Hand-eye coordination: The role of "motor memory"

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Ten Ss attempted to track a visual target, which was moved either by hand (test run) or by a tape recording of the same hand movements (control run). On some test runs, movement of the target lagged behind that of the hand by a fixed amount (.18, .36, .72, or 1.44 sec). The number of saccades occurring on a given test run was divided by the number on the matched control run, and the test/control ratio was studied as a function of the hand-to-target lag time. With lag times of .36 sec or less, the test/control ratios were less than 1, indicating that manual control of the target had a significant effect on oculomotor performance. This effect disappeared at a lag close to .72 sec. The results are discussed in terms of a hypothetical "motor memory."

Movement of the hand often depends on visual information, which, in turn, requires coordinated movement of the eyes. The latter is produced by specialized subsystems for acquiring and tracking visual targets (Robinson, 1968). While the separate manual and oculomotor systems have been studied in detail, little is known about the neuronal mechanism that coordinates their activities. Improved knowledge of this mechanism could have clinical, as well as theoretical, implications.

The present study was based on the observation that oculomotor tracking is better—the eye lags behind the target less and makes fewer saccades—when the visual target is moved by the S rather than by an external agency (Steinbach & Held, 1968). In order to explain this finding, Steinbach (1969) has postulated that "outflow" signals concerned with movement of the hand are used to improve performance of the oculomotor system. Subsequent work has shown that a self-moved target is followed with fewer saccades, even when a substantial delay is introduced between movements of the hand and target (Angel & Garland, 1972). Since this effect occurs with hand-to-target delays exceeding the visual and proprioceptive reaction times, it could be explained by sensory feedback from the moving limb, as well as by the postulated outflow signals. Furthermore, it is possible that each hand movement may be recorded in memory for some time preceding the coordinated oculomotor response. If there is a "motor memory" system that helps to improve hand-eye coordination, its properties would seem to deserve investigation.

The goal of the present investigation was to provide normative data concerning the effect of hand movement on subsequent oculomotor performance. Previous work in this laboratory has suggested that, when Ss track a hand-moved visual target, there is a tendency for the frequency of saccadic eye movements to increase with

increasing delay between the hand and target movements (Angel & Garland, 1972). Hence, it appears that the effect of hand movement on visual tracking may tend to decrease as a function of time. The experiment reported here was an attempt to define the time course of that effect. The independent variable was the delay between hand and target movement, and the dependent variable was the relative frequency of saccades.

METHOD

The position of the S's right eye was recorded by means of an eye-movement monitor (Model SGH/V2, Biometrics, Inc.). The visual target was a spot of light, 1 mm in diam, displayed on an oscilloscope about 40 cm from the S's eyes. The maximal excursion of the target was 4 cm (subtending 5 deg 43 min) to the right or left of the central position. During each experimental run, the position of the target was controlled by S, who moved a small joy stick (6 cm long) with the preferred hand. Movement of the joy stick to the right or left caused the target to move horizontally across the cathode ray tube in the same direction. Position of the joy stick was recorded by means of an Ampex (SP-300) tape recorder.

On four of the five test runs, there was a fixed delay between movement of the joy stick and that of the target. This was produced by running the tape recorder at 15, 7½, 3½, or 1-7/8 ips and displaying the output of the playback head. These tape speeds correspond to delays of .18, .36, .72, and 1.44 sec, respectively. The five display conditions, four with a fixed delay and one with no delay between hand and target motion, were used in a different, random order for each S.

The mechanical properties of the tape recorder caused a fast, low-amplitude ripple, which was filtered electronically in order to produce a clear target image. Any residual "flutter" was identical on test and control runs. For the test run with zero lag, the output of the joy stick was displayed directly.

Subjects and Test Procedure

The normal group consisted of one female and nine male Ss, aged 22 to 55, who were paid to participate in the experiment. For each test, S was seated facing the oscilloscope, with the chin on a headrest (Biometrics, Model 115). He was instructed to keep the eyes on the target at all times and to avoid movement of the head or neck. For each test run, S was required to move the target back and forth ad lib. The pattern of target motion was supposed to be irregular and slightly difficult, but not too difficult, for the eyes to follow. The run lasted 100 sec and was followed within 2 or 3 min by the paired control run, during which S watched a copy of the same target pattern, reproduced

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Fig. 1. Eye tracking of hand-moved target, test run. Displacement of visual target (second line) follows that of hand (top line) by 0.36 sec. Arrows indicate saccadic jumps.

Fig. 2. Control run. Top line indicates that hand is stationary. Middle line is an exact replica of target motion shown in Fig. 1, presented more than 1 min later. More saccades are present on the third line than on the corresponding line of Fig. 1.

by the tape recorder. A complete test consisted of 10 runs: 5 test runs, each paired with a control run.

Data Processing

Three variables were written out on a Grass polygraph: joy stick position, target position, and eye position. The paper speed was 2.5 cm/sec. Records were later examined to determine the number of saccades per 100 sec of tracking performance. Care was taken to insure that the beginning and ending points of each test run were identical to those of the matched control run. If any portion of a record had to be discarded because of faulty recording, exactly the same portion of the paired test or control run was also discarded.

One possible source of error was the occurrence of blinking, since the eye monitor is ineffective when the eyes are closed. In general, the frequency of blinking was low and roughly the same during test and control runs. Another source of error was the classification of some very small deflections in the record of eye position. While the majority of saccades were easy to recognize, very small ones were hard to distinguish from the background of smooth pursuit movements. Arbitrarily, a saccade was defined as a vertical pen deflection of at least 1 mm, standing out distinctly against the background of smooth pursuit. This deflection would correspond to approximately 17 min of arc, depending on the amount of gain used in the driver amplifier. Since the gain setting was identical on test and control runs, valid comparisons did not depend on the absolute value represented by 1 mm of pen deflection. The number of saccades in each test run was

divided by the number in the matched control run, giving a test/control ratio.

Nonparametric tests were used for differences in lag effects, since these tests do not require normality of the error variables; with the nonparametric tests, one can control the probability of rejecting the null hypothesis (when it is true), even when the errors are nonnormal. Furthermore, the nonparametric tests are often more powerful than their normal theory competitors when the underlying populations are not normal.

The data were subjected to a parallel analysis, using two sets of nonparametric procedures. One set of procedures was based on Friedman rank sums, and the other was based on Wilcoxon signed ranks (Hollander & Wolfe, 1973). The two approaches serve as checks on one another.

RESULTS

In normal Ss, visual tracking was achieved by a combination of smooth pursuit and saccadic jumps, as illustrated in Fig. 1. On this run, S was trying to keep his eyes on a target, which he moved back and forth by means of a joy stick. A delay of 0.36 sec was introduced between movement of the joy stick and that of the target. As shown on the bottom line, smooth ocular pursuit was interrupted by a number of saccades. The corresponding portion of the matched control run is shown in Fig. 2. Here the joy stick was not used, but the target motion was an exact replica of that presented on the test run. The number of saccadic jumps on the bottom line is obviously greater than the number shown in Fig. 1.

The results from all 10 Ss are summarized in Fig. 3 and Tables 1 and 2. Under the 0 lag or .18-sec lag conditions, all Ss had test/control ratios less than 1. With longer lag times, several of the ratios were greater than 1.

The statistical analysis attempted to answer the following questions. Do the test/control ratios exhibit an increasing trend as the lags increase? If there is a trend, for which particular pairs of lags do the ratios differ significantly? Where does the effect of manual control disappear? That is, where (at what lag) does the ratio get close to 1?

Since there were a priori reasons to believe that the ratios would tend to approach 1 as the lags were increased, we used statistical tests designed specifically for ordered alternatives. Page's test, based on Friedman rank sums, was significant at $p < .0001$. Hollander's test, based on Wilcoxon signed ranks, was also significant at $p < .0001$. We conclude that the size of the hand-to-target lag has a significant effect on the test/control ratios.

Since there appeared to be a (generally) increasing trend, we determined which particular lags differed significantly from one another. This was a multiple comparison problem, with 10 pairs to consider. Using Friedman rank sums, it was found that the test/control ratios obtained with the .18-sec lag differed from those obtained with .72- and 1.44-sec lags at $\alpha = .038$. The analogous comparison procedure, based on Wilcoxon signed ranks, found that a .18-sec lag differed from the

Table 1
Number of Saccades Per Minute of Tracking

S	Delay Between Movement of Hand and Target (Seconds)									
	0		.18		.36		.72		1.44	
	Test	Control	Test	Control	Test	Control	Test	Control	Test	Control
1	54	90	75	85	60	102	70	58	78	86
2	77	126	80	152	98	163	110	83	96	118
3	128	216	117	222	136	140	160	146	149	149
4	149	151	98	117	125	149	134	133	125	113
5	139	228	108	202	143	218	206	226	194	208
6	127	129	120	145	136	120	112	133	89	101
7	143	205	111	214	100	149	149	167	166	193
8	150	242	125	254	175	239	232	244	191	221
9	127	163	112	147	134	175	146	177	123	145
10	105	207	125	175	136	172	126	145	97	110

.72- and 1.44-sec lags at $\alpha = .05$ (Hollander & Wolfe, 1973).

To estimate the lag at which effect of target control disappears, confidence intervals were constructed for the population median (mean) at each lag. The 98% confidence intervals, derived from the Wilcoxon signed rank test, were: for 0-sec lag, (.56, .84); for .18 sec, (.52, .83); for .36 sec, (.63, .95); for .72 sec, (.86, 1.15); for 1.44 sec, (.85, 1.00). The midpoint of each interval is an excellent estimator of the population median (mean) at the lag corresponding to that interval. Since the midpoint of the interval corresponding to the lag .72 sec is almost exactly 1, it is reasonable to conclude that the

effect of target control disappears at a lag close to .72 sec.

To test for interactions between Ss and lags, we used Tukey's "one-degree-of-freedom" test (Scheffé, 1969). (This test assumes that the common population of the error variables is a normal population.) Tukey's test was significant at $p = .05$, but not at lower values. We infer that there is probably a significant interaction between patients and lag times.

DISCUSSION

The first conclusion to be drawn from this work is that oculomotor performance was measurably different under the various experimental conditions. When the visual target was moved by the S, rather than by an external agency, the frequency of saccadic eye movement was reduced significantly. The second conclusion is that the effect of manual target control seemed to persist for a measurable time, at least .36 sec. With increasing delays between movements of the hand and target, this effect grew smaller, becoming insignificant when the delay was 0.72 sec.

In previous reports (Steinbach, 1969; Angel & Garland, 1972), the frequency of saccadic eye movement has been considered as an index of error in visual tracking performance. When a S tries to keep the

Fig. 3. Relative frequency of saccades (test/control) as a function of delay between movement of hand and of visual target. Each point is the number of saccades in 100 sec of a test run divided by the number in the matched control run. Each vertical bar represents the 98% confidence intervals for the population median (mean) at the given delay time.

Table 2
Frequency of Saccades on Test Run ÷ Frequency on Control Run

S	Delay Between Movement of Hand and Target (Seconds)				
	0	.18	.36	.72	1.44
1	.60	.88	.59	1.21	.91
2	.61	.53	.60	1.33	.81
3	.59	.53	.98	1.09	1.00
4	.99	.84	.84	1.01	1.11
5	.61	.53	.65	.91	.94
6	.98	.83	1.14	.84	.88
7	.70	.52	.67	.89	.86
8	.62	.48	.73	.95	.86
9	.78	.76	.76	.82	.85
10	.51	.71	.79	.87	.88

eyes on a continuously moving target, the smooth pursuit system will tend to match the eye velocity to target velocity (Robinson, 1968), but occasionally the target will "escape." The saccadic system will then produce a sudden jump of the eyes, bringing the target back to the center of the field. The more accurate the smooth pursuit, the fewer saccadic corrections will be needed. Since manual control of the target tends to reduce the number of saccades, this effect could be viewed as an improvement of tracking performance. However, there is no direct evidence to show that error magnitude has a positive correlation with the frequency of saccades. In order to prove such a correlation, it would be necessary to measure the distance between the fovea centralis and the retinal image of the target during visual tracking.

As an alternative to the view that manual target control improves tracking performance, one should consider the possibility that hand and eye control interfere with each other. Then, during the trials with short delay between hand and target motion, decisions regarding the hand would intrude on oculomotor performance, and the S would have less "attention" left to do adequate visual tracking. With longer delays, the S might simply ignore what the hand is doing. Thus, hand movement would not interfere with eye movement. On the further assumption that more accurate tracking involves more saccades, one would then predict a higher frequency of saccades under the long-delay conditions. The data are compatible with this hypothesis as well as the preceding one.

For our purposes, it is immaterial whether hand movement tends to improve or to deteriorate the quality of visual tracking. The essential point is that manual control of the target has a definite effect on oculomotor performance and that this effect persists for a measurable time. The statistical analysis showed that test/control ratios tend to increase as the hand-to-target lag is increased and that there are significant differences when the various lag times are compared with one another. With hand-to-target lags of .36 sec or less, the mean test/control ratios were significantly less than 1. We may conclude, with a high degree of assurance, that the effect of manual target control persists for at least .36 sec.

When the lag was .72 sec, the effect was no longer evident, the mean ratio being 1. At the greatest lag time tested, 1.44 sec, the upper limit of the 98% confidence interval was 1.0, and the significance of the observed ratio is debatable. In a previous study, six out of six Ss were found to have ratios less than 1 when the lag was 1.44 sec (Angel & Garland, 1972). However, there is no conclusive evidence that the effect persists for longer than .36 sec.

This experiment, together with others in the literature, would suggest that information is normally transferred from the manual control system to the oculomotor system. In order to explain the delayed

effects, with hand-to-target lags exceeding sensory reaction times (Chernikoff & Taylor, 1952; Keele & Posner, 1968), one may assume that the information is stored in memory for some time. One cannot assume that all of the elapsed time is necessary for processing the information, because hand movement is also effective in the no-lag condition. Hence, it seems more likely that a storage system is involved.

Over the last few years, two components of human memory have commonly been distinguished: short-term memory and long-term memory. The main features of short-term memory are "its limited capacity, the ease and rapidity with which items are retrieved, rapid forgetting and apparently no permanent record [Craik, 1971]." These features are also consistent with those of the memory system postulated in the present study.

Neisser (1967) has used the terms "iconic memory" to refer to visual sensory memory and "echoic memory" to refer to its auditory equivalent. As a designation for the system that we postulate, the term "proprioceptive memory" would imply that the stored information pertains only to feedback from the moving limb, while "outflow memory" would imply that it pertains only to efferent signals. Perhaps the term "motor memory" is most appropriate to describe the storage system involved in hand-eye coordination.

Short-term memory, as ordinarily conceived, is characterized by rapid forgetting over a period of some 20-30 sec (Warrington, 1971). In the case of motor memory, forgetting appears to be much more rapid, probably within the range of the lag times used in the present work. Since one may presume that the related eye movements are all completed within a very brief interval following movement of a limb, the relatively brief duration of motor memory would seem to be adequate to insure proper coordination. The kind of information that is commonly presented in psychological experiments with memory consists of verbal or other symbolic material that might usefully be held in storage for a longer time, permitting its use in calculation and problem solving. By contrast, "motor memory" would have little biological utility after the completion of a given motor task.

The work reported here confirms and extends a previous report from this laboratory (Angel & Garland, 1972). The present investigation employed a larger number of Ss and tracking trials of longer duration, in an attempt to define the time course of the hypothetical memory trace.

Many diseases of the nervous system are known to impair control of the hand and eyes, separately or in combination, but clinicians have not described impairment of hand-eye coordination *per se*. One might assume that any such impairment, not affecting the manual or oculomotor systems individually, would involve higher levels of sensorimotor integration. Hence, future studies of patients with apraxia, dementia, and other disorders of integrative function might be

expected to reveal some individuals with abnormal hand-eye coordination. Comparison of these patients with normal controls could then provide evidence about the neural mechanisms involved.

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