Study of eccentric fixation with secondary visual feedback

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Secondary visual feedback (2VFB) is a visual signal derived from continuous measurement of eye position and provides an extra artificial indication of the point of gaze. 2VFB may be eccentrically displaced and subjects are able to visually superimpose 2VFB onto a visual target signal and thus achieve and maintain eccentric fixation. Initial transient patterns of movement depend upon training but even naive subjects can achieve eccentric fixation within the first 40 s of such a task. Individual strategies and idiosyncratic patterns are exaggerations of normal control and fixational eye movements. The variance of maintained fixation increases with eccentricity and appears to be related to visual acuity as well as to precision of ocular motor control.

INTRODUCTION

The fixational fovea is about 0.1 mm in diameter, corresponding to a visual angle of ½°.[1] It contains the highest resolution portion of the retina and accordingly must be directed at important operative subfields of the environment. If the visual stimulus is a single dot on a uniform background, the eye usually fixates foveally on the target and the movement-control system effects a sequence of microscopic movements—slow drifts with amplitude 3–30 min of arc, separated by microsaccades of the same order of magnitude and modulated by a smaller tremor, a noise-like irregular oscillation.[2,3] As a subject fixates such a visual stimulus in primary gaze position, the retinocentric image is coaxial with the "egocentric" axis, in which case also the oculomotor system is at its zero point. If, however, the eye tracks a laterally shifted target, retinocentric fixation is reestablished. The oculomotor system indicates to the subject its own deviation from "egocentricity", by means of the efferent copy of the position-control signal.[4–6]

An interesting question is whether it is possible to fixate on extrafoveal targets and, if so, what kind of eye movements are characteristic of such a task and how do they vary as a function of eccentricity. At first it appears as though ability to fixate should decrease steeply with increasing eccentricity, and there should be a direct relationship between visual acuity and fixation characteristics. However, as was originally pointed out by Helmholtz[4] in 1866 and verified by Grindley and Townsend,[7] acquisition of peripheral visual information can be enhanced by shift of attention. Another study using eye movement recordings was undertaken by Sansbury *et al.*[8] who showed that the standard deviation of both horizontal and vertical eye positions, the inverse of fixation stability, increases with eccentricity; this, however, refers to *normal* fixation of a stimulus symmetrically eccentric with respect to the retinocentric axis but centric with respect to the egocentric axis. For our task the subject had to acquire and maintain fixation on a stimulus which was eccentric with respect to both retinocentric and egocentric axes. For this the subject needed an extra artificial indication of his eye position as a means of overcoming the tendency to fixate retinocentrically (foveally). A technique employing secondary visual feedback (2VFB for short) was devised by us to provide this extra artificial indication.

We first present the experimental procedure which implements 2VFB in these dual eccentric-fixation tasks. Initial findings indicated that extrafoveal fixation tasks elicit mul-

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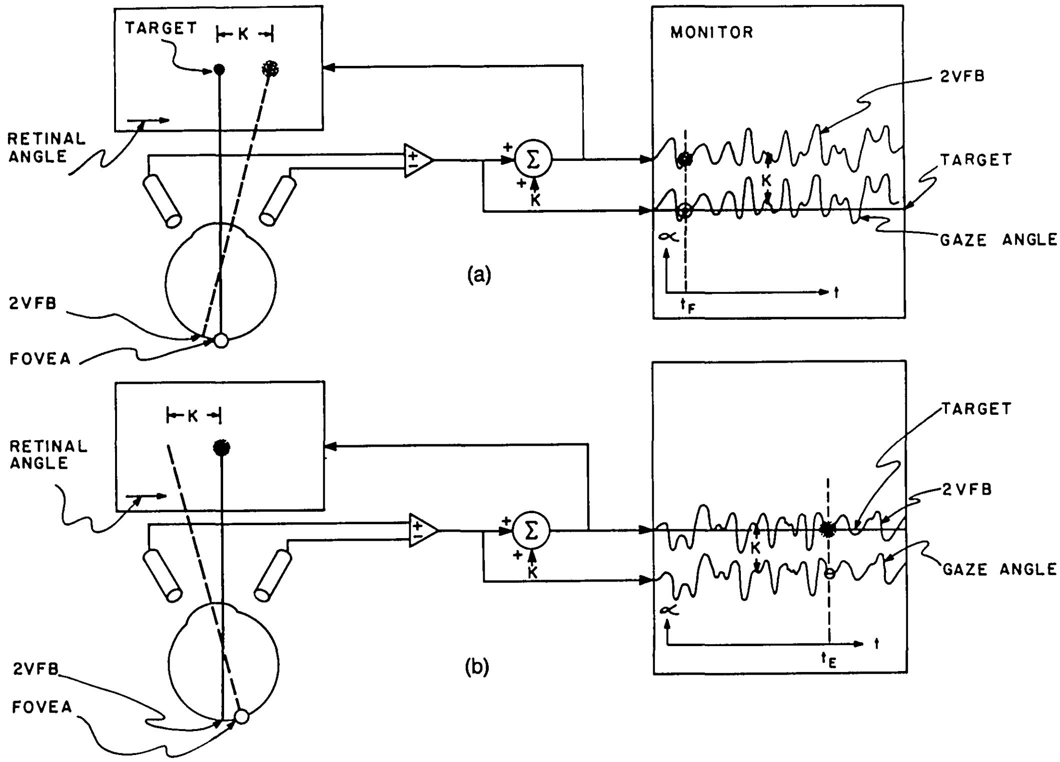

FIG. 1. Schematic diagram of a setup for eccentric fixation tasks, using 2VFB. (a) Illustration of foveal fixation on a point target. (b) Illustration of eccentric fixation on same point target. t_f and t_e are instants when foveal and eccentric fixation are achieved.

timodal idiosyncratic patterns of eye movement. These results are interpreted in terms of peripheral visual information processing with respect to the retinal eccentricity and in terms of oculomotor physiology.

METHOD

Acquisition of foveal visual information, such as in fixation on a stationary target or in tracking a moving target, involves a feedback process which centers the target in the fovea[9] and in which the gain of the feedback loop can actually be manipulated externally.[10] The process is distinct from visual feedback in manual control tasks, e.g., vehicular control.[11] In addition to the "built-in" visual feedback, there is the possibility of closing an external sensory loop.[4,12–14] However, while such sensory input, being of the cross-modality type, is effective as a control signal for the oculomotor system,[13,14] the resultant performance is not an exclusive measure of visual processes. Accordingly, we chose to close the external loop by superimposing the target and eye position signals on the display system, in which circumstances the constructed position error equals the distance between the target and the 2VFB signal.

Apparatus

Target and 2VFB signals are displayed on a dual-beam CRT system with separate focusing and intensity controls for each beam. The target beam is first focused to a diameter of less than 0.1° and its position is chosen by the experimenter; the second beam is then partially focused on an effective diameter of 0.5° of visual field and its intensity adjusted so as to permit discrimination of the two beams even when superimposed. Position of the second beam is controlled by the eye-position signal, thereby providing secondary visual feedback displaying to the subject his point of gaze, and together with the first target beam indicating by spacing of the beams the fixation error. A dc shift is then added to the eye position signal to achieve a specified eccentric retinal image of the 2VFB. Such manipulation of the position signal is analogous to the function of a prism and may thus be characterized as an "electronic prism". Given a stationary target, the subject has then to fixate eccentrically with that visual angle corresponding to the degree of eccentricity specified by the dc shift in order to superimpose the two signals (Fig. 1). Unlike foveal fixation tasks, whenever the 2VFB signal appears to the left of the target, the subject has to move his eye rightward, and vice versa.

Subjects viewed the ±10° display CRT from a distance of 30 cm with head immobilized by means of a headrest and a bite bar. Only monocular movements of the right eye were recorded and the left eye was covered with an eye patch. Eye position was monitored with the aid of an infrared photoelectric device[15,16] adjusted by means of a micromanipulator with three degrees of freedom. Eye movement monitor recording bandwidth was 40 Hz and the 2VFB signal was limited to 4 Hz. System noise limited the resolution to about 0.1°. Target position and 2VFB signals were sampled by a PDP-11/55 computer at a rate of 100 samples per s per channel.

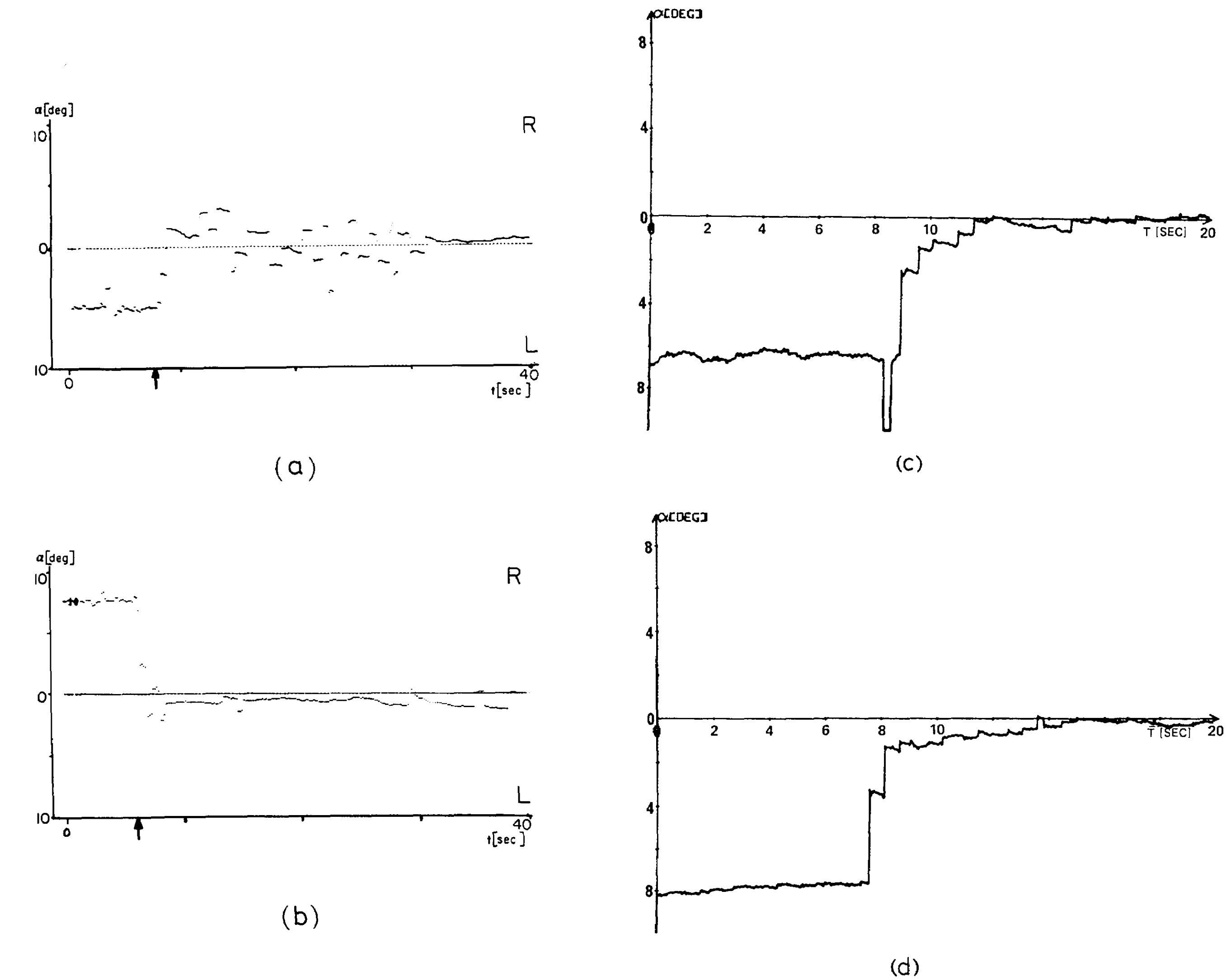

FIG. 2. Eye movement patterns elicited during eccentric fixation task. An arrow indicates instant of closing 2VFB loop. (a) and (b) are from subject RO who is myop. (a) 4° left eccentric task before training. (b) 8° right eccentric task after training. (c), (d) 6° and 8° left eccentric task respectively. (Subject ME after training.) Note the short blank period in (a) which represents editing out of blink artifact.

Procedure

The transducer was positioned by the subject, who was instructed to align it symmetrically relative to the iris, using a mirror situated above the CRT. Fine readjustments took place during every experimental session as part of the frequent on-line calibrations of the system.

A typical run lasted 40 s, beginning with about 7 s of foveal fixation. Then the 2VFB loop was closed abruptly at a specified eccentricity. The subject was instructed to foveate on the target until the 2VFB appeared and then to superimpose this 2VFB on the target by moving the eye. A first task was foveal fixation with 2VFB of zero dc and therefore zero eccentricity; it was followed by eccentric fixation tasks of 2°, 4°, 6° and 8° of eccentricity to both right and left. Sequencing was varied from session to session, to randomize the effect of fatigue on the last runs. A typical session lasted about 10 min, the longest most subjects were able to concentrate on the task, and terminated with a check on calibration consistency. After each session the subject was required to report his impressions and subjectively inferred strategy, including specific difficulties experienced during the task.

RESULTS

In the first few sessions of subject exposure to this dual point-target task, as soon as the 2VFB loop is closed, the sudden appearance of the signal triggers a quick reflexive saccadic movement which attempts to foveate the newly received signal. However, since the 2VFB image has a fixed retinal eccentricity, this attempt results in a movement pattern characteristic of an open loop mode as shown in Fig. 2c. During this phase, the subject actually "loses" the target and only after a few saccadic steps he becomes aware that he should be working his way in the opposite direction, and he proceeds to do so by means of a "staircase" pattern of stepped saccades. This "open loop" mode is eliminated in subsequent sessions where typical responses start right away with the staircase pattern as shown in Figs. 2 and 3—note the similarity

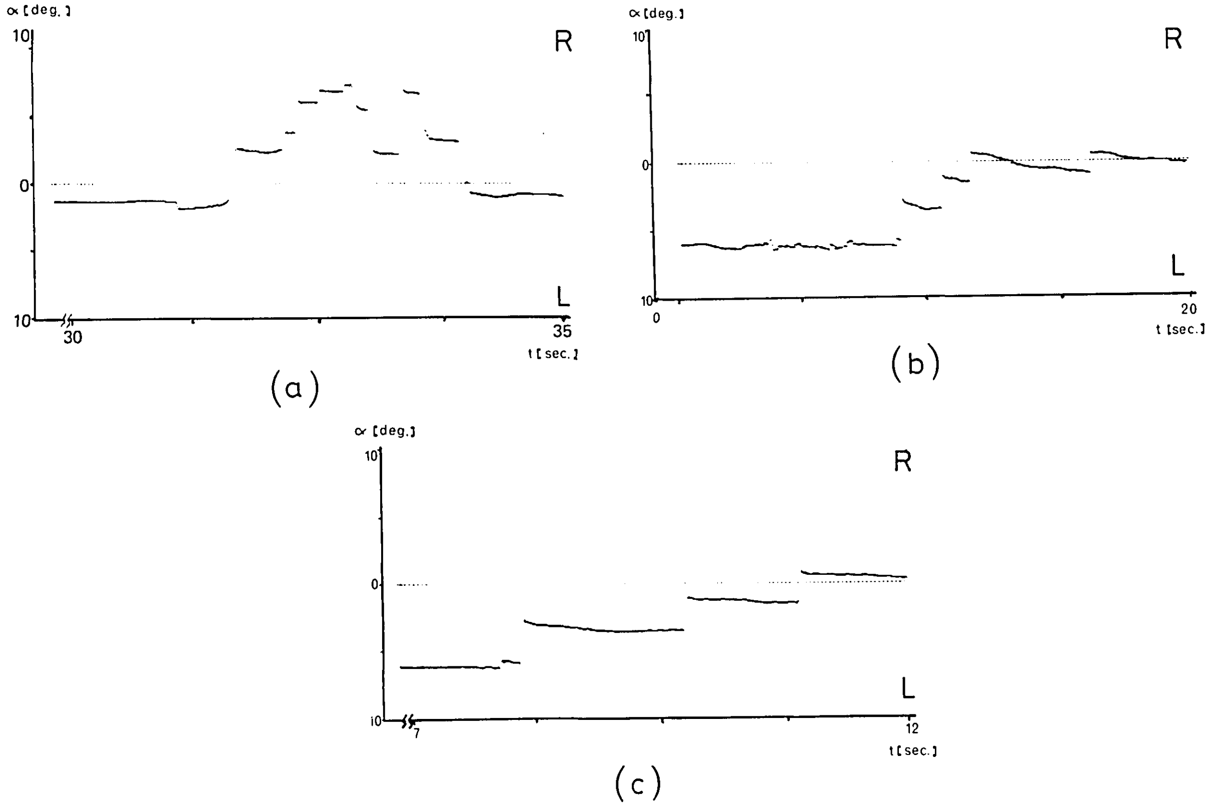

FIG. 3. Examples of "staircase" patterns of eye movement. (a) 8° right eccentricity (subject GD). (b) 6° left eccentricity (subject RO). (c) Same as (b) on an expanded time scale.

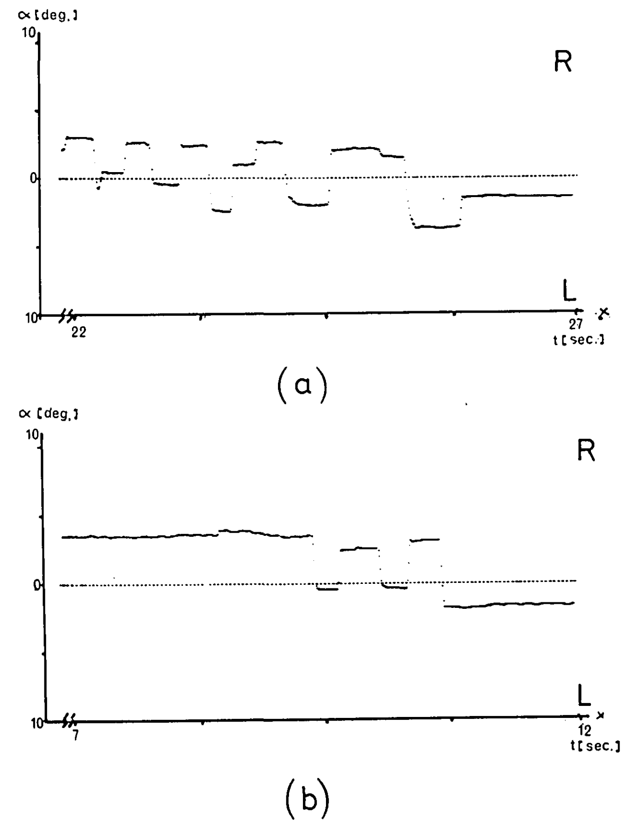

FIG. 4. Slow square-wave oscillations. (a) and (b) two segments of 4° right eccentricity. (Subject GD.)

of 2*c* and 2*d* obtained from the same subject, where the only difference is the open loop behavior (in *c*) recorded in the first session of this subject. This is usually followed by slow square-wave oscillation about the target (with a period of about 1 s), probably due to confusion of the target and 2VFB as shown in Fig. 4. A similar response was observed by Young and Stark in their variable-feedback experiments.[10]

Following this mode, the subject adopts an individual strategy in achieving eccentric fixation, depending largely on his degree of training (see Fig. 5). Naive subjects usually converge on the target by means of damped square-wave oscillations (see Figs. 2*a* and 5*a*), while others converge by means of a long, slow drift (see Fig. 5*b*). Well-trained subjects converge on the target immediately on closing the 2VFB loop by means of either a few saccades or a short drift as shown in Figs. 2*d* and 5*c*, respectively.

Eventually eccentric fixation is achieved. Of the identified types of "locking on" the target, the most common one is characterized by slow drifts separated by saccades (Figs. 6*a* and *b*). This pattern is often similar to that of gaze nystagmus with its sawtooth pattern[2,17] but there is scaling of amplitude and durations. Typical amplitudes of saccades and drifts during eccentric fixation are of the order of one degree. Another type of "locking on" the target is characterized by short-duration fixations separated by small saccades (Figs. 6*c* and *d*). Similar to the above pattern, here too the durations of the fixations and the amplitudes of the saccades are larger than those characteristic of foveal fixation.

Following the approach of Sansbury *et al.*, we also use the standard deviation, sd, as an inverse criterion of fixation stability. This criterion is sensitive to the duration of fixation over which it is calculated. For this reason we select sessions in which the subject maintained his eccentric fixations in all the runs for more than twenty s; some subjects achieved this only after some training. In Fig. 7 we compare results obtained from two of our subjects, averaged over horizontal left and right eccentric fixations, with those of Sansbury *et al.*

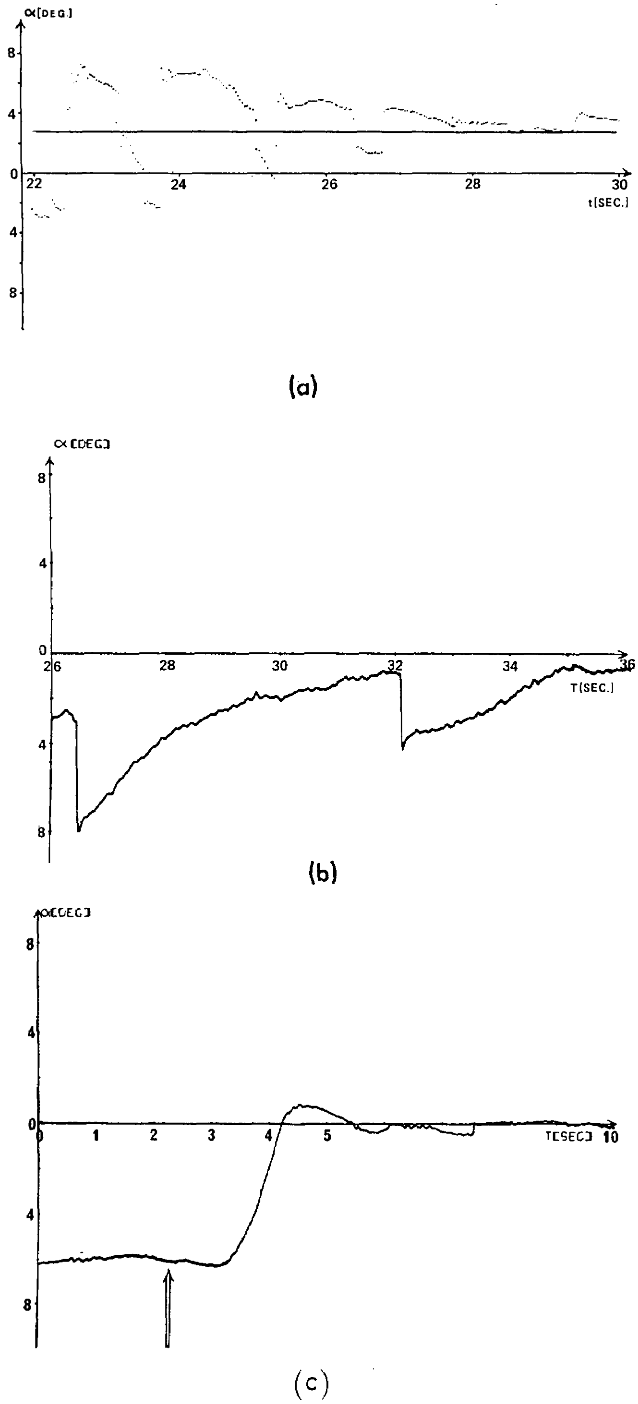

FIG. 5. Eye movement patterns achieving eccentric fixation. (a) Damped square-wave oscillations (subject ST, 6° left). (b) Long slow drift towards the target (subject GD, 3° left). (c) A short drift towards target (subject YO, 6° left).

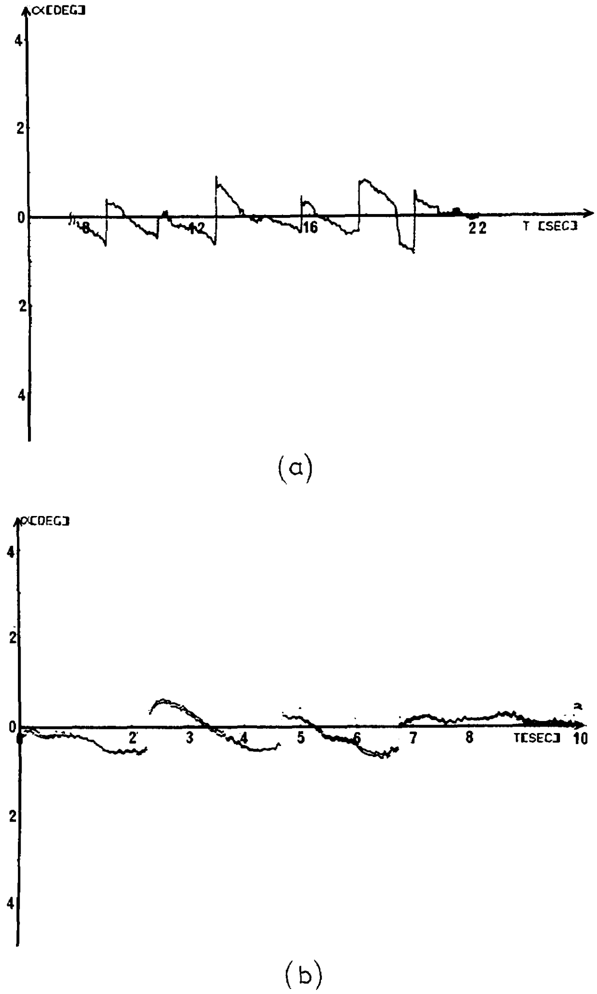

FIG. 6. Types of "locking on" the target. (a) and (b) Intermittent drifts and saccades. (c) and (d) Small saccades around target. Note amplitude scale.

DISCUSSION

The most important finding is that fixation is feasible with extrafoveal vision and achievable within 10–40 s of the first run, even by naive subjects. With regard to this finding, it should be noted that because of technical limitations, our experiments were so far confined to the range of ±8°, the so-called near periphery[18]; once the dynamic range can be extended, the temporal structure of the stimulus is expected to become important. It will then be of interest to compare the performances with a stationary target to those with a temporally modulated one.

In comparing our results of fixation stability with those of Sansbury, there is a consistent trend of increase in the variance of eye position with increase in eccentricity. Quantitatively, however, the standard deviations measured in our study are consistently larger, possibly due to the complexity of using 2VFB in the task of error elimination required of the subject even in the case of foveal fixation (eccentricity = 0°). Yet another reason may be the difference in the tasks specified in these two studies, viz holding versus fixation. It has been shown by Steinmann *et al.*[19,20] that saccades are suppressed in the "hold mode", which should result in a decrease in eye

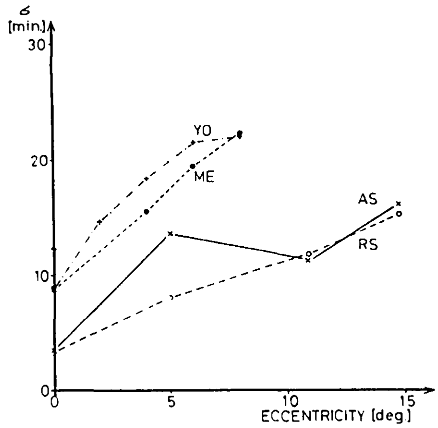

FIG. 7. Horizontal eye position standard deviation as a function of eccentricity. Data for AS and RS adopted from Sansbury *et al.*[8]

position sd. It is also possible that noise level, which is somewhat higher in our system, contributed to some of this difference.

A motivation in conducting this study was to explore the fidelity of extrafoveal vision. Visual-oculomotor fidelity, defined as the inverse of standard deviation of eye position in fixation tasks, depends upon visual information processing, and as such is a function of acuity, and upon oculomotor control. The relationship of visual-oculomotor fidelity to visual acuity is compared in Fig. 8, where we see the sensory data of Mandelbaum and Sloan,[21] the retinocentric eccentricity data of Sansbury *et al.*,[8] and the data of this report, which has both retinocentric and egocentric eccentricity as well as dual task complexity. This initial exploration of peripheral vision shows a consistent trend in decrease of visual-oculomotor fidelity with eccentricity and is being further studied.[22]

Patterns of eye movement observed during the transient phase provide insight into algorithms and mechanisms of oculomotor control involved. Both the staircase and square-wave patterns are characteristic of variable feedback experiments.[10] The staircase is in fact understood as such, noting that the 2VFB signal is analogous to an open-loop stimulus. The time-scaling factor is inconsistent with the sampled-data model for foveal tracking. Clearly, one of the subtasks for the subject in achieving or maintaining eccentric fixation with the aid of 2VFB is to inhibit or suppress the tendency to foveate either of the two visual signals present on the CRT.[22] Control of fixation and attention directing mechanisms are not well understood; however, even the microsaccades of fixation can be voluntarily inhibited or suppressed.[19] A well-trained subject is able to eliminate the staircase and square-wave saccadic patterns altogether, and either hits on the right position in a short sequence of saccades, or converges on it by means of a short drift; here, too, the delay is of the order of one-half s as compared with the 200 ms normal saccadic interval. Further, the dual target task complexity may require longer central-processing time. Similarly, the square-wave oscillation is characteristic of variable feedback experiments, but in the 2VFB task it may also be the consequence of combined confusion and incorrect estimation of position error. Again the longer period of this square-wave oscillation may be considered in a fashion analogous to the case of the staircase.

Our experimental procedure of providing 2VFB has proved to be both adequate and convenient for quantitative studies of eccentric fixation. It is currently being exploited in exploration of spatiotemporal characteristics of the peripheral visual system.

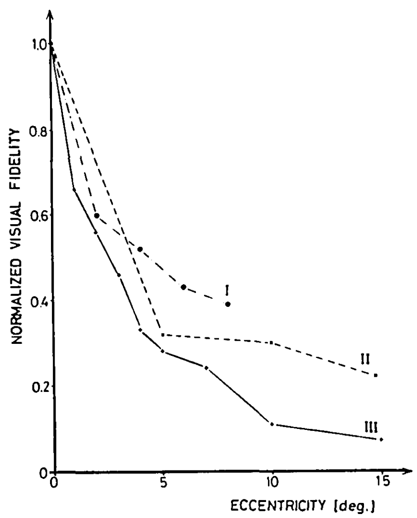

FIG. 8. Normalized visual fidelity as a function of eccentricity. Curve I represents inverse of s.d. data averaged over two subjects. Curve II—same as I, data adapted from Sansbury *et al.*[8] Curve III—acuity as a function of eccentricity adapted from Mandelbaum and Sloan.[21]

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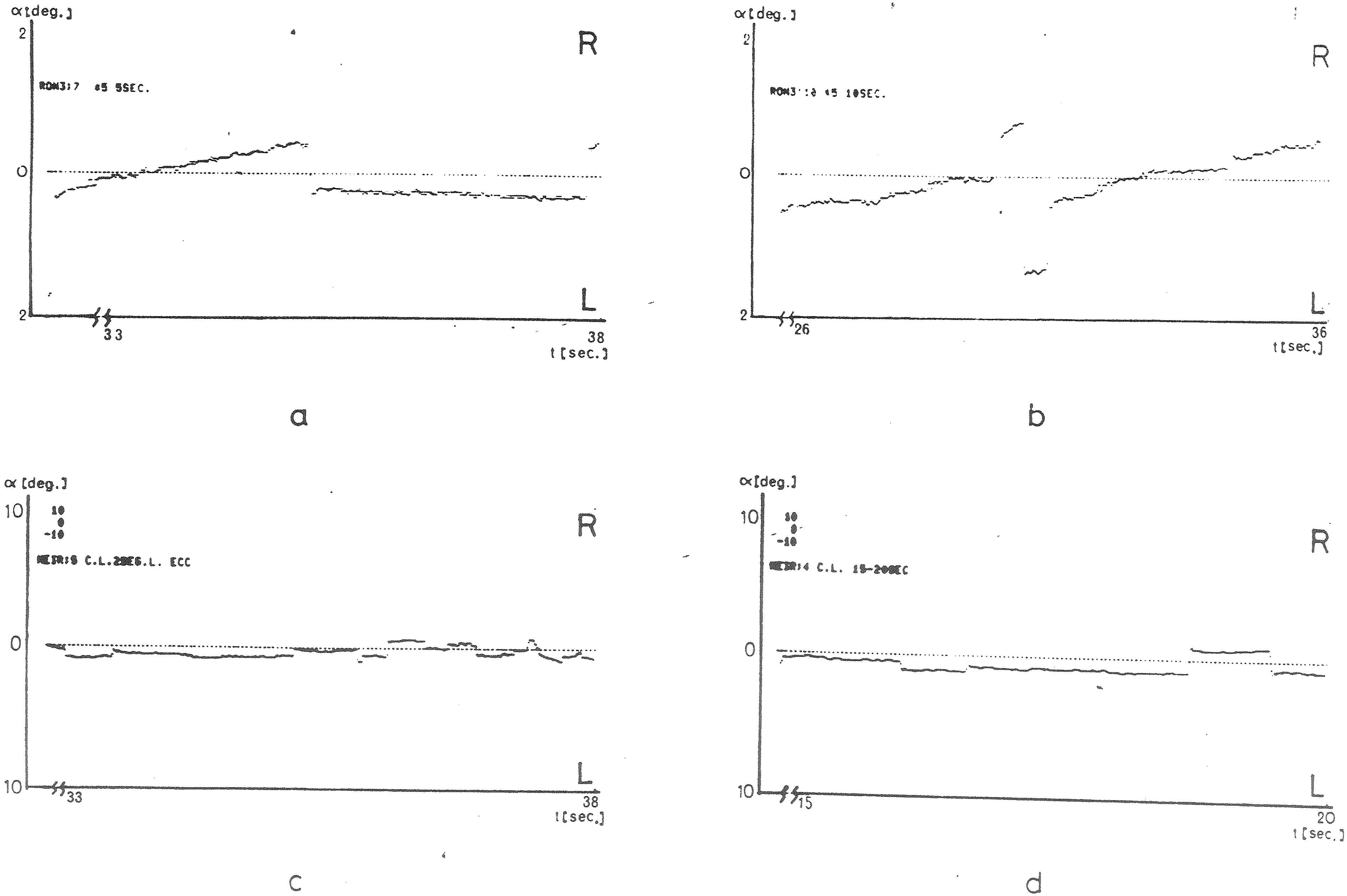

FIG. 6