A simple technique for tracking visual fixations without restricting head movements*

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A system for tracking visual fixations without restricting head movements is described. Method and circuitry are provided along with the calibration technique.

Normally, changes in visual fixation result from three kinds of movement: rotations of the eye, rotations of the head, and lateral displacements of the head. Most techniques for tracking visual fixations in the laboratory involve clamping the head in a fixed position so that changes can be related directly to rotations of the eyes. Restricting movement may, in certain circumstances, affect the pattern of those changes.

A technique for tracking visual fixations is described here which leaves the S free to make normal head movements when the image of the display subtends an angle of less than 35 deg on the retina. Although techniques that allow more freedom of movement are available (Mackworth & Mackworth, 1958; Rashbass & Westheimer, 1960; Cornsweet, 1958), the present method is within the technical and financial capabilities of most small laboratories, and it involves a minimum of discomfort and inconvenience.

Displacements of the fixation point can be related to movements of the eyes and head by the following equation:

$$e = x[\tan(\mu^\circ + \alpha^\circ + \nu^\circ + \beta^\circ) - \tan(\mu^\circ + \alpha^\circ)] + d, \quad (1)$$

where e is the size of the displacement, x is the distance of the S from the plane of fixation, μ is the angle which the line of sight subtends to the frontoparietal axis of the head before the displacement, ν is the angle through which the eyes rotate in their orbit during the displacement, α is the complement of the angle subtended by the frontoparietal axis of the head to the plane of fixation before displacement, β is the angle of rotation of the head during the displacement, and d is the lateral displacement of the eyes during the displacement.

In the arrangement described here, the S is seated so that the image of the display subtends an angle of about 35 deg on the retina when viewed perpendicularly and never moves more than 5 deg from the center of the retina if the S makes a lateral movement of the eyes. In consequence, angle $\mu + \nu + \alpha + \beta$ in Eq. 1 rarely exceeds 20 deg. Since the tangent function is almost linear over the range 0-20 deg, the equation:

$$e = C(\nu + \beta) + d \quad (2)$$

can be substituted for Eq. 1 with very little loss of accuracy.

Our technique provides an approximate measure of displacement of fixation in accordance with Eq. 2. Measures are obtained on both horizontal and vertical coordinates, so that by suitable calibration, the exact location of the fixation point can be tracked as it moves round the display.

MEASURING ROTATIONS OF THE EYE

Several methods have been developed for measuring the angle through which the eye rotates in its orbit (Ratliff & Riggs, 1950; Mackworth & Mackworth, 1958; Shackel, 1967; Smith & Warter, 1960). Electro-oculography was chosen as being the most suitable for present purposes. This technique is less accurate than some methods, but it causes very little discomfort and does not introduce distracting objects into the visual field.

Methods of electro-oculographic recording and their rationale have been described by Shackel (1967). A voltage is obtained by comparing potentials (with respect to an earth point) from electrodes placed at the outer canthi of the two eyes. This voltage changes in a roughly linear manner as the eyes rotate. A voltage that changes in a similar manner in response to vertical movements can be obtained from electrodes placed above and below the eyes. If the skin is suitably prepared by puncturing the epidermis, the level of noise can be reduced to a value corresponding to 1 deg of rotation in the horizontal axis and 2 deg of rotation in the vertical.[1] Zero drift rates as slow as ½ deg/min can also be obtained easily. Recordings should be made with high-quality silver/silver chloride electrodes mounted in a protective cup (Shackel, 1967) so that the electrode itself is not in contact with the skin. The space between electrode and skin should be filled with electrolyte jelly, and the electrodes kept in position by attaching the protective cup to the skin with either collodion or adhesive tape.

A differential dc amplifier with high input impedance is used to amplify the difference in potential of the two electrodes on each axis. It is important that the amplifier be fitted with facilities for backing off the input.

MEASURING ROTATIONS AND LATERAL DISPLACEMENTS OF THE HEAD

Measurements of head movement are made with a position-sensing phototransistor[2] attached to the head between the eyes by a headband, so that its receptive

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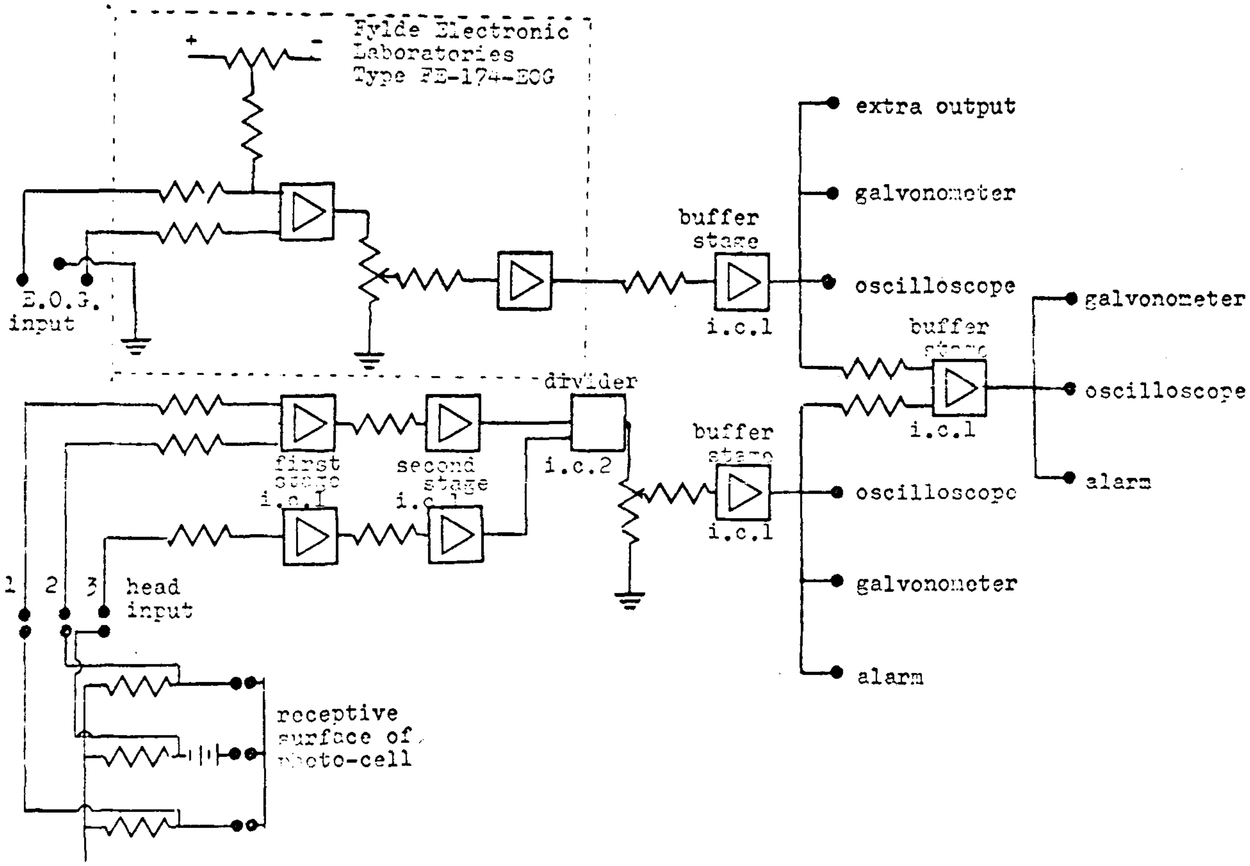

Fig. 1. One channel of eye- and head-monitoring systems. (i.c.1 is a R.S. Components operational amplifier, Type 741; i.c.2 is a four-quadrant divider made by Analogue Devices; Head Inputs 1 and 2 are position; and Input 3 is intensity.)

surface is perpendicular to the frontoparietal axis of the head. The phototransistor allows one to obtain two signals linearly related to the position of an incident spot of light along each of two coordinates. The origin of the two coordinates is the center point on the receptive surface. In the present application, a small spot of light originating from the center of the display is focused onto the surface of the phototransistor by a lens mounted in front of the phototransistor on the headband. With this arrangement, rotations and lateral displacements of the head that result in equivalent displacements of fixation also result in equivalent displacements of the spot of light on the receptive surface of the photocell.

Displacements of the spot of light on the photocell can be related approximately to changes in the angle which the incident beam of light subtends to the frontoparietal axis of the head by the equation

$$u = y \tan \Delta p, \tag{3}$$

where u is the size of the displacement of the spot of light on the receptive surface of the photocell, y is the distance between the lens and the receptive surface of the photocell, and Δp is the change in the angle which the incident beam of light subtends to the frontoparietal axis of the head.

A displacement of fixation (e) brought about either by a rotation of the head or by a lateral displacement of the head can be related approximately to angle Δp by the equation:

$$e = x \tan \Delta p, \tag{4}$$

where x is defined as in Eq. 1. It follows, therefore, that in the case of both head rotation and head displacements, displacements (e) of fixation can be related to displacements (u) of the spot of light on the receptive surface of the photocell by the equation

$$u = e\, y/x. \tag{5}$$

The phototransistor can be regarded as two differential devices, each measuring movement along one axis. As the spot of light moves on an axis, the current flow increases in one circuit and decreases in another. Signals from the two circuits are applied to the two inputs of a differential amplifier, and the latter provides an output linearly related to the position of the spot of light on the axis. However, signals obtained in this way are also related to the intensity of the spot of light on the phototransistor. In the present application, the light does not diffuse evenly from the source, so its intensity on the photocell varies with lateral movements. To

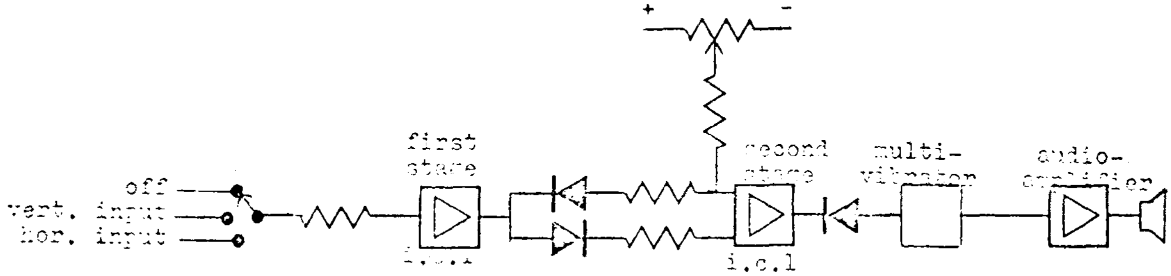

Fig. 2. Head-movement alarm. (i.c.1 is a R.S. Components operational amplifier.)

eliminate the confounding effect of light intensity on the output signal, the latter is divided by a figure proportional to the amount of light falling on the photocell. This figure is obtained by measuring the total amount of current flowing in the phototransistor. Four-quadrant dividers made by Analogue Devices[3] are used to perform the dividing operation. Before being added to the eye-movement signal, the head-movement component is passed through a final buffer stage to obtain output impedance matching between the two systems.

CALIBRATING

It is essential to the validity of the technique that equal angles of head and eye rotation give equal changes in signal level at the output. The change in signal level obtained from the photocell will be the same for a given angle of head rotation irrespective of who is S. The same is not true of the signal obtained from rotation of the eyes. Before recording from any S, therefore, the gain of the eye-movement system has to be adjusted so that the change in output signal for any angle of eye rotation is the same as for a corresponding angle of head rotation. This can be done by getting the S to fixate consecutively two points on the screen which subtend a known angle on the retina. The gain is then adjusted so that the change in signal level is the same as that which would be obtained if the S rotated his head through a similar angle.

The combined signals from the head and eye obtained during recording can be related to the exact position of the fixation point on the screen if, during the calibration procedure, the signal level obtained at either of the fixation points is noted. In practice, the simplest way of calibrating is as follows:

The S holds his head so that the frontoparietal axis is in line with the light source in the center of the screen and the head movement signal reads zero. The S then fixates a point in the center of the screen while the E adjusts the backing-off facilities of both the horizontal and vertical electro-oculography amplifiers so that the outputs read zero. Finally, the S fixates a peripheral point on each of the horizontal and vertical axes while the E sets the gain of the electro-oculography amplifiers so that the eye- and head-movement systems give the same change in signal level for the angle through which the S has rotated his eyes.

If this procedure is followed, the output voltages can be considered as values on a coordinate system that can easily be mapped onto a facsimile of the display.

An alarm can be used to warm the S when he moves his head from the zero position. This is done by using the output signal from the head-movement system to control a multivibrator, which in turn drives an audio-amplifier. The output signal from the head-movement system is rectified and amplified, and subsequently applied via a diode to the base of one transistor of the multivibrator. A backing-off voltage is also applied to the base of the transistor through the diode. When the backing-off voltage exceeds the voltage of the rectified signal, the diode is forward-biased and the multivibrator is cut off. If the rectified signal exceeds the backing-off voltage, the diode becomes reverse-biased and the multivibrator ceases to be cut off. By adjusting the backing-off voltage, greater and less movement from the zero level is tolerated before the multivibrator ceases to be cut off and the alarm sounds.

THE DISPLAY

Careful design of the display system is essential for obtaining satisfactory results with the technique described here. Two main factors have to be borne in mind. First, the change in signal level obtained with electro-oculography for a given rotation of the eye varies with the total amount of light falling on the retina. It is, therefore, essential to keep the level of illumination in the area of the display constant throughout one recording session so as to avoid continual recalibration. Second, the method of display must be such that the light source at the center of the screen does not distract the S, either by physically obscuring part of the display or by visibly increasing the level of illumination of some part of the display.

The layout of the display system is shown in Fig. 3. The displays are photographed on 35-mm slides and back-projected onto an opal-glass screen with an Aldis 2000 projector. A second projector with an identical light source and condenser system illuminates the screen while the display is being changed. A shutter determines which of the projectors illuminates the screen. The shutter consists of a metal disk mounted on a rotary solenoid at a central position between the lenses of the two projectors. A small sector is cut out of the metal disk, allowing the light from only one of the projectors

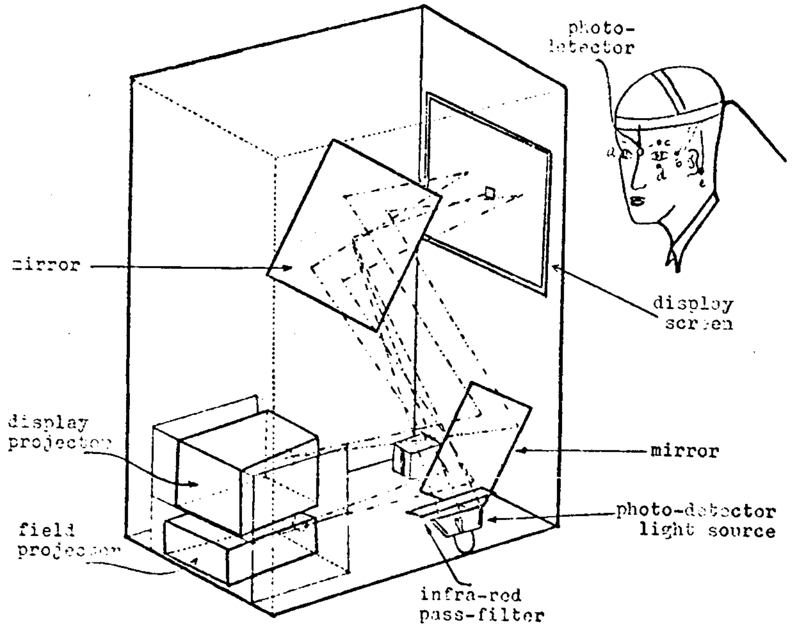

Fig. 3. The display system. (Letters on face show electrode placements.)

to reach the screen. To prevent light from the display reaching the photodetector and distorting the signal from the head-movement system, advantage is taken of the fact that the phototransistor is most sensitive to light in the infrared region of the spectrum. Infrared rejection filters are placed in front of the projectors, and an infrared pass filter is placed in front of the phototransistor.

The spot of light at the center of the screen which acts as reference for the position-sensitive photo device is projected from a quartz-iodine bulb by a concave reflector. An infrared transmission filter is placed in front of the projector to prevent light in the visible region of the spectrum from reaching the screen and distracting the S.

SIGNAL READOUT

A permanent record of signals from horizontal and vertical movements together with the S's statements while scanning the display are recorded on magnetic tape. The recorded signals are then used to replot the fixation points on a suitably calibrated large-display oscilloscope with a facsimile of the display placed over the tube. We have also used the signals in conjunction with an analog-to-digital converter and a digital computer to obtain a paper readout of the sequence of areas fixated, the duration of individual fixations, and the total amount of time spent fixating in each area when scanning a display.

ACCURACY

Accuracy of the recording technique was assessed in the following manner. The machine was calibrated as described above, and the gain was adjusted so that a 9-cm excursion of the fixation point along the horizontal axis resulted in a 5-V change in output signal. The S then made repeated excursions of the fixation from the center point to points at a distance of 4.5, 9, and 13.5 cm in the horizontal axis, simultaneously rotating his head around a vertical axis. Mean levels of output signal (accurate to within 100 mV) for excursions of each of the three magnitudes were 2.6, 5, and 7.3 V. The corresponding measures of variance expressed as a percentage of the mean were 10%, 5%, and 3.5%.

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NOTES

1. Eyelid movements are an unavoidable source of artifact in recordings of vertical eye movements. Blinks are easily detectable, taking the form of large-amplitude, and highly transient, changes of signal level—equivalent to a very rapid upward glance during which the eyes move through several tens of degrees. Other eyelid movements, resulting in changes of signal level equivalent to only a few degrees of eye movement, usually occur simultaneously with movements of the eye. Spontaneous eyelid movements often occur, particularly when a S is engaged in a difficult perceptual task.

2. The position-sensing photodetector is a dual-axis Type PIN-SC/4 made by United Detector Technology, 1732 21st Street, Santa Monica, California; price, £65.60.

3. The four-quadrant dividers are Type 426J made by Analogue Devices, 59, Eden Street, Kingston-upon-Thames, Surrey, England, and Cambridge, Massachusetts; price, £30.

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