2b1)}, \quad (14)$$

$$Q = \frac{b4a3 - a4b3 + b3HOR - a3VER}{(a1b2 - a2b1)}. \quad (15)$$

V can be found by formula (9).

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