II.5

Role of Eye Movements in Maintaining a Phenomenally Clear and Stable World[1]

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Five weeks ago I received a letter from Dr. Volkmann (whom I had not yet met at that time) asking me to address myself to the question of the role of eye movements in the maintenance of a phenomenally clear and stable world. That letter came as a shock. I am not sure that the answer to this question is known to God (Jones, 1966); perhaps only to Leon Festinger (Marquis, 1972). I had not yet met either of these distinguished persons and knew no one to whom I could turn. But after a few weeks of thinking about the question and discussing it with several young collaborators, who had both ideas and the energy to do new experiments, I am ready to attempt a tentative answer. Before answering, however, I must make a few observations about human eye movements–these observations have influenced the answer that I will give.

Perhaps the most striking aspect of human oculomotor performance is its independence from stimulus variables. By this I mean that a normal human adult can look about in his visual world and attend whatever region catches his fancy undisturbed by the distribution of light on his retina, or, in perceptual terms, the way the visual world looks at a particular moment.

[1] I thank my colleagues G. Haddad, E. Kowler, P. McGrath, B. Murphy, and B. Winterson for many valuable suggestions as well as their reassurances during the weeks of terror following receipt of the assigned topic.

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Such independence is very useful. It permits the human being considerable freedom in directing his attention to any region without regard to the color, brightness, shape, or motion of objects within it. The freedom we each have as individuals, however, makes problems for those of us who wish not only to use our eyes to look around, but who also try to model the oculomotor system—a system whose output is determined by a large variety of inputs, including many that are in the mind's eye and, therefore, rarely under control of the unsuspecting experimenter. The human oculomotor system is not entirely without constraints imposed by visual input, but I will reserve comment about what is constrained until after I have presented some support for what some of you may feel is a presumptuous declaration of oculomotor independence.

I got my first hint of such independence more than 10 years ago when I did my very first eye-movement experiment (Steinman, 1965). At the time it was disheartening. I had examined the effects of size, luminance, and color on characteristics of maintained fixation, hoping to induce oculomotor characteristics from the orderly variations one usually finds in the visual system when such variables are manipulated. Instead, I found that variations in the luminance, size, and color of the fixation target had statistically reliable but quite trivial effects on mean fixation position and stability—effects not larger than 3 or 4 min of arc.

Now, this result was a disappointment. It was also a disappointment abroad where it provoked considerable activity in R. W. Ditchburn's laboratory. First, Boyce (1967) reexamined the effects of luminance and color on fixation, confirming my results and extending the work over a larger range of stimulus values. Next, Rattle (1969) looked at the effects of the size of the stimulus display and also found "unexpected fixation stability" when subjects maintained the line of sight at the imagined center of targets as large as 240 min of arc.

Murphy, Haddad, and Steinman (1974), in the most recent extension of this line of work, found that the line of sight can be maintained anywhere within or at the edges of simple forms without any influence of the form on mean fixation position or stability. Here I will run through some of the data because it not only supports the notion of oculomotor independence, it also has bearing on topics that will be discussed in other sessions.

Figure 1 shows the variety of simple forms and fixation positions studied. The subject's task was to keep his line of sight on the specified positions within or on the boundary of each of these simple forms while his two-dimensional eye movements were recorded [see Haddad & Steinman (1973) for a description of the recording apparatus whose position sensitivity was about 3 sec arc as used in these experiments].

Fixation trials were run in blocks. First, the subject would be asked to place a point in one of the specified positions on or within one of the forms. He then fixated the point and started the trial. When he started the trial, the form would disappear and he would maintain fixation on the point for 5 sec. At the end of

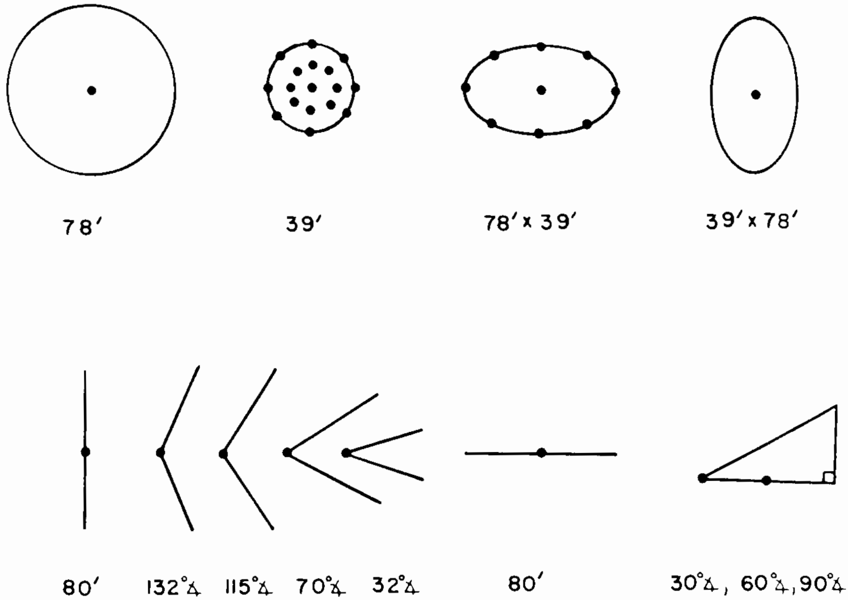

FIG. 1. The stimuli (shapes) and fixation positions (filled circles) used in the experiments on the fixation of forms. Each point represents one of the fixation positions studied. Subjects fixated either one of the specified regions within each of the forms or a small point in the same physical position in the absence of the form. (After Murphy et al., 1974.)

that time the trial ended, the form reappeared; he repositioned his eye on the point, and started the next trial. But this time the point disappeared and he maintained fixation at the specified position within or on the boundary of the form for 5 sec. Many such alternating trials were run for each position shown in Fig. 1.

The results of the experiment are shown in Tables 1, 2, and 3. Table 4 summarizes the main result for those who prefer prepackaged information.

I take these data to mean that, at least when the form is confined to the foveal floor [Polyak's (1941) designation], the oculomotor system is capable of maintaining the line of sight in whatever region a subject is required to fixate free from stimulus constraints. For those not impressed by standard deviations, I can say that the differences in mean fixation positions (constant errors) averaged only 3 min of arc and were not systematically related to the form or fixation position required. Human beings may have preferences to orient the line of sight to particular places within such forms, but these preferences are not imposed by oculomotor system control characteristics. This is contrary to a conclusion drawn by Kaufman and Richards (1969) a few years ago from the fixation behavior of naive subjects.

TABLE 1

Inverse Fixation Stability of Subject GH[a]

	Mean standard deviations, $\overline{SD}$ (min. arc)[b]							
	On horizontal meridian			On vertical meridian			Trials[d]	
Stimulus conditions	$\overline{SD}_F$	$\overline{SD}_P$	Δ^c	$\overline{SD}_F$	$\overline{SD}_P$	Δ^c	N_F	N_P
Circle (78′) center	7.4 (.0)[e]	7.4 (.0)[e]	.0	6.1 (.0)[e]	6.1 (.0)[e]	.0	8	9
Circle (39′) center	4.5 (1.4)	3.2 (.9)	1.3	3.0 (1.8)	3.0 (1.1)	.0	36	39
Edges:								
Horizontal	3.2 (.9)	3.4 (1.1)	–.2	2.8 (.5)	2.8 (.6)	.0	30	32
Vertical	3.6 (.9)	3.2 (.7)	.4	2.9 (.7)	3.1 (1.1)	–.2	29	30
Right oblique	3.5 (1.1)	3.3 (.7)	.2	3.3 (.9)	3.3 (.8)	.0	31	31
Left oblique	3.7 (1.2)	3.6 (1.3)	.1	3.4 (1.1)	3.1 (1.1)	.3	30	33
Halfway to edge:								
Horizontal	4.2 (1.5)	3.0 (.8)	1.2	3.2 (.9)	3.0 (.7)	.2	30	33
Vertical	3.9 (1.3)	2.9 (.5)	1.0	2.7 (.7)	2.7 (.6)	.0	29	31
Right oblique	3.7 (1.1)	3.2 (.5)	.5	3.8 (1.8)	3.7 (1.3)	.1	30	32
Left oblique	3.6 (1.4)	3.0 (.7)	.6	3.2 (1.1)	3.5 (.8)	–.3	29	33
Vertical ellipse (78′ × 39′) center	4.6 (1.5)	2.5 (.7)	2.1	3.2 (1.1)	3.1 (.8)	.1	31	31
Horizontal ellipse (39′ × 78′) center	5.6 (2.1)	3.2 (1.0)	2.4	2.2 (.6)	2.5 (.6)	–.3	29	30

Edges:								
Horizontal	4.0 (1.3)	3.5 (.8)	.5	2.7 (.8)	2.9 (.9)	–.2	33	35
Vertical	4.1 (1.4)	3.2 (.7)	.9	2.9 (.8)	2.9 (.6)	.0	30	30
Oblique	4.0 (1.6)	3.0 (1.4)	1.0	2.9 (.9)	2.9 (1.3)	.0	57	59
Horizontal line (78′) center	5.4 (1.6)	3.5 (1.1)	1.9	3.0 (.7)	2.9 (.6)	.1	35	33
Vertical line (78′) center	3.7 (.6)	4.1 (.8)	–.4	4.8 (1.1)	4.0 (1.0)	.8	31	33
Angle at vertex								
115°	5.1 (1.2)	4.4 (.9)	.7	4.4 (1.2)	3.9 (.7)	.5	36	36
70°	2.9 (.6)	2.6 (.6)	.3	2.0 (.4)	2.3 (.4)	–.3	32	32
32°	3.7 (1.4)	2.9 (.8)	.8	2.2 (.5)	2.6 (.8)	–.4	32	33
Triangle								
At 30° corner	3.7 (.8)	3.3 (.6)	.4	3.4 (1.0)	3.8 (.9)	–.4	30	30
Center of line between 30° and 90° angles	4.1 (1.7)	3.4 (.8)	.7	3.2 (1.0)	4.1 (1.2)	–.9	30	30

[a]Fixation maintained at selected positions within a variety of forms F or at a point P in the same physical position in the absence of the form.

[b]Inverse fixation stability is summarized as mean standard deviations $\overline{SD}$ in min. of arc on horizontal and vertical meridians.

[c]Differences $\Delta = \overline{SD}_F - \overline{SD}_P$.

[d]Number of trials run for form (N_F) and point (N_P).

[e]The standard deviations of the standard deviations are given in parentheses.

TABLE 2
Inverse Fixation Stability of Subject RS[a]

Stimulus conditions	Mean standard deviations, $\overline{SD}$ (min. arc)[b]							
	On horizontal meridian			On vertical meridian			Trials[d]	
	$\overline{SD}_F$	$\overline{SD}_P$	Δ^c	$\overline{SD}_F$	$\overline{SD}_P$	Δ^c	N_F	N_P
Circle (78′) center	4.3 (1.3)	4.6 (1.3)	–.3	2.8 (.8)	3.3 (.9)	–.5	29	29
Circle (39′) center	3.6 (1.3)	4.5 (1.7)	–.9	2.6 (1.1)	3.3 (1.1)	–.7	32	29
Edges:								
Horizontal	4.6 (2.0)	2.5 (.6)	2.1	4.7 (1.7)	3.4 (1.2)	1.3	31	33
Vertical	3.8 (.8)	4.2 (1.6)	–.4	2.8 (.8)	3.5 (1.2)	–.7	32	32
Right oblique	4.9 (1.9)	5.0 (2.0)	–.1	2.6 (.9)	3.7 (1.2)	–.3	35	31
Left oblique	4.2 (1.4)	4.2 (1.3)	.0	2.4 (.8)	3.5 (1.1)	–1.1	30	31
Halfway to edge:								
Horizontal	3.4 (1.5)	4.1 (1.9)	–.7	2.0 (1.5)	3.4 (1.3)	–1.4	30	31
Vertical	3.1 (1.1)	4.1 (1.6)	–1.0	2.3 (.8)	3.2 (1.2)	–.9	32	34
Right oblique	3.4 (1.5)	3.9 (1.7)	–.5	2.1 (1.5)	3.0 (1.1)	–.9	32	32
Left oblique	3.3 (1.2)	3.9 (1.3)	–.6	2.1 (1.2)	3.2 (1.1)	–1.1	31	31
Vertical ellipse (78′ N 39′) center	4.0 (1.1)	4.4 (1.6)	–.4	3.1 (1.2)	3.7 (.9)	–.6	31	31

Horizontal ellipse (39′ × 78′) center	4.3 (1.4)	4.3 (1.4)	.0	2.8 (0.6)	3.3 (.8)	–.5	36	42
Edges:								
Horizontal	4.4 (1.3)	5.0 (2.0)	–.6	3.0 (.8)	3.7 (1.4)	–.7	28	32
Vertical	4.2 (1.4)	5.0 (2.0)	–.8	3.1 (1.2)	4.1 (1.3)	–1.0	33	33
Oblique	4.3 (1.5)	5.4 (2.2)	–1.1	3.7 (1.5)	5.0 (1.6)	–1.3	57	47
Horizontal line (78′) center	5.0 (1.6)	5.8 (2.6)	–.8	3.9 (.8)	5.6 (1.6)	–1.7	27	27
Vertical line (78′) center	4.2 (1.4)	5.3 (2.1)	–1.1	3.9 (.9)	4.6 (1.4)	–.7	25	25
Angle at vertex								
132°	5.7 (1.7)	6.1 (2.2)	–.4	4.3 (1.2)	5.0 (1.2)	–.7	22	24
70°	4.7 (2.0)	4.8 (2.0)	–.1	3.4 (1.2)	3.9 (1.5)	–.5	27	28
32°	3.9 (0.8)	4.4 (1.1)	–.5	3.1 (.8)	3.3 (.8)	–.2	27	26
Triangle								
At 30° corner	4.5 (1.5)	5.1 (1.7)	–.6	2.8 (.7)	3.8 (.7)	–1.0	26	26
Center of line between 30° and 90° angles	3.7 (1.0)	4.5 (1.4)	–.7	2.6 (.5)	4.5 (1.2)	–1.9	25	25

[a]Fixation maintained at selected positions within a variety of forms F or at a point P in the same physical position in the absence of the form.

[b]Inverse fixation stability is summarized as mean standard deviations $\overline{SD}$ in min. of arc on horizontal and vertical meridians.

[c]Differences $\Delta = \overline{SD}_F - \overline{SD}_P$.

[d]Number of trials run for form (N_F) and point (N_P).

[e]The standard deviations of the standard deviations are given in parentheses.

TABLE 3

Inverse Fixation Stability of Subject RS[a]

	Mean standard deviations, $\overline{SD}$ (min. arc)[b]							
	On horizontal meridian			On vertical meridian			Trials[d]	
Stimulus conditions	$\overline{SD}_F$	$\overline{SD}_P$	Δ^c	$\overline{SD}_F$	$\overline{SD}_P$	Δ^c	N_F	N_P
Circle (78′) center	2.8 (1.8)	3.2 (2.1)	–.3	2.4 (1.2)	2.1 (.7)	.3	27	27
Vertical ellipse (78′ × 39′) center	3.8 (1.9)	4.1 (2.0)	–.3	2.6 (1.0)	2.8 (1.7)	–.2	29	29
Horizontal ellipse (39′ × 78′) center	4.0 (1.7)	4.3 (2.2)	–.3	2.2 (.9)	2.2 (1.1)	.0	31	32
Edges:								
Horizontal	3.8 (2.1)	4.1 (2.3)	–.3	2.5 (1.4)	2.8 (1.7)	–.3	33	33
Vertical	4.0 (2.7)	4.0 (2.1)	.0	3.1 (1.8)	3.4 (2.6)	–.3	32	34
Oblique	4.2 (2.0)	3.6 (1.2)	.6	3.0 (1.5)	3.7 (2.0)	–.7	44	43
Horizontal line (78′) center	4.2 (1.7)	3.9 (2.2)	.3	2.6 (1.1)	3.2 (2.1)	–.6	27	27
Vertical line (78′) center	3.7 (2.1)	3.5 (2.1)	.2	3.0 (1.7)	2.7 (1.8)	.3	25	25
Angle at vertex								
132°	4.0 (2.2)	4.2 (2.1)	–.2	2.5 (1.0)	3.2 (1.4)	–.7	25	24
70°	4.8 (2.9)	4.9 (2.5)	–.1	3.0 (1.6)	2.7 (1.3)	.3	28	28
32°	3.0 (1.0)	3.1 (1.7)	–.1	2.3 (.7)	1.7 (.5)	.6	28	28
Triangle								
At 30° corner	3.8 (1.9)	2.6 (1.4)	1.2	1.8 (.6)	1.8 (.9)	.0	30	31
Center of line between 30° and 90° angles	2.6 (1.5)	2.8 (1.6)	–.2	1.7 (.7)	1.9 (1.5)	–.2	27	26

[a] Subject uses slow control exclusively to hold his eye at selected positions within a variety of forms F or at a point P in the same physical position in the absence of the form.

[b] Inverse fixation stability is summarized as mean standard deviations $\overline{SD}$ in min. of arc on horizontal and vertical meridians.

[c] Differences $\Delta = \overline{SD}_F - \overline{SD}_P$.

[d] Number of trials run for form (N_F) and point (N_P).

[e] The standard deviations of the standard deviations are given in parentheses.

TABLE 4
The Take Home Message

	Horizontal $\lvert\bar{\Delta}\rvert$[a] in min arc	Vertical $\lvert\bar{\Delta}\rvert$[a] in min arc	Number of trials
Subject GH	.80 (.65)	.23 (.25)	1463
Subject RS	.62 (.46)	.90 (.43)	1357

[a]Differences in fluctuations of the line of sight are less than 1 min of arc regardless of where or what you are fixating.

Subjects also have the option of maintaining the line of sight on an attended target without jumping about (making saccades). This is a long story and I will not attempt to review it in detail (see Steinman, Haddad, Skavenski, & Wyman, 1973) but the basic finding is summarized in Fig. 2. A typical fixation pattern is shown in the record on the left. The typical slow control pattern is shown at the right. The difference between the two conditions is simply a matter of instructions. The subject has been told not to make saccades in the record on the right. Standard deviations of eye position are typically only 2 to 3 min of arc under slow control and 4 to 6 min of arc during fixation. Saccades can be suppressed with a variety of targets, e.g., a point, a disk, a foveal annulus, and annulus in the periphery regardless of whether they are steadily illuminated or flickering (Haddad & Winterson, 1975). Slow control is best and saccade suppression easiest with a steadily illuminated foveal disk about .5° in diameter.

Subjects also can use these different oculomotor options while tracking a moving point. This is shown in Fig. 3. In the bottom record a subject is shown tracking a ramp stimulus with pure slow movement. In the top record the same subject is making many small saccades while tracking. The stimulus was the same in both cases, again only the instruction changed. There were no step-ramps or other engineering tricks. The subject was just told to do one thing or to do the other.

We have also found that subjects can adjust the velocity of their smooth pursuits to specified fractions of the velocity of the target as is shown in Fig. 4 and summarized in Fig. 5.

We also know that the subject has the option of not tracking as long as he looks at a stationary detail in the visual field. Robinson made reference to this option earlier. This option is illustrated in Fig. 6 which is taken from a recent series of experiments reported by Murphy and Kowler (1974) and by Murphy, Kowler, and Steinman (1975). The performance of two subjects is shown in Fig. 6: BW, running in her first eye-movement experiment without any prior tracking experience, and myself (RS). I have been doing this kind of thing for many

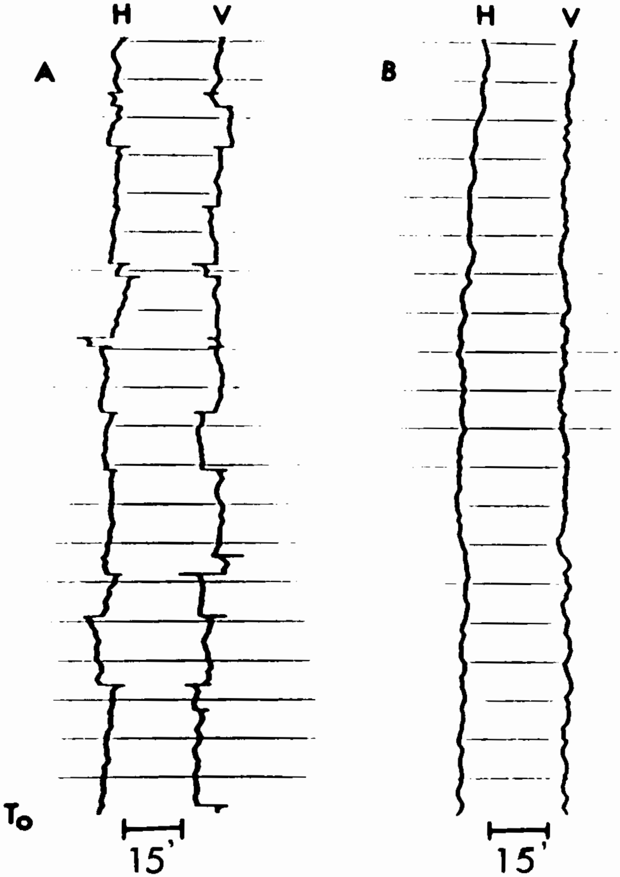

FIG. 2. (A) A representative two-dimensional record of human fixation. (B) A representative two-dimensional record of human slow control. Both records begin at the bottom (T_0); repetitive horizontal lines show 1-sec periods of time and the bars show 15 min of arc on both horizontal (H) and vertical (V) meridians. (After Steinman et al., 1973.)

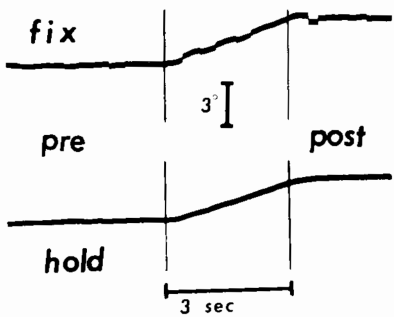

FIG. 3. Selected recordings for subject RS fixating (fix) and holding (hold) before (pre), during, and after (post) a constant velocity (60 min arc/sec) displacement of the target. The onset of target motion is shown by a thin dark line to the left of center in the figure and the end of target motion if shown by a similar dark line to the right of center. The target moved to the right on these trials (upward in the recorded trace). (After Puckett & Steinman, 1969.)

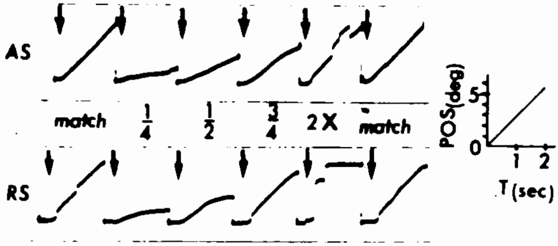

FIG. 4. Horizontal eye-movement recordings of the subjects AS and RS tracking a horizontal constant-velocity target moving at 172 min arc sec to the left (upward) through an angle of 6°. The record for each subject shows six consecutive trials run under the following sequence of instructions: on the first trial (shown at the left of the figure) subjects tried to match velocity with the target, on the subsequent four trials they tried to pursue at ¼, ½, ¾, or twice (2×) the velocity of the target. This sequence was followed by a final attempt to match the velocity of the eye to the velocity of the target. The arrows point to a faint dark line that marked the time of appearance of the moving target on the film. (After Steinman, Skavenski, & Sansbury, 1969.)

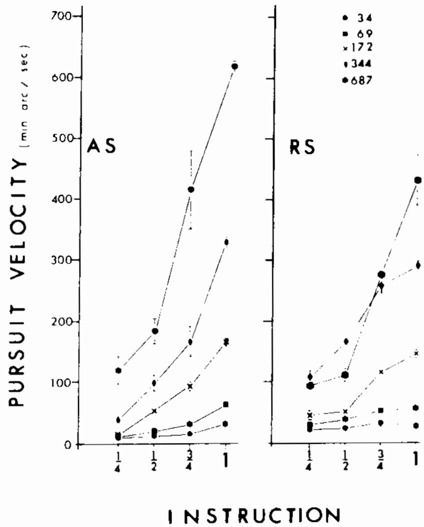

FIG. 5. Mean smooth pursuit velocities for subjects AS and RS tracking constant-velocity targets under instructions to smoothly pursue at ¼, ½, ¾, or 1, the velocity of the moving target. The symbols in the upper right of the figure refer to velocities (min arc/sec) of the five targets used in this experiment. Error bars show one standard deviation above and below the mean pursuit velocity for those cases where variability exceeded the size of the symbols used to make this graph. (After Steinman et al., 1969.)

years. We both performed in the same way. The stimulus was a point of light seen superimposed on a high-contrast foveal square-wave grating (4° arc diam). The subject's instruction in the particular experiment illustrated in this figure was to use slow control to stay on the point while the grating moved to the left. The velocity of the grating was 5 min arc/sec, 48 min arc/sec, or 480 min arc/sec—a range that extends from a velocity near the normal drift of the eye with a stationary target up to a velocity that the engineers consider brisk enough to be a good input for smooth pursuit (Robinson, 1965). Figure 6 shows the average result. There was virtually no effect of the moving high-contrast grating on slow control. Smooth pursuit and slow control can be activated voluntarily. These subjects tracked these stimuli quite well once they were told to track rather than to stay in place.

Figure 7 summarizes one of the results of Wyman and Steinman (1973a). It shows that a subject can track very small target steps. I put this material in because Fuchs suggested that I would say something about such small voluntary movements. It seemed quite reasonable to do so since these tiny saccades are

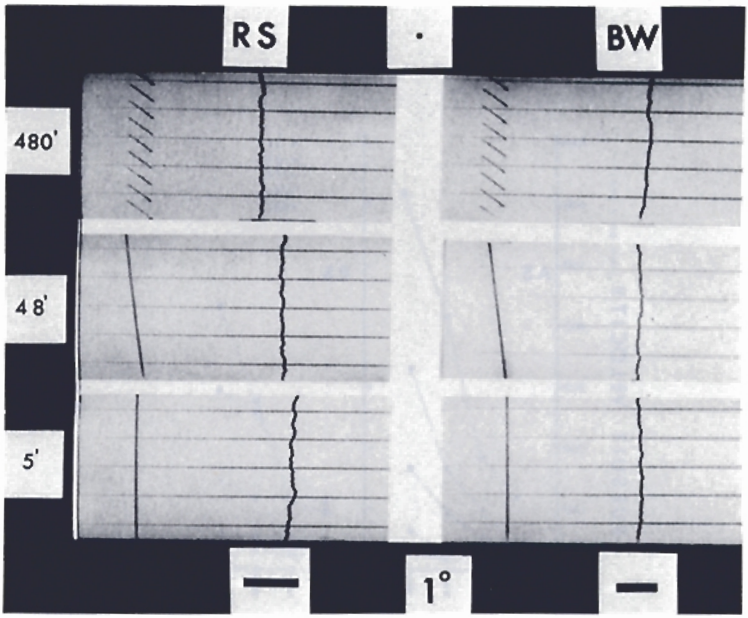

FIG. 6. Three representative records of horizontal eye movements of subjects RS and BW using slow control to maintain a steady line of sight on a stationary point superimposed on a leftward moving grating whose velocity was 5, 48, or 480 min arc/sec. Records are read from bottom to top. Horizontal lines are 1-sec time markers. The eye trace is at the right of each record. Grating velocity is proportional to the slope of the trace at the left of each record. The bar below each subject's records represents a 1° arc rotation. (After Murphy & Kowler, 1974.)

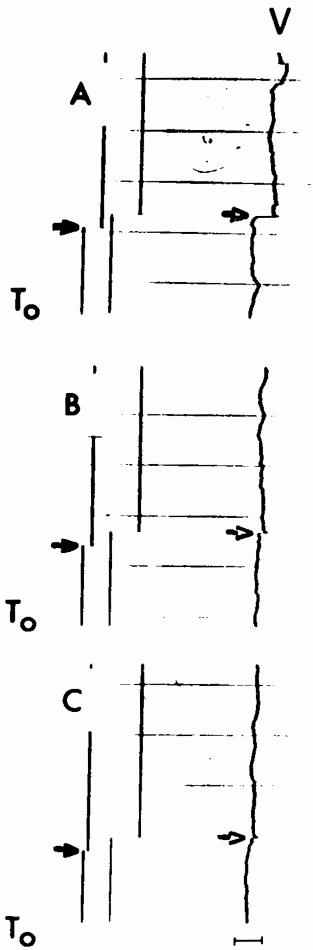

FIG. 7. (A) A representative record of small-step tracking on the vertical (V) meridian. The record begins at the bottom (T_0) and the filled black arrow points to the time a small point target moved downward 15 min of arc. The open black arrow points to the saccade made to follow the instantaneous displacement of the target. (B) A similar record of the saccade made in response to a downward target step of 7 min of arc. (C) A similar record of the saccade made in response to a downward step of 3.5 min of arc. Repetitive horizontal lines in all records show 1-sec periods of time and the black bar at the bottom indicates 15 min of arc. The event marker to the left of the eye position analog shows the operation of a trigger that monitored the eye-position channel and stopped a timer that was started when the target stepped, permitting us to measure the reaction time for small-step saccadic tracking. (After Steinman *et al.*, 1973.)

among our many oculomotor options. Both Haddad and I did equally well in this kind of task despite the fact that at the time she was beginning in the eye-movement game and ran as a totally inexperienced subject. We both found this task easy, tracking 98–99% of unpredictable target steps that were 3.5 min of arc or larger.

Figure 8 shows that we could also make microsaccades down in the 5–6 min of arc ball park without any change in the position of the stimulus (Haddad & Steinman, 1973). The stimulus was a stationary point of light seen in an otherwise completely dark environment. When a tone sounded, the subject's task was to make the smallest possible saccade in a randomly chosen direction specified before the trial by the experimenter. We found that the smallest average voluntary saccade was the same size as the average fixation microsaccade (5.6′, S.D.<3) which shows that we have the option of looking away from a

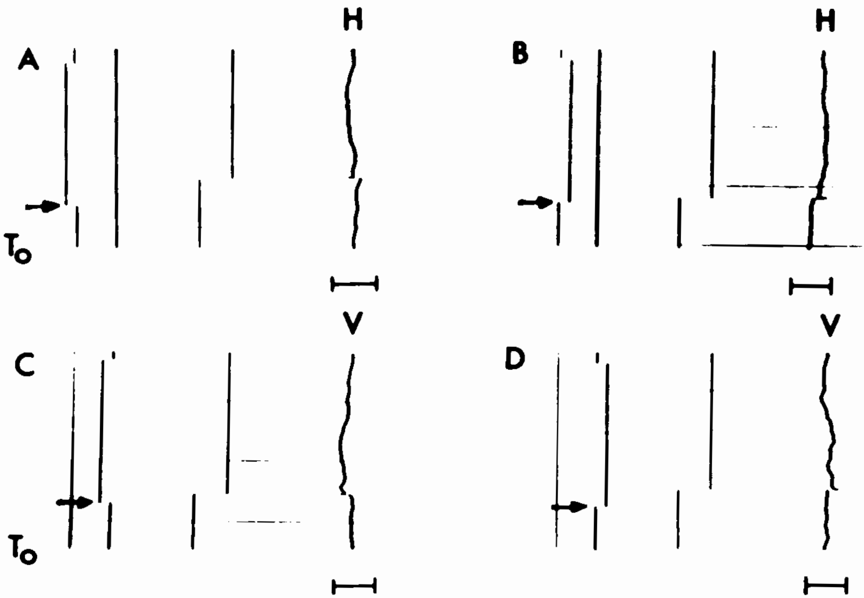

FIG. 8. (A) A record of the eye-movement pattern on the horizontal (H) meridian when the subject was asked to make one small voluntary saccade to the left while looking at a point that remained stationary throughout the trial. The record begins at the bottom (T_0). The black arrow indicates when an auditory signal told the subject to make his smallest possible saccade to the left. The eye-position trace shows that a small saccade was made to the left after the signal was given. The size of this small voluntary saccade can be estimated from the black bar (15 min of arc). The event marker to the left of the eye-position analog shows the operation of the trigger which stopped a reaction timer when the saccade was made. The other three records show small voluntary saccades made in the other directions: (B) to the right, (C) up, and (D) down. (After Steinman et al., 1973.)

stationary fixation point in any direction. We can do this with the same precision with which we can correct small eye-position errors produced by drifts of the eye or changes in the position of the fixation target.

Now let me say a word about constraints on the oculomotor system that otherwise seems to allow the human being to move his eye in any way that he pleases. First, it is well known that smooth pursuit without a moving target is extremely difficult. It is easy when a vivid afterimage is provided, as Robinson and Young have demonstrated at this symposium. But this exception, although very important in our understanding of the oculomotor system, requires a vivid afterimage which is rarely encountered in ordinary visual search. There is another constraint on what you can do with your eyeball. It is well known that it is hard to maintain eye position if there is no visual input. Skavenski & Steinman (1970) found that the line of sight can only be maintained within ¾° over periods of 40 sec in the dark and only within 3° or 4° over 7.5-min periods (Skavenski, 1972). Your eye is also constrained by the luminance of the fixation target. Everything I have said about oculomotor independence applies only to the operation of the oculomotor system under photopic illumination. If targets are too feeble to be seen when they fall on the fovea, a good deal of voluntary control is lost and a maladaptive eye-movement pattern ensues. A feeble target, placed in the near periphery where it can be seen, will be returned to the central fovea where it disappears (Steinman & Cunitz, 1968).

Finally, I must emphasize that I have been talking about human oculomotor capacity, what an individual can do, not what he will choose to do if you flash a light at him or have something dance about in his visual world without telling him what you want him to do. Observing these capacities requires explicit instructions to the subject who does best when provided with feedback about his success. Once he is instructed and told how he is doing, a large degree of independence from stimulus variables and a wide range of oculomotor options can be demonstrated in ordinary adults.

Given such voluntary control of the way in which the eye can be moved or kept in place in the presence of a wide range of perturbations in the visual scene, all kinds of possibilities open up for using this motor skill for information processing. This motor skill is most highly developed in man where it is perhaps second only to control of the larynx in importance. This skill might be very significant for maintaining a phenomenally clear and perceptually stable environment. It could, in addition, provide a useful tool for the measurement of such things as distances and velocities in visual space.

However, recently I have come to doubt that the human oculomotor system is ever used, outside the laboratory, in the ways that I have described. My doubts were provoked by Winterson who insisted that I could not answer the question at issue without some idea of what the eye does when the head is not held rigidly in place on a bite board (the way we study small eye movements in the laboratory). So, having spent a good deal of time extolling free will and describing oculomotor options, I would like next to consider the conditions

FIG. 9. Murphy in position for two-dimensional recording of rotations of his head by means of the magnetic-field search-coil technique. The head search coil is mounted on a dental bite plate. The field coils can be seen surrounding the subject.

under which man might be able to use these options when his head is not stabilized by artificial means.

Our first experiment on this problem is illustrated in Fig. 9. Figure 9 is not what it appears to be. It is not a photograph of a Druid sitting on an ancient Celtic throne, but rather Brian Murphy sitting comfortably in Robinson's magnetic-field search-coil recording apparatus. Clenched between his teeth is an acrylic bite board. Attached to the front of the acrylic bite board is a little coil of wire whose twisted lead is carried up above the head on the way to a phase-lock amplifier. Murphy is surrounded by large coils of wire that (by means of magic understood best by a small group of people who have worked with magnetic phonograph cartridges) make it possible to detect the orientation of the moving coil attached to his bite board with respect to the stationary magnetic field in which he is immersed. Murphy has been asked to be as still as possible for 40 sec while the rotational components of his head movements are recorded.[2] Let me emphasize that Murphy is committed, obviously very serious, and obviously relaxed. He is fully prepared to try to be as still as possible while

[2]The head movement trials were 40 sec in length to conform with a suggestion by Ditchburn and Foley-Fisher (1967) who proposed that we all adopt 40 sec as the interna-

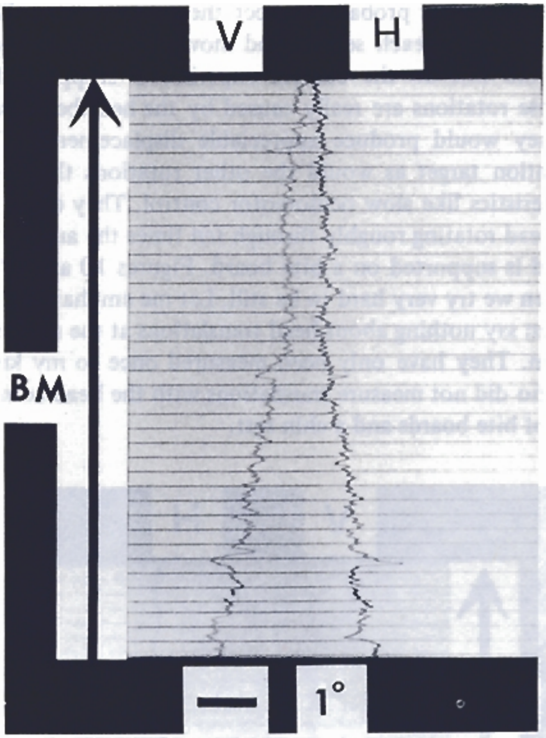

FIG. 10. A representative two-dimensional head-rotation record of the least stable subject. The record begins at the bottom and the repetitive horizontal lines indicate 1-sec periods of time. The bar beneath the record shows 1° arc rotation on both horizontal (H) and vertical (V) meridians.

he uses normal human postural supports to keep his head in place. Five subjects participated in this series of experiments. The typical performances of the worst and the best subjects are shown in Figs. 10 and 11.

We have not had time to do a power spectrum on these head-movement records but it is quite clear that there are appreciable oscillations at about 2–3 Hz that have a peak-to-peak amplitude of about 15 to 20 min of arc. There also seems to be a relatively large .2 to .4 Hz component and a large d-c component as well. These movements are very large in the worst subject (Fig. 10) but appreciable even in the best subject (Fig. 11) where we can also see rotations on

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tional fixation duration. They hoped that we could develop some normative oculomotor data and ignore individual differences by standardizing conditions. I think that it would be better to find out why these differences are observed, but we used the recommended duration and formally propose that we all use 40-sec trials to study head rotation in the future. If we agree to do this, it might lead to an International Commission for the *Evaluation of the Fixation Duration that could meet annually in Paris.*

the horizontal meridian that probably reflect the human pulse. The pulselike rotations occur about once each second and move the head through about 12 min of arc. We did not do the control experiment–stopping the heart to guarantee that these rotations are really caused by the heartbeat. But regardless of their origin they would produce appreciable displacements of the retinal image of the fixation target as would the other rotations that seem to have frequency characteristics like slow oculomotor control. They differ mainly by a scale factor–the head rotating roughly through ten times the angle shown by the eye when the head is supported on a bite board. Figures 10 and 11 show what the head does when we try very hard to be still. Let me emphasize that these are just rotations. I can say nothing about head translations at the moment. We have not recorded them. They have only been measured once to my knowledge by Findlay (1969) who did not measure translations with the head completely free. He used a variety of bite boards and a chin rest.

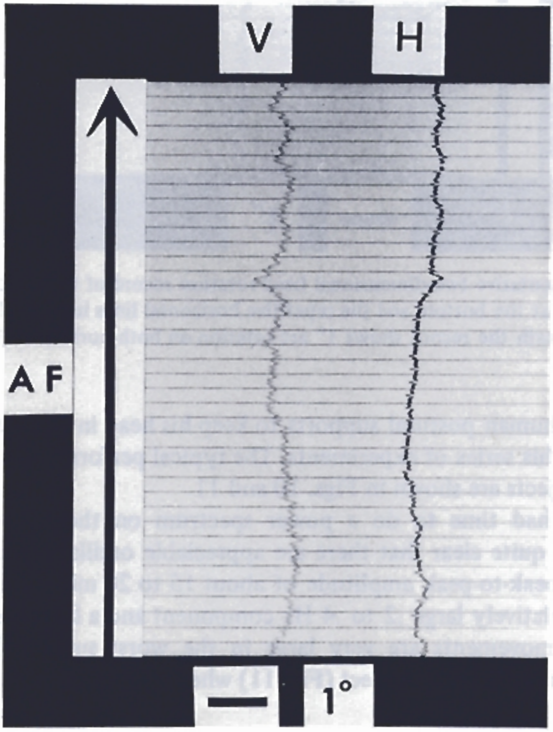

FIG. 11. A representative two-dimensional head-rotation record of the most stable subject. The record begins at the bottom and the repetitive horizontal lines indicate 1-sec periods of time. The bar beneath the record shows 1° arc rotation on both horizontal (H) and vertical (V) meridians.

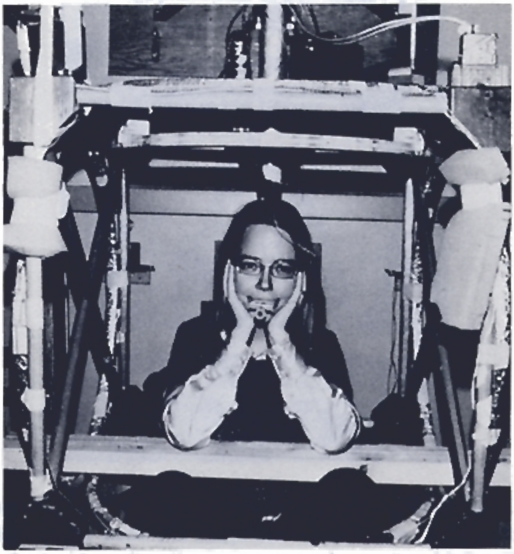

FIG. 12. Winterson in position for two-dimensional recording of rotations of her head by means of the magnetic-field search-coil technique. The head search coil is mounted on a dental bite plate. The field coils can be seen surrounding the subject who is using her hands to support her head.

Next, an attempt was made to see whether our subjects could improve matters by using special but natural supports to hold the head in place. How this was done is shown in Figs. 12 and 13 where you can see Winterson (who got this whole thing going) holding her head while its rotations are recorded. This kind of posture is natural and frequently used outside the laboratory. It is, however, subject to individual differences as can be seen in Fig. 13 which shows Kowler ready to run. The results of this experiment with a stabilized head are shown, once again, for the worst and the best subjects in Figs. 14 and 15.

We are beginning to get something resembling a stable platform—the d-c level shift is much reduced but there is still a large low-frequency a-c component. This proved to be caused by breathing as can be seen in Figs. 16 and 17 which show the best and the worst performances when the head was supported and the breath held.[3]

[3] I call the reader's attention to a new biological phenomenon in the horizontal trace in the 12th second in Fig. 14. I call such small high-velocity rotations of the head "head" flicks. Another example can be seen in the horizontal trace in the 32nd second of Fig. 17. These are not electrical artifacts. Skavenski (private communication) subsequently observed such head flicks in his laboratory. I cannot imagine what the significance of these strange movements might be but I call them to your attention because they are seen from time to time in the records of all the subjects.

FIG. 13. Kowler in position for two-dimensional recording of rotations of her head by means of the magnetic-field search-coil technique. The head search coil is mounted on a dental bite plate. The field coils can be seen surrounding the subject who is using her hands to support her head.

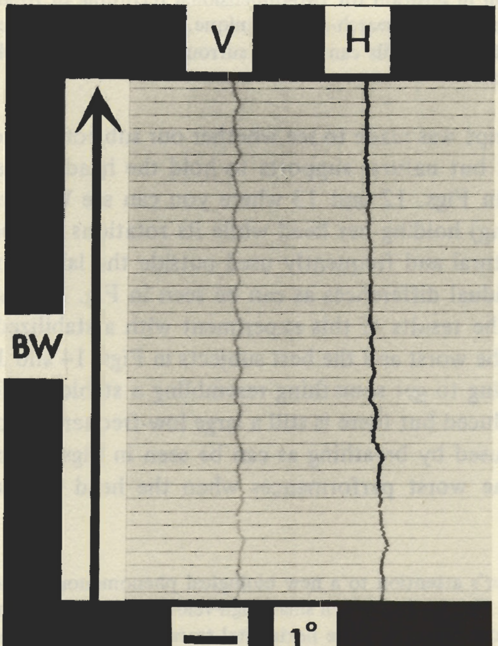

FIG. 14. A representative two-dimensional head-rotation recording of the least stable subject when the head was supported. The record begins at the bottom and the repetitive horizontal lines indicate 1-sec periods of time. The bar beneath the record shows 1° arc rotation on both horizontal (H) and vertical (V) meridians.

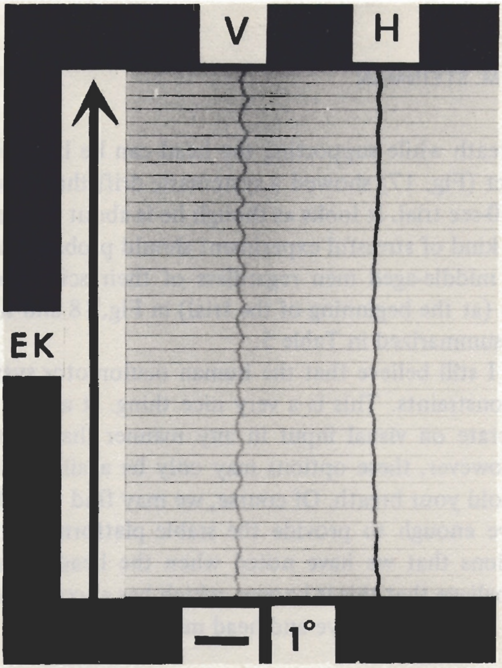

FIG. 15. A representative two-dimensional head-rotation recording of the most stable subject when the head was supported. The record begins at the bottom and the repetitive horizontal lines indicate 1-sec periods of time. The bar beneath the record shows 1° arc rotation on both horizontal (H) and vertical (V) meridians.

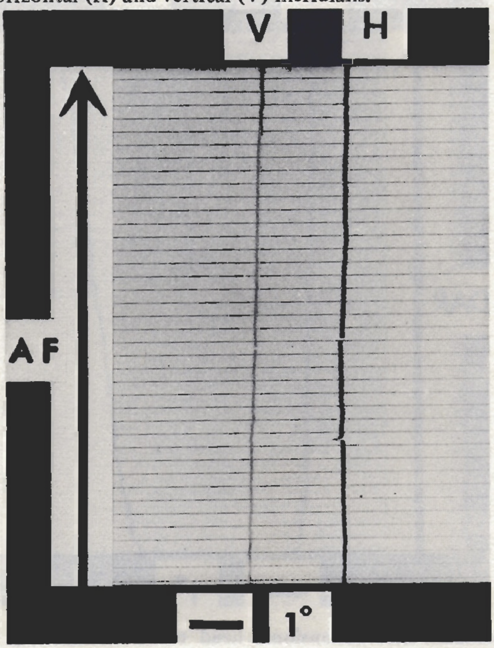

FIG. 16. A representative two-dimensional head-rotation recording of the least stable subject when the head was supported and the breath held. The record begins at the bottom and the repetitive horizontal lines indicate 1-sec periods of time. The bar beneath the record shows 1° arc rotation on both horizontal (H) and vertical (V) meridians.

Holding the breath while supporting the head can be helpful, but not always. The worst subject (Fig. 17) showed a systematic drift that became very large by the end of the 40-sec trial. It looks as though he is about to keel over by the end of the trial. This kind of stressful experiment should probably not be undertaken by emphysemic middle-aged men regardless of their scientific dedication. The subject is shown (at the beginning of the trial) in Fig. 18 and the results of these experiments are summarized in Table 5.

In conclusion, I still believe that the human oculomotor system is largely free from stimulus constraints. This is a very nice thing. It allows you to pick, and choose, and operate on visual input in any manner that seems suitable to the task at hand. However, these options may only be available after you stabilize your head and hold your breath. Of course, we may find that the vestibuloocular reflex is effective enough to provide the stable platform that would allow the oculomotor options that we have noted when the head is stabilized on a bite board. I do not believe that this is known, which has encouraged us to prepare to do simultaneous recordings of eye and head movements.

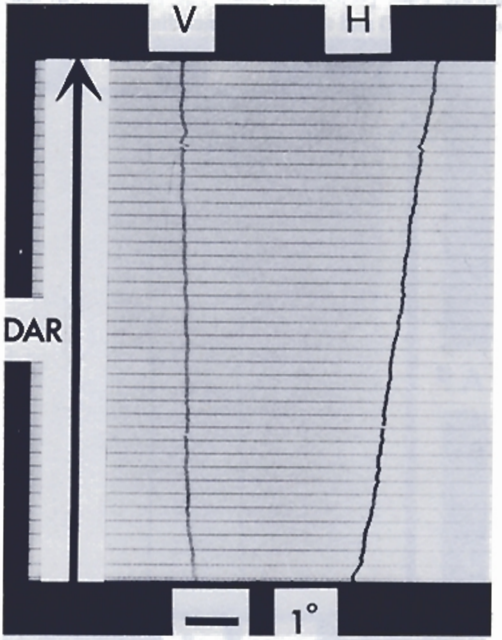

FIG. 17. A representative two-dimensional head rotation recording of the most stable subject when the head was supported and the breath held. The record begins at the bottom and the repetitive horizontal lines indicate 1-sec periods of time. The bar beneath the record shows 1° arc rotation on both horizontal (H) and vertical (V) meridians.

FIG. 18. Robinson in position for two-dimensional recording of rotations of his head by means of the magnetic-field search-coil technique. The head search coil is mounted on a dental bite plate. The field coils can be seen surrounding the subject who is using his hands to support his head.

As matters now stand, I must end on a note of gloom. I think there is a very good possibility that our oculomotor system is completely committed to and very busy compensating for movements of our bodies. Whether this system has any time left to do other things remains to be seen. My answer, then, to the question posed by our Chairperson is that eye movements are essential to maintaining a phenomenally clear and stable world. They serve to stabilize image motion produced by our normal bodily activities. It seems unlikely to me that the eye moves to keep images from fading because of stabilization.[4] Of great

[4]We now have good reason to believe that the eye moves to stabilize retinal image motion produced by normal bodily movements. The gain of the slow compensatory oculomotor subsystem does not exceed .8–.9 over the frequency range of .1–10 Hz when both vestibular and visual imputs are provided. This means that there is a great deal of retinal image motion when the head is not supported on a bite board. Now we must find out why the visual world looks stable and why visual acuity is excellent in everyday life. See Steinman (1975) and Winterson *et al.* (1975) for details of our experiments that report characteristics the "Minivor" (the miniature vestibuloocular response) and "natural" retinal image motion.

TABLE 5
Mean Error and Inverse Head Stability for Five Subjects

		Inverse head stability[b]		
		SD (min. arc)		
Subject	Error (min. arc)	*H*	*V*	Bivariate area (min. arc)²
		Naturally[c]		
AF	25 (10)[e]	9 (3.6)[e]	10 (2.9)[e]	530 (206.9)[e]
EK	41 (23)	8 (1.8)	19 (5.6)	802 (229.4)
BM	80 (26)	18 (8.2)	20 (7.3)	1407 (428.0)
DR	89 (16)	22 (8.3)	29 (16)	2271 (971.9)
BW	86 (29)	24 (9.3)	21 (9.5)	2003 (924.2)
Mean	64 (29)	16 (7)	20 (7)	1403 (748)
		Supported, breath held[d]		
AF	18 (7)	3 (.1)	7 (1.6)	90 (50.0)
EK	19 (8)	6 (3.8)	4 (2.5)	186 (216.6)
BM	30 (18)	9 (4.8)	8 (3.5)	338 (182.2)
DR	63 (25)	18 (9.4)	9 (6.3)	340 (215.6)
BW	37 (22)	7 (3.5)	12 (6.9)	262 (146.1)
Mean	33 (18)	9 (6)	8 (3)	243 (107)
Noise[f]	0	4	.4	1.4

[a]Absolute distance between median head position during the first 5 sec of a trial and median head position during the last 5 sec.

[b]Mean bivariate contour ellipse areas and mean standard deviations SD.

[c]Maintaining head position naturally.

[d]Head was supported by the arm and hand for 40 sec. while the breath was held.

[e]Standard deviations are given in parentheses.

[f]The noise level of the recording and digitizing apparatus.

interest is a report by a physician whose vestibular mechanism became effectively functionally destroyed through clinically administered streptomycin. He reports (C., 1952) that even the pulse beat in his head while reading made the letters on a page jump and blur, and that walking destroyed his ability to read signs and recognize faces. The loss of the vestibulooculomotor control system apparently led to a wide range of bizarre and distressing experiences. I recommend the article for those who would like a naturalistic view of the real meaning of the vestibuloocular control system.

However, since much of this symposium is devoted to the role of the oculomotor system in human perception and cognitive processes, I close by reassuring you that there are circumstances during which the head is stabilized and there is no pulse or breath—circumstances in which a human being may be able to tap the wide range of oculomotor skills he has evolved. This is shown in Fig. 19.

DISCUSSION

FUCHS: You said that for the small target steps of 6 min of arc or so that 98 to 99% of the microsaccades were in the right direction. Were they also the right size?

STEINMAN: Their accuracy depends on the subject, the direction, and the experiment. For example, Haddad typically tracks target steps that go to the left

FIG. 19. Rodin's Thinker.

with a burst of 3 to 5 saccades. This is true even when the steps are as small as 6.9′. In all other directions Haddad tends to follow a target step with a single saccade that is reasonably accurate. I tend to make a single saccade that ends near the new target position. [See Wyman & Steinman (1973a) for the details of this work.] However, in a prior experiment (Timberlake, Wyman, Skavenski, & Steinman, 1972) both Skavenski and I went only half way to the target position when the target stepped from 5′ to 180′. We had no idea that we were doing this while the data were collected. I suspect that for some mysterious reason we both decided that overshooting was a bad thing and erred in the other direction just to be sure that we did not go too far. People show similar quirks when they play tennis or golf, which requires quite similar motor skills.

In my opinion the only way to find out about the actual accuracy and precision of saccades is to give the subject feedback about the size of his off-set error and run him until performance is asymptotic. This should make it possible to estimate the limits of the high-velocity subsystem's operation. Until now we and everyone else have been studying various individuals' styles and preferences when they use saccades to reduce position errors in a particular experiment. I know of no data on saccade accuracy collected in an experiment designed to measure the limits of the subsystem's performance.

FUCHS: In all those microsaccades, an overshoot made up a considerable portion of the response.

STEINMAN: That is my characteristic response. Haddad and Winterson, for example, do not usually show such overshoots.

BROWN: Why, do you think, was Rashbass (1961) unable to show these microsaccades?

STEINMAN: I do not know the answer to the question. Rashbass' result never made any sense to me or to Cornsweet or Nachmias when it was first published. Nachmias showed me his correspondence with Rashbass in which Nachmias asked Rashbass how he reconciled his "dead zone" results with Nachmias' (1959) and Cornsweet's (1956) finding that very small saccades can be corrective during maintained fixation. Rashbass could not answer the question. I cannot answer the counterquestion. Our result, unlike Rashbass', is at least consistent with other well-known aspects of the use of microsaccades. I have run in many tracking experiments and I am convinced that if I can see a target move, I can track it. I am as certain of this as I am certain that if an engineer sees something move, he will model it.

HALLETT: Do you have to follow small steps?

STEINMAN: No. It is very easy to see steps and to ignore them. You do not have to follow them. Saccades are used voluntarily—at least in adults.

HALLETT: There could be variations in different people's data, then, of the sort observed by Rashbass.

STEINMAN: Yes, I think that Rashbass' instruction to track may not have been explicit enough. Alternatively, Rashbass' subjects may not have been able to see small target steps for one reason or another. I do not think that this was the case and suspect that the difference in our results was due to instructional or motivational factors.

CORNSWEET: There is another possible explanation of Rashbass' results. If a target steps to the right, stays there a second or so, and then returns, a subject will usually follow it, but if it repeats that pattern a few times, many subjects, and maybe all of them, stop responding. They just keep looking at the original location of the target.

STEINMAN: But I do not see how this explains the difference between Rashbass' and Wyman's results because unpredictable target steps were used in both experiments.

CORNSWEET: Even if the time of occurrence and the size of the step are unpredictable, the subject will fail to respond if the target always returns to its original position at the end of the step. I have been a subject in this situation, and, although I am not really aware of it during the experiment, it is as if I just keep looking at the place where the target used to be because I know it will be coming back there sooner or later. Sometimes the brain that is hooked up to the eyes messes up our neat system models.

YOUNG: Did you say how long you waited for this corrective miniature saccade?

STEINMAN: A short time. Average latencies ranged from 400 to 200 msec as steps ranged from 3.5 to 28.4 min arc (Wyman & Steinman, 1973b). Rashbass reproduced a record to show his "dead zone" in which no saccade was observed in about 800 msec. We waited half as long and got consistent saccadic tracking of very tiny steps.

YOUNG: I was looking up some old records we had taken on the probability of a corrective saccade as a function of target step size and latency. For our longest allowable interval, 750 msec, the probability of a corrective saccade decreased from over .9 for large steps (50 min arc) down to .4 for the smallest steps we used (5 min arc).

STEINMAN: Rashbass reported "no responding with quarter- to half-degree" steps after a wait of 800 or so msec. No quantitative treatment of the results is presented in his paper, however, which makes it difficult to know precisely what he found.

YOUNG: We found a probability of a corrective saccade which decreases monotonically with step sizes below about $\frac{1}{2}^{\circ}$. For the shortest allowable interval (250 msec) and smallest target step (5 min arc), the probability of a corrective saccade was down to less that .2 (Young, 1971).

STEINMAN: In our experiment both the experienced subject and the inexperienced subject tracked on 98–99% of the trials. The latency depended on the step size, but even 3.4-min steps were tracked in 400 msec.

YOUNG: In our experiments, in which subjects were not specifically instructed to attempt corrective saccades, we did not get those high probabilities.

STEINMAN: I do not think this issue can be resolved by counting up experiments for or against dead zones. Let me explain by saying something that may seem outrageous to some of you. I am not an engineer and had no commitment to a saccadic dead zone (which seems to be useful in modeling certain kinds of servosystems) when I ran in the tracking experiments. In fact, I had quite the opposite expectation based on my work on fixation of stationary targets. I also knew, however, that I could perform as though the oculomotor system does have a saccadic dead zone by deliberately ignoring fixation errors. I could have used this strategy in the tracking experiment and obtained data that supported the dead-zone notion quite easily, or I could have run naive subjects and seen what they would do. However, I do not think that this strategy is useful in developing models of the oculomotor machinery. The dead-zone notion implies that the oculomotor system *cannot* do something. If it can be shown that the oculomotor system can, in fact, do it, models that use the notion must be prepared to put the dead zone in a decision process box and not somewhere deep down in the oculomotor machinery. This, of course, may leave you (as it does me) with the feeling that it may be hard to use the model to make predictions about performance without telling the subject precisely what you want him to do.

Afterthoughts[5] YOUNG: I think that you misinterpret the system's ideas. The "dead zone" is a system function—not sensory or motor. If the system, subject to instructions and needs for extracting visual information, is *indifferent* to the target location on the fovea, then there is a functional dead zone. The fact that under different instructions (e.g., "move your eyes to fixate") there are smaller saccades indicates that the functional dead zone seen in normal tracking is not based on any hard sensor or motor resolution limit.

STEINMAN: It is my impression that Rashbass interpreted his results as a hard-wired limit and not simply a performance characteristic of his subjects. It is this interpretation that I have been discussing. Wyman and Steinman (1973a) have discussed this as well as other interpretations of the dead zone in some detail elsewhere.

SENDERS: I find myself frustrated by the fact that although the expressed subject of the session was the phenomenon of the apparently clear and stable visual world, we have heard only about its stability and nothing about its clarity. To me the world, whether it be the external visual world of things, people, landscapes, or the world of the printed page, appears subjectively to be all there, all clear and not subject to the degraded image quality which we know must exist for objects seen far from the point of regard. The experiments on reading show that what is *seen* is only a very small part of what there is. That is to say, as will be described later, one can alter drastically the form and the content of

[5] Conferees were invited to submit additional thoughts after the conference. Some of these follow.

words only a few degrees removed from the point of regard without interfering in any way with the reading process. I imagine that under these conditions the printed page looks whole and stable. When I look at a page, I think I see all the words on it and when I look at the world I have the illusion that even those parts of it in my periphery are clear. It is only when I artificially constrain my eye to stop moving that this clarity fades and the true fuzzy quality of visual space becomes apparent. The clarity in both cases is in the head. Presumably, the saccades and fixations of normal vision, that we make when we are not constrained in the laboratory, are designed to fill in this picture and make it whole and thus preserve the illusion. Perhaps at some future meeting we'll know more about this question.

II.6

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