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A new horizontal eye movement calibration method: Subject-controlled "smooth pursuit" and "zero drift"

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A subject-controlled smooth pursuit method of calibration of eye movement apparatus is proposed for the horizontal axis which is more rapid, requires no interpolation and no linearity assumption, and is as accurate as the fixation point method usually used. The zero drift method of verification proposed then permits accuracy to be estimated in a way that distinguishes apparatus errors from fixation errors. This is only possible in the fixation point method by asking the subject to make repeated long fixations.

Although many of the currently operating methods of tracking eye movements can measure very small changes in the position of the eye (for surveys, see Ditchburn, 1973, Chapters 2 and 3; Young & Scheena, 1975), the accuracy with which they can detect the absolute direction of the gaze in space is severely limited, even when extensive precautions are taken to eliminate artifacts. The reason lies only partly with technical difficulties, such as amplifier noise or instability and compensation of head movements. A less obvious but more fundamental problem is connected with the way the apparatus is calibrated, and more particularly, with the definition of "direction of gaze."

CLASSICAL METHODS

The Fixation Point Method of Calibration

In the classical "fixation point" method of calibration, the output of the eye movement monitor is recorded while the subject fixates several calibration points. To know where the eye is looking at a subsequent instant, some kind of interpolation procedure is used to deduce eye position from the values obtained for nearby calibration points.

But there is no such thing as a perfect fixation. On the one hand, when a person is asked to fixate a point, microsaccades may, over a period of a few seconds, bring the eye several minutes of arc from the initial direction of gaze (cf. Ditchburn, 1973, Chapter 4). An even larger source of variation comes from fatigue and changes in the subject's fixation criterion. As noted by Young and Scheena (1975, p. 238), subjects sometimes claim to be fixating a point when their eyes are more than 1 deg away from it. There is much controversy concerning the reasons for fixation instability, but it is clear that the reasonable way to define direction of gaze is by statistics: It is the mean direction adopted by the eye when the attention is focused on a point. Ditchburn (1973, pp. 94-95, p. 313) proposes that, for reliability, fixation be maintained for 10-20 sec. This becomes tedious over a number of calibration points.

A second problem with the fixation point method of calibration is also associated with the statistical definition of direction of gaze. Suppose one wants to know the error of calibration at a given point of the visual field. The subject is asked to fixate the point and an error is found. There is no way of knowing whether the error comes from faulty calibration or from the subject's fixation instability. Only by statistical evaluation of many fixations can any reliability be expected.

The third problem with the fixation point method is that interpolation of some kind must be used, and so some assumptions about the linearity of the apparatus response must be made. These assumptions are hard to verify on a real eye, since to do so requires a calibration procedure that does not require assumptions about linearity.

A "smooth pursuit" method of calibration overcomes the problem of interpolation and linearity, and to some degree, the problem of fixation instability. A "drift" method of verification of the calibration is able to distinguish the subject's fixation errors from calibration and apparatus errors.

NEW METHODS

The Smooth Pursuit Method of Calibration

Apart from an error of lag, the eye is able to follow closely and smoothly the motion of a slowly moving target (cf. Robinson, 1965, for example). The tracking is even more accurate when the target is moved by the subject (Angel & Garland, 1972; Steinbach & Held, 1968). This fact has been used in the design of the following computer-controlled calibration technique for the horizontal axis.

Figure 1 shows the arrangement. The subject controls

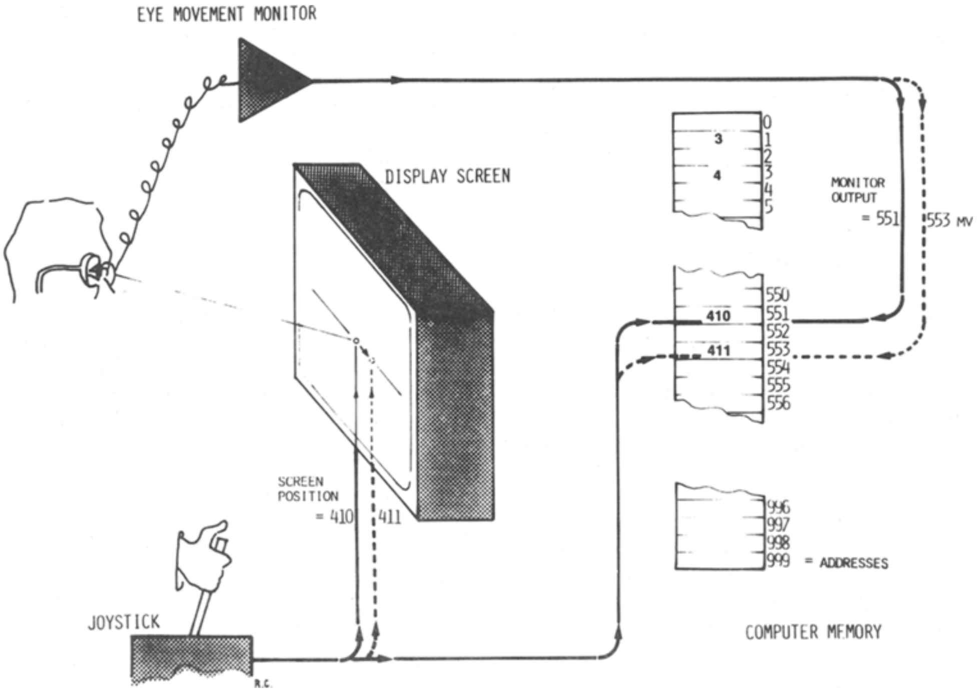

Figure 1. Subject-controlled tracking of a dot target in the smooth pursuit calibration method, and generation of an inverted calibration table (see text). At the instant depicted, the dot is at Position 410 of the screen and the eye movement monitor registers a voltage of 551 mV. The value 410 is put into Address 551 of the computer memory. At the next instant (dotted line), the dot moves to Position 411 and the monitor voltage changes to 553. The value 411 is put into Address 553 of the memory; empty memory locations are filled out after the calibration.

the motion of a point on the computer's display screen by moving a potentiometer knob or "joystick" connected to the computer via an analog-to-digital converter. He is asked to cause the dot to move from a starting position on (say) the left of the screen to a finishing position on the right of the screen. The output of the eye movement monitor is sampled for each position of the dot on the screen, and output-voltage/screen-position pairs are stored in the computer memory. After a complete scan across the screen, the memory contains a list or "calibration table" giving the correspondence between each screen position and its corresponding monitor output voltage. The calibration table can be used in subsequent experimentation to determine the eye position at any moment: It suffices to look up in the table the screen position corresponding to the voltage currently at the output of the eye movement monitor. Details on the best way to organize the calibration table are given later in this paper. Note that since a monitor voltage is recorded for each point of the screen, no assumption about linearity need be made, and no interpolation is needed. The method is also very rapid: A scan of the screen takes place in about 5 sec.

The Zero Drift Method of Verification

The problem in evaluating the accuracy of a calibration is to distinguish errors of calibration from the subject's fixation instability. A solution is provided by the use of feedback between the display and the subject's eye position. There are several variants of the method, all based on the following principle.

At every moment, the computer displays a point on the screen precisely where it calculates the subject is looking. If there is a small error of calibration, then the point will not in fact be exactly where the subject is looking, but slightly to the side. Seeing the point slightly to the side, the subject will move his eye to capture the point, but the point moves also, remaining constantly off center. If the error is smaller than a few degrees, a slow sideways drift occurs, whose speed is proportional to the error and to the contrast in luminosity between point and background (Andreeva, Verguiles, & Lomov, 1977). The phenomenon is similar to that which occurs when one tries to observe an afterimage or a speck in the eye that is not exactly central. It seems that the speed of the drift can be made arbitrarily small by observing an afterimage close enough to center. By taking advantage of this fact, the calibration error at a given position of the screen can be measured.

Thus, in the zero drift method, the computer does not display a point at the calculated eye position, but at a small variable distance to the side. As this offset is changed, drift speed changes. The offset required to bring the drift to zero equals the calibration error at the point being fixated. If two points are displayed, one a distance D to the left, and one a distance D to the right of the calculated point of regard, then the region of the horizontal axis can be obtained where the error is less than plus or minus D. In this region, if the left-hand point is fixated, the eye drifts to the left; if the right-hand point is fixated, the eye drifts to the right. In regions where the error is greater than plus or minus D, the drift will be in the wrong direction.

I have used the zero drift method extensively to estimate calibration errors as small as .01 of the width of my display screen (i.e., absolute position of errors of about 12 min of arc).

Further improvement may come from the "constant drift" method, which must still be investigated: Instead of adjusting the offset of the displayed point until an equilibrium state of zero drift occurs, the computer sets a given offset value and measures the changes in speed that occur when the eye drifts across the whole horizontal axis. These changes should be proportional to the calibration error near the point at which they occur.

Accuracy of the Methods

Is the position of zero drift the same as the mean position occupied by the eye in fixating a point? Clearly, the answer is yes, since when the eye is not drifting, it is actually fixating. In fact, the feedback used in the zero drift method has the effect of amplifying calibration errors relative to fixation errors. This is a process more clumsily accomplished by repetitive measurements in the fixation point method. On theoretical grounds, therefore, the zero drift method should be at least as sensitive and possibly more sensitive to calibration errors than the use of repeated fixations.

Practically, there can be no direct way of testing the method, since there is no absolute way of knowing where the subject is looking. The only possibility is to compare the dispersion obtained by the method to that obtained using other methods. This was done in the following experiment, which also applied the smooth pursuit calibration described above.

With his head fixed by a dental bite, the subject executed a series of trials, lasting in all 12 min. In each trial, lasting about 30 sec, the subject did three things. First, he performed a smooth pursuit calibration from left to right across the screen. Second, he verified its accuracy at a point at the center of the screen by use of the zero drift method: Two dots were displayed, 6 screen units apart (width of horizontal axis, 512 units), and the offset was adjusted so that when the left-hand dot was fixated, the eye drifted to the left; when the right-hand dot was fixated, the eye drifted to the right. The offset obtained in this way was added as correction to the calibration table obtained by the smooth pursuit method. In the final stage of each trial, the subject did a fixation point calibration by successively fixating from left to right a series of five points for about 1 sec each.

Ideally, if there were no artifacts such as head movements and apparatus drifts, this experiment should show which of the two methods, fixation point or smooth pursuit plus zero drift, gives the most stable assessment of eye position. As it is, there was an overall drift in the output voltages correlated across the five fixation points. This can be seen in Figure 2 from the fact that the curves for the five fixation points have a common drift component. This source of variability masks the variability due to each of the methods of calibration. It is not, therefore, possible to determine which has greater disperson, and it can only be said that they are about equally viable, noticing that for each fixation point, all three curves run approximately parallel.

A second issue regards the fact that for the more eccentric fixation points (especially 1 and 5), the

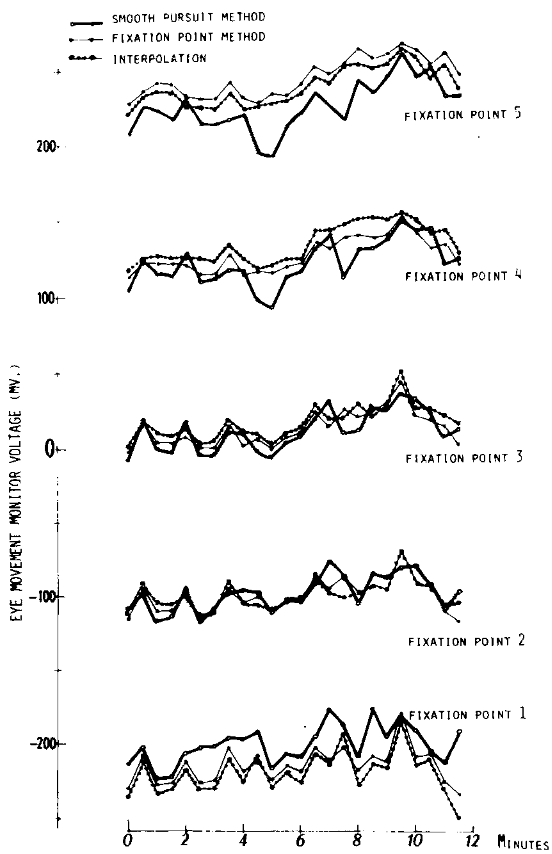

Figure 2. Comparison of three calibration methods during 12 min of successive trials. The thick line shows the values of the eye movement monitor voltage during the smooth pursuit calibration (with zero drift correction done at Fixation Point 2 added in) at the instant the eye passed the locations where the five fixation points were during the fixation point calibration phase of each trial. The thin line shows the successive values of the output monitor voltage when each of the five fixation points of the fixation point calibration was fixated. The dotted thin line shows the correction to these values obtained by using a linear interpolation across all five fixation points.

smooth pursuit curve appears to differ systematically from the fixation point method curves, although they run approximately parallel. This shows that at the edges of the screen, the subject's eye position tended to be less extreme in the smooth pursuit method than in the fixation point calibration. Use of the zero drift method to test the smooth pursuit calibration showed that the error arises because the subject tends not to follow the dot as perfectly near the extremities of the motion.

Finally, the good correspondence of the curves for Fixation Point 2, for which the zero drift method of verification was used, shows that this method is at least as reliable as the fixation point method. Further work with better apparatus is needed to confirm the theoretical expectation that the zero drift method should be more reliable.

TECHNICAL DETAILS

To make the above discussion more comprehensible, it may be worthwhile to discuss some of the problems and technical details involved in the construction of a real calibration system.

Tracking Speed

A subject's pursuit movements may not be satisfactory if he moves the dot across the screen too slowly or too quickly. For example, blinks are likely to occur with very slow tracking, thus interfering with correct monitoring of the eye's position. If a subject moves the dot too quickly, he may tend not to look at it directly, and make saccadic corrections or a winding movement around the dot. It seems that for many subjects, a tracking rate of about 2 deg/sec is ideal. Although the calibration method works even if the subject stops the dot or reverses its motion or changes its speed, tracking seems to be most accurate if he moves it fairly smoothly across the screen. It is also best if the potentiometer controlling the dot's position permits easy, smooth movement over the whole width of the screen. A joystick is very suitable.

Sampling Rate

The rate at which the output of the eye movement monitor should be sampled by the analog-to-digital converter is not critical, and depends mainly on the kind of eye movement phenomenon being studied. In the investigation of eye movements during reading, for example, the exact temporal development of saccades is not of interest. Since the quickest saccades usually found in reading are no shorter than 10 msec, a sampling rate of this order is sufficient. There is a calibration problem associated with sampling at these slow rates, however. If the speed at which the subject moves the dot across the screen in the calibration is of the order of 2 deg/sec, then for a screen subtending, say, 10 deg, the time taken will be 5 sec. At a sampling rate of 10 msec, the eye movement monitor will be sampled 500 times. If the screen is divided into more than 500 points, some of these points will not correspond to eye movement monitor voltages, since the eye will have moved past them during the 10 msec between the two samples. The monitor voltages corresponding to points that have been missed can be calculated after the calibration by interpolation, but accuracy is lost if the number of missing points is large.

The Inverted Calibration Table

The way the calibration table is organized influences the speed with which eye position can be deduced from a monitor output. Suppose, for example, that each screen position corresponds to a position or "address" in memory. After calibration, the address contains the monitor voltage corresponding to that screen position. If at a later time one wants to know the screen position the eye is looking at, one has to go through all the memory addresses in search of a voltage as close as possible to the voltage coming out of the eye movement monitor.

It is more convenient to use an inverted calibration table, where memory addresses correspond to monitor voltages instead of screen positions. Given a monitor voltage, this monitor voltage is itself the address in memory where the associated screen position will be found: No search is necessary. The principle is illustrated in Figure 1. Suppose that there exist 1,000 distinguishable monitor voltages from 0 to 999 mV. An area of 1,000 registers is reserved in memory, the locations having addresses from 0 to 999. While a person is calibrating, he moves a dot across the screen by turning a potentiometer knob or joystick. Since he follows the dot with his eye, the monitor voltages change gradually in step with the changes in dot position. Every time the computer distinguishes a change in the position of the dot on the screen, it looks at the current monitor voltage. At the memory address corresponding to that monitor voltage, it enters the new screen position. Figure 1 shows the eye moving from Screen Position 410 to 411, with corresponding monitor voltages of 551 mV and 553 mV being used as the memory addresses where the screen positions are entered. Note that, in general, during the calibration, not all possible monitor output voltages will occur. This is because the screen is probably divided into fewer positions than there are distinguishable monitor voltages. Some memory locations in the inverted calibration table are therefore empty.The empty locations can be filled with the same values of screen position as the adjacent locations. It is advantageous to smooth the calibration table before use, by taking a running average over about eight points.

Blinks

In most eye movement records, blinks appear as gross disturbances lasting around 100 msec. A smooth pursuit calibration in which a blink occurs must therefore be rejected. In the system described here, this is done in the following manner. The computer verifies that the changes in monitor voltage during the calibration are never greater than a certain threshold. The actual value of the threshold is not critical because blinks produce such large changes. If the change in monitor output voltage exceeds the threshold, the calibration is aborted, and another one is begun. In practice, this occurs infrequently: Subjects tend not to blink while they track the point they are moving.

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