Smooth eye-movement control with secondary visual feedback

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A signal derived from continuous measurement of eye position is displayed on a visual frame of reference, thereby closing a secondary visual feedback (2VFB) loop. The distance between a target and the displayed gaze point provides the subject with an extra, artificial position error. Experiments show that subjects can use the 2VFB to generate smooth eye movements, even in the absence of any smoothly moving independent targets. Under these conditions, both direction and velocity can be brought under voluntary control by the subjects. As a control signal for the smooth-eye-movement mode, the 2VFB is robust and easily manipulated and provides an attractive means for the investigation of the smooth-movement control system in a variety of tasks and under different conditions.

INTRODUCTION

Various studies[1,2] have demonstrated that smooth movement can be elicited by visual means other than a real moving stimulus. For example, either the foveal afterimage[3] or an optically stabilized foveal image[4] can elicit smooth movement. The direction of the movement is apparently selected by the subject, who shifts his attention to the left or to the right of the afterimage.[3]

Recently, we introduced a new technique to investigate control of eye movement and acquisition of visual information. The eye-position signal was either displayed together with the target or was superimposed on a visual scene, thereby closing a secondary visual feedback (2VFB) loop.[5,6] Since this 2VFB situation is similar to that of an afterimage, it can be expected to allow the control of smooth movement. Unlike the afterimage, because of measurement imprecision and noise, the 2VFB does not generate a perfectly fixed retinal image and therefore does not fade away. This signal has the advantage of being easily manipulated electronically, permitting a wide range of experimental conditions.[5–7]

The 2VFB signal can also be presented while tracking a smoothly moving target. In this case, the tracking task is to superimpose the displayed eye-position signal on the independently moving target. It was previously shown that for velocities within the range of 1–10 deg/sec, the 2VFB task does not impede the tracking performance and even improves it.[7] It thus became of interest to investigate the tracking of a discontinued target. Stark[8] and Gauthier and Hofferer[9] showed that when a periodic smoothly moving target disappears, the memorized repetitive target motion can be used for saccadic position control. The pattern of movements elicited in this way clearly indicates that the subjects retain the target's trajectory well and that the spatial and temporal components of the target motion can be used for the saccadic position control but that all these factors are insufficient for a continual control of smooth eye movement. Therefore we designed an experiment to show that 2VFB can be combined with the internal model of target motion to maintain smooth tracking of the disappearing target.

In tracking a smoothly moving target, the eye velocity is, in most cases, somewhat lower than the target velocity.[10,11] This agrees with the classical description of smooth-pursuit eye-movement control as a velocity-servo mechanism, in which the retinal image velocity serves as the tracking error.[11] With 2VFB, this retinal slippage can be nullified and can also be manipulated to generate a negative retinal slip. The result can no longer be described as simple tracking but rather is similar to a predictive control situation. Thus experiments with a conditioned 2VFB should provide a better understanding of the smooth-pursuit control system.

METHOD

The 2VFB technique was described in detail elsewhere.[5] By displaying to the subject the point of gaze, in addition to a target or a visual frame of reference, a 2VFB is provided. Although this is rather similar to the open-loop condition in a variable-feedback experiment,[11,12] here there is also an independent point target. The two signals are displayed so that they are easily distinguishable on the screen even when superimposed, and subjects are informed which of the two represents the measured point of gaze. The distance between the two displayed signals indicates to the subject his tracking or position error.[7] The 2VFB signal can also be manipulated electronically to give rise to interesting experimental paradigms (Fig. 1). For example, a dc shift was useful in the study of eccentric fixation and peripheral saccades.[5–7] In the experiments described below, the 2VFB signal was conditioned either by low-pass filtering or by phase inversion. The target and the 2VFB signals were displayed on a dual-beam cathode-ray-tube (CRT) system with separate focusing and intensity controls for each beam. The target beam was focused to a diameter of less than 0.1 deg; the second beam was par-

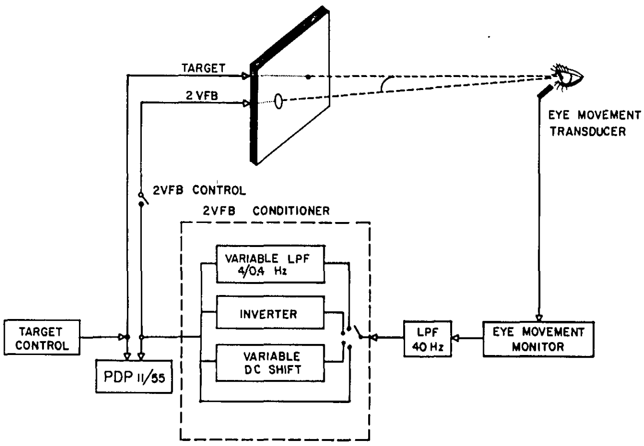


Fig. 1. Schematic diagram of setup for conditioning and implementation of 2VFB in eye-movement studies.

tially focused to an effective diameter of 0.5 deg. The intensity was adjusted to permit discrimination of the two beams when superimposed. The position of the second beam was controlled by the eye-position signal, thereby providing 2VFB. In a second setup, the target and 2VFB were generated on separate display systems and superimposed on the optical axis by means of a beam splitter. Although ten subjects with varying amounts of training participated in this study, only five took part in most experiments with a conditioned 2VFB.

The subjects viewed the 10-deg display from a distance of 30 cm with their heads immobilized by means of a headrest and a bite bar. Only monocular movements of the right eye were recorded; the left eye was covered with an eye patch. Eye position was monitored with an infrared photoelectric device.[5,13] To improve the signal-to-noise ratio, the bandwidth was limited in most experiments to 40 Hz, giving a resolution of about 0.1 deg. Target positions and 2VFB signals were sampled by a PDP-11 computer at a rate of 100 samples per second per channel. A variable filter (K&H Model 3323 with active and passive options) was used for 2VFB low-pass filtering.

EXPERIMENTS

Experiment (a): Foveal Open Loop

The subject was presented with his point of gaze using the unconditional 2VFB signal (gain = 1, eccentric bias = 0). The 2VFB signal was locked on the fovea, and no retinal slip was possible in any eye movement. (This is rather similar to the foveal afterimage condition.[2,14]) The 40-Hz cutoff and the measurement-system noise prevented fading of the image. The target was then driven as a saccadic stimulus, translating abruptly from one position to another. Subjects exhibited the normal saccadic trajectory typical of the response in the absence of 2VFB. Each subject was then asked to smooth out his eye-movement response to the same saccadic stimulus by moving the 2VFB signal smoothly toward the independent target. A short period of training (less than 10 min) was needed for all ten subjects. Examples from three subjects (Fig. 2) show that each one used a different velocity, but all were able to move their eyes smoothly toward the target with hardly any saccadic interruptions (Table 1). The few exceptions were mostly codirectional saccades toward the target (Fig. 2b and 2c). Typically, fewer interrupting saccades were observed in one direction (nasal in all three examples shown in Table 1) than in the other. Four subjects actually responded with saccade-free smooth movement in both directions and exhibited better performance in all tasks. Thus there was no need for cumulation of the smooth movement to make it appreciable.[9,14]

To compare the 2VFB-controlled smooth eye movements with those elicited under the foveal afterimage condition, we repeated the same experiment using a cross-hair foveal afterimage with four of the ten subjects. By and large, the performance was similar, but in some of the experiments, we found, and experienced subjects reported, that they could more easily affect and control the smooth movement with the 2VFB. In all tasks with an afterimage, fading limited the experiments to a few seconds before the image had to be re-

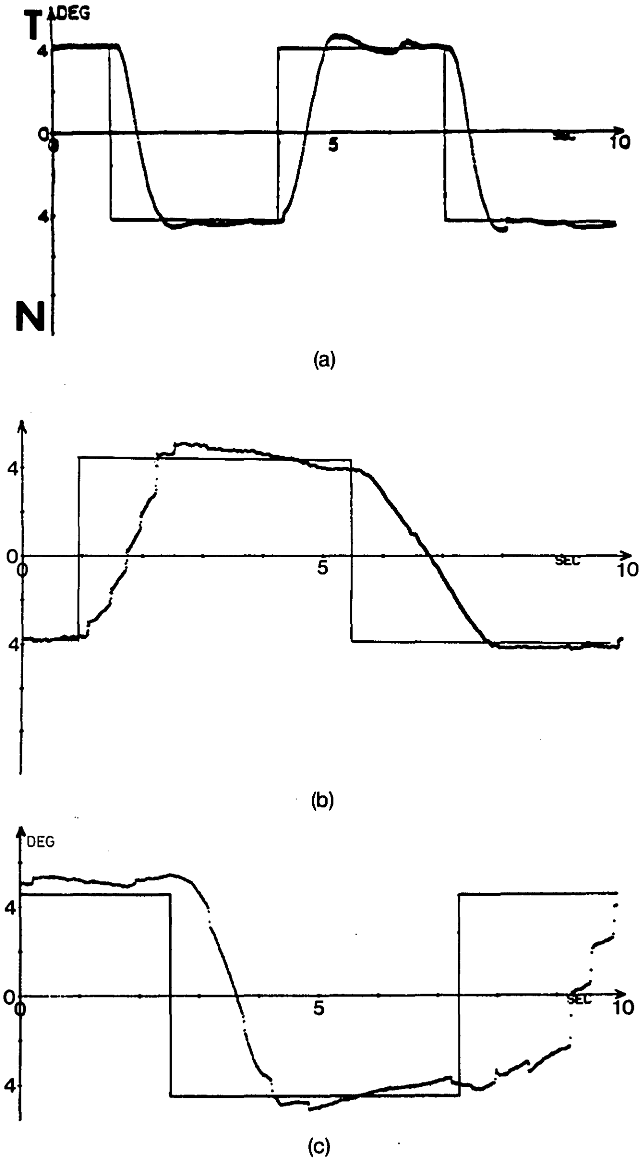
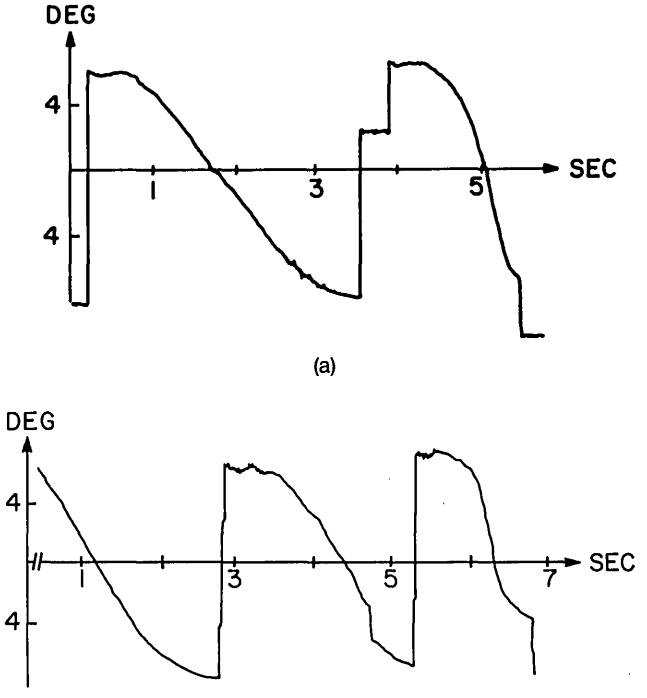


Fig. 2. Examples of smooth response to saccadic stimulus affected by unconditioned 2VFB (except for the 40-Hz low-pass filtering) when subjects are instructed to smooth their response. (a) Subject YO. (b) Subject RO. (c) Subject PE. *T* and *N* indicate temporal and nasal directions, respectively.

Table 1. Number of Saccadic Interruptions and Intersaccadic Velocity in Smooth-Movement Task[a]

Task	Direction	Parameter	Subject		
			YO	PE	RO
With 2VFB	Nasal	Number of interrupting saccades	0.6 ± 0.3 (30)	2.9 ± 0.6 (15)	0.8 ± 0.5 (20)
	Nasal	Intersaccadic velocity (deg/sec)	7.9 ± 1.8 (20)	4.2 ± 1.3 (30)	3.2 ± 0.9 (15)
	Temporal	Number of interrupting saccades	0.8 ± 0.6 (30)	4.3 ± 0.7 (15)	3.1 ± 1.2 (20)
	Temporal	Intersaccadic velocity	7.3 ± 2.6 (15)	1.8 ± 1.2 (30)	2.9 ± 1.3 (30)
Without 2VFB	Nasal	Number of interrupting saccades	2.1 ± 0.8 (13)	7.0 ± 0.5 (8)	4.5 ± 0.9 (10)
	Nasal	Intersaccadic velocity	5.3 ± 1.9 (20)	0.3 ± 0.1 (20)	0.4 ± 0.2 (15)
	Temporal	Number of interrupting saccades	2.3 ± 0.7 (13)	6.8 ± 0.6 (8)	5.5 ± 0.8 (10)
	Temporal	Intersaccadic velocity	6.0 ± 2.3 (20)	0.3 ± 0.2 (20)	0.3 ± 0.2 (15)

[a] Data pooled from experiments with 4- and 40-Hz low-pass filtered 2VFB. Mean ± standard deviation. The number of segments is given in parentheses.



(a)

(b)

Fig. 3. Voluntary control of smooth-movement velocity. Consecutive segments of right to left scans are shown. (a) Subject YZ exhibiting velocity range of 6–18 deg/sec at midtrajectories. (b) Subject JM exhibiting velocity range of 8–30 deg/sec.

freshed by flickering the background illumination or by the subject's blinking.

Subjects were next required to control voluntarily the velocity of movement and to increase or decrease it when ordered. They could do so with relative ease over a wide range of velocities. The preferred free-running velocity was subject specific and varied from a fraction of a degree to a few degrees per second (Table 1). When instructed to control and achieve higher velocities, the subjects typically demonstrated ranges from a few degrees to 20 deg/sec (Fig. 3).

Experiment (b): Smooth Movement Task Without 2VFB

Both for comparison and as a control, the subjects were required to execute smooth movements when tracking the same saccadic stimulus but without the 2VFB. This is equivalent to moving the eyes smoothly with no smoothly moving target. Although the subjects were trained in this task, only one achieved smooth movement without 2VFB, and even his tracking was interrupted by 2–3 saccades in each direction. The other nine subjects exhibited a typical saccadic staircase pattern (Fig. 4). Experienced subjects were conscious of their inability to smooth the movement and characterized their response as a series of small discrete jumps, whereas novice subjects were unaware of their saccadic staircase response.

Experiment (c): 2VFB With Variable Positional Error

Next we attempted to find out how far the 2VFB could be driven away from the ideal stabilized image and still allow subjects to maintain their smooth-movement control. Low-pass filtering was chosen as the simplest way to generate a velocity-dependent position error; it simulates a real limitation of any mechanical system that could be driven potentially, by the eye-position signal in a variety of man–machine system applications. When steady-state velocity is achieved, the foveal position leads the 2VFB signal with a constant error.

The eye-position signal was low-pass filtered before being displayed (Fig. 1). At a cutoff frequency of 4 Hz, all subjects were able to perform smooth movement without difficulty (Fig. 5). Despite intersubject velocity variability (Table 1), each subject exhibited a typical velocity approximately equal to that observed in Experiment (a) with a 40-Hz cutoff. There were differences in the characteristics that were direction specific: a lower velocity in the nasal direction, as well as fewer interrupting saccades. Although the resultant positional error frequently exceeded the dead-zone dimensions,[11,12] it did not give rise to corrective saccades.

A cutoff frequency of 0.4 Hz further increased the positional error and dramatically affected performance of this task. Saccadic patterns comprised the typical response (Fig. 6), and observed overshoots resulted from an attempt to eliminate the positional error with respect to the 2VFB loop (separation of target from the 2VFB).

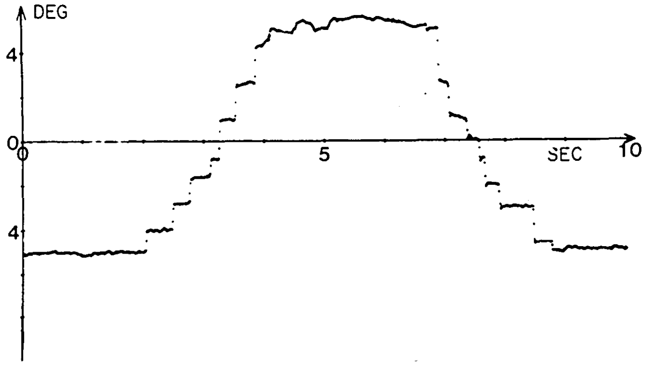
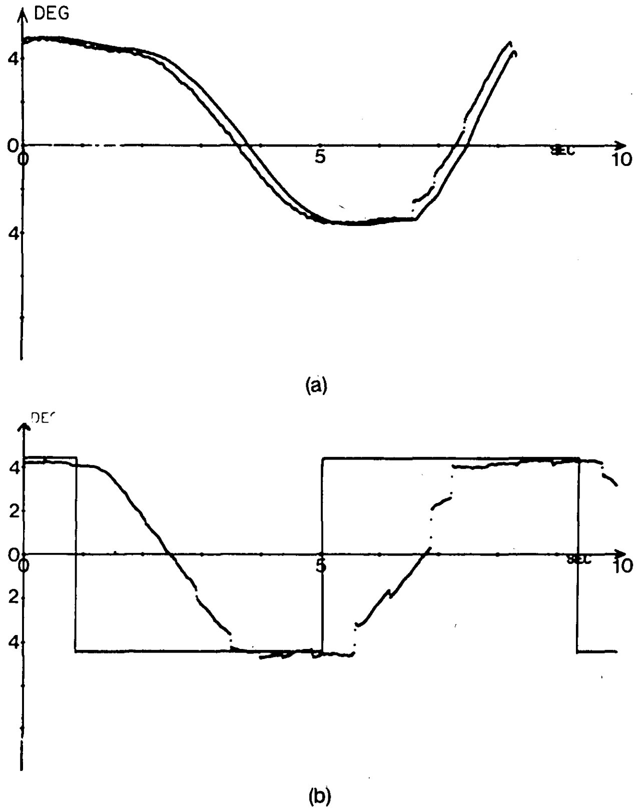


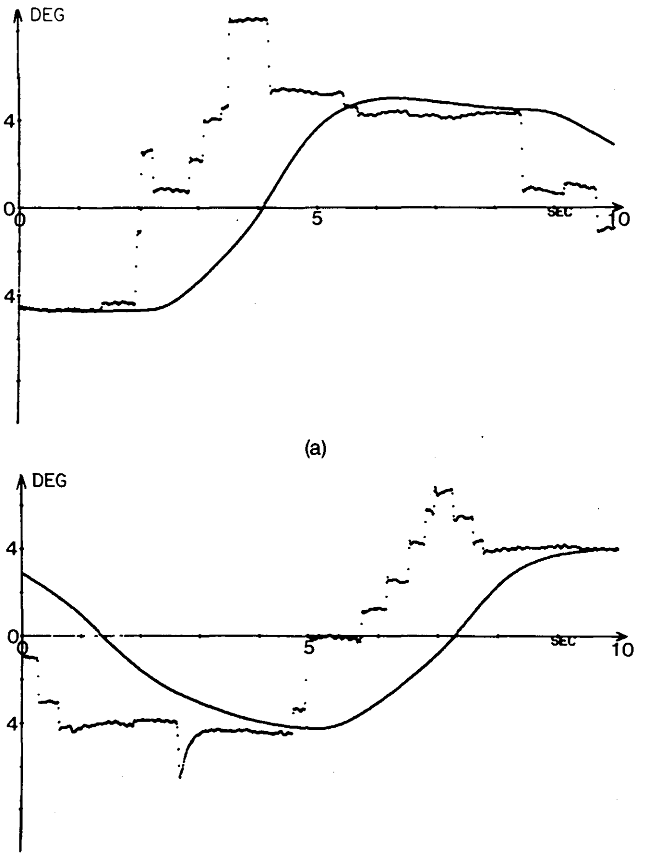
Fig. 4. Response pattern in smooth-the-movement task without 2VFB. Example of staircase pattern characteristic of this task (subject PE).



(a)

(b)

Fig. 5. Effects of 4-Hz low-pass filtered 2VFB. (a) Eye position and 2VFB are shown (subject RO). Note that 2VFB is delayed (because of the low-pass filtering). (b) Eye-movement response and target position are shown (subject PE).



(a)

(b)

Fig. 6. Effects of 0.4-Hz low-pass filtered 2VFB and its resultant long delay. Saccadic staircase patterns with saccadic overshoots for (a) subject RO and (b) subject PE.

Experiment (d): Inverted 2VFB Signal

Since the results of Experiment (c) with 4-Hz cutoff imply that smooth control can be achieved even with negative retinal slip, at least for short periods of time, we investigated continuous negative slip as an additional control signal. To generate negative retinal slip, the 2VFB signal was inverted before being presented to the subject. Thus the subject had to move his eye leftward to superimpose the 2VFB on a target that had moved toward the right, and vice versa. This inversion was confusing but with some training two of the ten subjects were able to perform the task with smooth movement (Fig. 7), whereas a third subject managed to generate short episodes of counterdirectional smooth eye movement. It should be noted that when the subject superimposes the 2VFB on the target, he is gazing away from it and thus achieves eccentric fixation.[5] While the eye is moved from one position to another, the 2VFB image slips across the retina with double the velocity of eye rotation.

Experiment (e): Pursuit of a Disappearing Target

The subjects were presented with a sinusoidally moving target[15] that disappeared from the display after a few cycles. The subjects were required to continue the smooth movement as though they were still tracking the target. This experiment was repeated with 2VFB that was unconditioned except for the 40-Hz filtering. In agreement with the results of Gauthier and Hofferer[9] and of Stark,[8] we found that the subjects utilized an internal model of the target as a control signal after

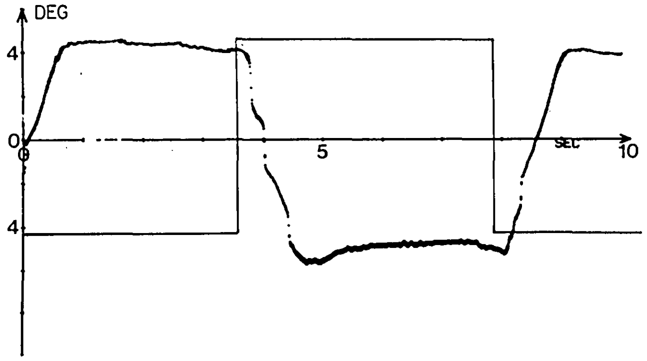


Fig. 7. Eye-movement response pattern in smooth-eye-movement task with inverted 2VFB. Both eye movement and target position are shown (subject YO).

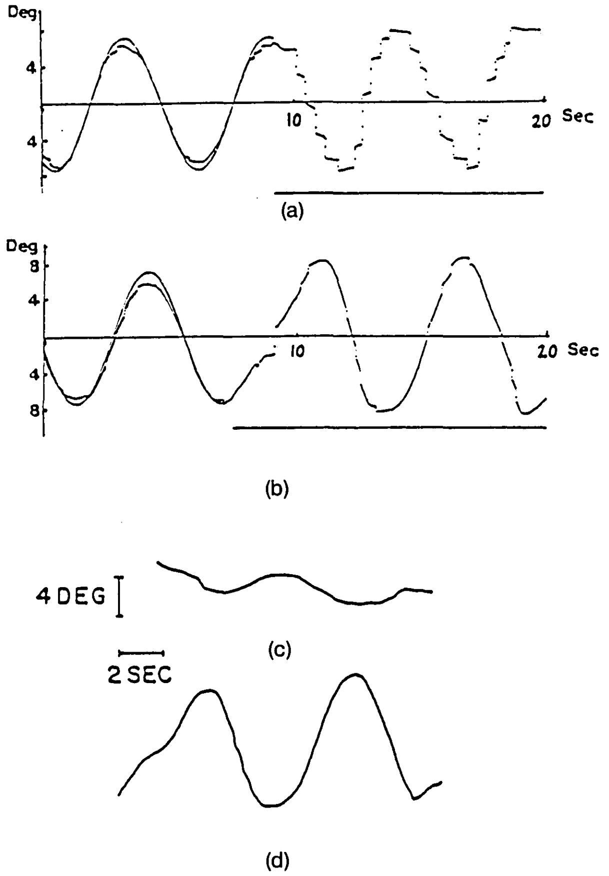


Fig. 8. Smooth tracking of a disappearing target. Target and eye position are superimposed. Straight lines indicate disappearance of target. (a) Without 2VFB (subject PE). (b) With 2VFB (subject PE). (c), (d) Cumulative smooth movement from (a) and (b), respectively.

its disappearance, using a saccadic staircase pattern [Fig. 8(a)]. When a display of the 2VFB continued after the disappearance, however, subjects were able to realize smooth movement, except for occasional saccades [Fig. 8(b)]. Examination of Fig. 8(a) reveals a smooth-movement component superimposed on the staircase pattern. The direction of this smooth movement is not random; rather it is always in the required direction. The cumulated smooth movement [Fig. 8(c)] thus generated a sinusoidal pattern of the right frequency but with a small amplitude. The movement, therefore, is a low-gain smooth movement that is compensated for by saccadic position corrections. With the 2VFB [Fig. 8(d)], however, the smooth-movement gain is close to unity, requiring only slight and less frequent saccadic corrections. The 2VFB thus seems to facilitate a higher gain in the smooth-pursuit system similar to the effect of an afterimage on the vestibular nystagmus system.[13]

DISCUSSION

Our experimental paradigm is similar to stabilized-image conditions previously reported.[4,16] The simple case of centric and unconditioned 2VFB is equivalent to the fixed stabilized foveal image, and results similar to those obtained in previous studies may be expected. However, in studies with an afterimage[1,16] and with an optically stabilized image,[4] only involuntary smooth nystagmuslike oscillations were observed, and any attempt by the subject to move his eyes by command distorted and broke down the smooth movement into a staircase pattern. Kommerell and Taumer[3] reported different results using foveal afterimages: The subjects could move their eyes smoothly in a specified direction, and the experimenter could control the velocity of movement by changing the eccentricity of the afterimage. Our experiments with an afterimage and 2VFB further substantiate the findings of Kommerell and Taumer.

Some important differences between our experiments with 2VFB and studies reporting experiments with an afterimage should be noted. The 2VFB implies that the measured eye-position signal is superimposed on an independent target or on a visual scene. Three types of positional errors are consequently generated,[7] and a subject can select the one appropriate to a specified task and/or strategy. The first positional error is related to the primary, built-in feedback loop (the angular separation between gaze and independent target position). The second error relates to the 2VFB signal, which can be considered a secondary visual target. Only in the case of foveal afterimage is this error nullified. Any manipulation of the 2VFB, as depicted in Fig. 1, or imprecision in measurement will result in this error's being different from zero. This error cannot be eliminated by eye movements, and, therefore, the resultant situation has been referred to as open loop. The third error is defined by the angular separation of the independent target and the secondary target. Selection of this error as a control signal permits, for example, a subject to stabilize his eccentric fixation on a target.[5] Without such a reference signal, any attempt to eliminate the second and only positional error generated by the fixed eccentric image results in an unstable staircase pattern.[5,12]

We have previously shown that some subjects can achieve eccentric fixation by using smooth movements,(5) but switch to primary feedback error, which results in intermittent foveation, when the independent target is displaced abruptly.[7] In this study, we have shown that with 2VFB, the smooth-movement control can tolerate a variable positional error. With 2VFB, subjects can voluntarily control both the direction and velocity of smooth movement. Although the preferred, free-running velocity varies from subject to subject, the controlled range exceeds a decade. It is not clear, though, what kind of mechanism or strategy permitted this voluntary control. In the Kommerell and Taumer study,[3] the control of velocity was demonstrated only for the eccentric afterimage in which the velocity was not subjected to voluntary control. Under these circumstances, an increase in velocity also resulted in an increased number of interrupting saccades. Another study found that a real smooth movement was required for initiation of smooth eye tracking.[17] With 2VFB we did not find this necessary, and it appeared as though voluntary effort was sufficient. Once initiated, we have shown that the smooth movement with 2VFB can subserve the function of foveation, indicating that these movements are under voluntary control. Foveation by smooth movement was previously observed only when the saccadic feedback loop was electronically opened.[18]

The results with both afterimage and 2VFB clearly demonstrate that a fixed retinal image, presented along with an independent target fixed in space, is a sufficient condition for generating voluntarily controlled smooth movements. These findings support Young's hypothesis[2] that "an adequate visual stimulus for generating smooth pursuit is one which can create the perception of continuous target motion relative to the head, even when retinal velocity is always null." Further, it appears that the perceived velocity can even be manipulated before being utilized as a smooth-movement control signal, similar to the control of saccades to goals defined by instructions.[19] Thus, for example, the hyposaccade, to a fraction of a stimulus step, finds its counterpart in the subject's ability to track a smoothly moving target with only a fraction of target velocity.[20]

Similarly, we have demonstrated that subjects can elicit smooth movement counterdirectionally to the target movement when the 2VFB is inverted. This complements the antisaccade task, which requires the ability to respond with an equal amplitude but opposite direction to a saccadic stimulus.[9] A word of caution is necessary, however; not all our subjects could perform the inverted 2VFB task, and, in some cases, extensive training was required even to achieve intermittent smooth movement. Indeed, this task allowed us to identify those subjects who performed better in all tasks, demonstrating superior oculomotor control. It is our impression that with sufficient training most subjects could execute this task. For this we draw inference from our limited success as well as from other studies indicating that plasticity of the human oculomotor system can be effectively exploited by training with 2VFB.[6,21] In particular it was shown that by using the 2VFB paradigm, subjects could be trained to control voluntarily cyclotorsional smooth eye movements.[21] Like smooth movement with inverted 2VFB, the performance of such a novel task required both extensive training and voluntary effort. This study[21] also clearly demonstrated the distinction between an open loop and 2VFB condition. The opening of the loop by using an afterimage did not suffice as a control signal for torsional smooth movement, nor did the primary visual feedback of a smoothly rotating target. Only the combination of the two signals satisfying the requirements of a 2VFB condition permitted torsional smooth pursuit.

Foveal 2VFB is used clinically in the training of patients with eccentric fixation, in conjunction with tagging of the fovea using afterimages, Maxwell spots, or Haidinger's brushes.[22] Patients are trained to shift their fixation center back toward the fovea. We have noticed that individuals trained in this way do indeed use smooth eye movements for the final alignment of their fovea on the target.

The 2VFB could also be applied to acquisition of stationary information tasks, when it is advantageous to mediate the processing through the smooth eye-movement mode, with the trajectory and time course of the smooth scan path being controlled by the subject. The 2VFB has obvious advantages over the afterimage technique, as it does not fade and can be either gradually or abruptly turned on and off. Preliminary results indicate that it is possible to search for and detect a target in this mode.[23] There appears to be a reciprocal relationship between the probability of target recognition and the scanning velocity.

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