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EYE MOVEMENT IN RESPONSE TO SINGLE AND MULTIPLE TARGETS

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Two major studies were pursued under this research program: one was devoted to eye-movement responses in multi-target situations, and the other to smooth scanning behavior when viewing eye-slaved targets. For multiple targets, a computer-controlled arc perimeter display comprised of 21 LED point targets (5 arc-minutes) placed 5 degrees apart was utilized. Results showed that oculomotor reaction time increased from 200 ms for single targets to 240 ms for multiple targets (20% to 25% increase). Furthermore, delaying the appearance of one of the targets by 10 ms increased the reaction time even further, to about 300 ms. Further increases in second target delay produced a monotonically decreasing function of response time versus delay, until at delays of 100 ms, the reaction times were normal. For the experiments on eye-slaved target scanning behavior, the subject was presented with a target controlled by that person's own eye position. This eye-slaved target was then delayed 1 to 200 ms before being presented to the subject. With no delay, subjects were able to move their eyes smoothly across the screen and back; i.e., self-initiated smooth pursuit. Small delays (40 to 60 ms) tended to increase the smooth pursuit oscillations in both velocity and amplitude. The results suggest that smooth pursuit is facilitated by small delays in the eye-position feedback signal. At larger delays (100-200 ms), smooth pursuit was not obtained. The implications of these results for eye-slaved, area-of-interest displays are discussed.

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Eye Movement in Response to Single and Multiple Targets

PREFACE

The research reported herein was conducted in support of the Aircrew Training thrust of the Air Force Human Resources Laboratory (Operations Training Division) at Williams Air Force Base, Arizona. The research was undertaken to define basic timing relationships in eye movement pertinent to eye-slaved, area-of-interest displays.

The authors wish to express their gratitude to Marti Barsotti for her expert assistance in running the experiments; Bob Grimes for his outstanding software support; Bob Renshaw for his insightful technical assistance, Sherry Modestino for her tireless administrative support of this program; and Margaret Armour and Marilyn Williams for their assistance in preparing this manuscript.

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INTRODUCTION

The experiments described in this report represent the efforts of 3 years' work laying the foundations for understanding visual scanning behavior so that such information may be used to aid in the enhancement of pilot scanning behavior and of those systems that may be controlled by eye position. This report is divided into four sections, each dealing with a separate aspect of the research conducted. Parts 1 and 2 deal with self-initiated smooth pursuit. Part 1 discusses the effects of delay, while Part 2 deals with the extremes of Secondary Visual Feedback (SVFB) target separation from the fovea and how such variations affect the characteristics of secondary visual feedback. Part 3 deals with the appearance of multiple saccadic targets and how such stimuli increase the latencies to one target. Part 4 deals with multiple smooth-pursuit targets and how they affect the reaction times of tracking movements. This work represents a first step in exploring the uses and enhancement of visual scanning for purposes of improving the acquisition and detection of targets that might be present in the visual scene.

Understanding the scanning pattern of a subject presented with a rich visual scene can be an overwhelming analysis task. To help reduce the complexitiy of this situation, the visual scene has been reduced to its basic parts. Thus, much of what was used to investigate scanning behavior involved "simple displays," with little complex content. The logic was first to understand how reaction times in simple situations might be affected by various visual environments and, based on this work, to build a framework for further analysis of more complicated visual environments. In order to understand how multiple objects in the visual field are treated, the latency of saccadic and smooth-pursuit oculomotor reactions was investigated. In the past, most studies have dealt with single-target stimuli. Very few have discussed how multiple targets, both saccadic and smooth pursuit, might be processed by the visuomotor system. The findings clearly show an increased saccadic latency to multiple targets. Smooth-pursuit targets, however, do not show this increase, but the latency of the initial refixation saccade was increased by 50%.

Aside from the rudimentary aspect of scanning to gather information, another important aspect of a pilot's scanning behavior is to track and detect targets, some of which are at the limits of the visual resolution. Many times object motion is the first thing detected. However some targets have little or no perceptible motion and direct fixation of the target is needed. We wished to enhance this detection by self-initiated smooth pursuit. The rationale was to move the eye to improve detection of the target when the target motion is slower than needed for its perception. As a first step in this investigation, we sought to characterize the effects of various delays that might be experienced in the initiation of smooth movement by electronic means. Such electronic systems which monitor eye movements result in delays of 50 ms or more (e.g. TV oculometers). How such delays might affect the self-initiated smooth responses is of interest if such a system is to be useful.

Future work in this area should explore more complex visual scenes by controlling the volume and type of information presented to the pilot, measuring reaction times to detection and/or acquisition of important targets that might appear in the visual field. The practical uses of secondary visual feedback should be demonstrated in the simulator to aid in the detection of slowly moving targets. Further exploration of smooth pursuit as an aid to detection of targets might be undertaken using Head-Up Display (HUD) targets that can be tracked by the pilot over the area where the target is believed to be. More practical explorations of these research issues in the simulator are appropriate and should continue.

Eye Movement in Response to Single and Multiple Targets

PART 1. SELF-INITATED SMOOTH TRACKING

INTRODUCTION

Identifying distant objects which subtend a small visual angle at the eye is a challenging task that pilots must face during any mission. Often, a distant object is detected because its movement was sufficient to stimulate the motion sensors in the visual system. However. many times such motion is below threshold and the target can be detected only if it falls in the foveal area (e.g., two aircraft on the same heading). This research was undertaken to investigate the utility of self-initiated smooth eye movements to aid in the detection of distant targets. The first step, was to examine the characteristics of self-initiated smooth eye movements and how present oculometer and computational delays in present-day simulators might affect this response.

Tracking objects that move across the visual field involves the smooth pursuit system. Under normal circumstances, smooth-pursuit eye movements are elicited by a moving target. However, some individuals can apparently produce smooth eye movements at will. However, these individuals are not commonly found in the normal population. Nevertheless, under special circumstances it is possible for many individuals to perform smooth eye movements without a moving target when a target remains fixed on the retina of the subject. After-images have been successfully used to permit subjects to generate smooth eye movements (Heywood & Churcher, 1971; 1972; Kommerell & Taumer, 1972; Yasui & Young, 1975). Targets can also be stabilized on the fovea by electronically monitoring the eye's movement, and this signal can be used to control the position of the target being viewed (Zeevi, Peli & Stark, 1979). This SFVB technique has produced the same results as the after-image technique. While all these studies have demonstrated the ability of stabilized images to elicit smooth pursuit eye movements, none have explored the parameters that influence the velocity of secondary visual feedback and the control which it elicits. This part of the report discusses how delaying the oculomotor feedback is dealt with by the sensory motor system and the responses of SVFB.

METHODS

Each subject was seated 57 cm from a display screen, and the subject's head was in a head and chin rest. The subjects' head movements were further restrained by the use of a full-mouth bite-bar that was attached to the head rest. The eye movement system was first calibrated to ensure a full linear range over the ± 7 degree range of the screen. The subjects controlled the position of the beam prior to the experiment so that the spot could be placed in the center of the fovea. A check of the instrument's calibration was performed by having the subject move both eyes in the horizontal direction and report any deviation of the spot from the central visual field. The experiment was conducted when the spot fell within the foveal region (± 0.5 degree) over the range indicated above.

Prior to recording data, subjects were permitted to practice generating smooth eye movements under this SVFB condition without a delay being introduced into the signal path. After about 5 minutes of practice, the experiments were conducted. (Some subjects were experienced in generating SVFB smooth eye movements and practice time was substantially reduced in their cases.) Each experiment started with the subject fixating in the center of the screen with the SVFB system off. When the SVFB system was activated, the experimenter asked the subject to begin generating smooth eye movements. After 15 to 20 cycles of smooth eye movements, the subject was instructed to stop and rest. Between runs, the experimenter changed the amount of delay between the movement of the eye and the movement of the SVFB target. The subject was not informed of the magnitude of the delay during the experiment. The delays ranged from 1 ms to 250 ms, with a total of 13 discrete values being used. The order of the delays was randomized by using a random number table, and each delay was repeated at least once during the course of the experiment. The entire experiment lasted approximately 30 minutes per subject.

Secondary Visual Feedback System

The SVFB was generated by having the movements of the right eye control the position of an oscilloscope beam in the horizontal direction. However, both eyes were monitored during the experiment to ensure that the SVFB movements were not the result of voluntary convergence or divergence movements. Eye movements were monitored using the photocell infrared reflection method (Stark, Vossius & Young, 1962) which had a noise level of 2 arc min, a linear range of ± 10 degree, and a bandwidth of 500 Hz.

To produce a variable delay, the eye-position signal was first sampled by a PDP 11/34 minicomputer at a rate of 5000 samples/sec. The sampled signal was placed in a first-in-first-out (FIFO) ring buffer of variable length. The length of the ring buffer controlled the delay each sample would receive before being sent to the digital-to-analog (D/A) converter which was connected to the X-axis of an oscilloscope. For example, if a 20-ms delay was desired, the length of the ring buffer would be set at 100 points. (With a sample interval of 0.2 ms and the FIFO structure of the buffer, this 100th point would be displayed 20 ms after it was sampled.) Thus, the most recent signal from the eye movement monitor would be displayed on the screen 20 ms after it was sampled. Due to the high sample rates needed to perform these experiments, the computer was not used to store the eye movement data. Binocular eye movement data were stored on an FM instrument tape recorder Precision Instrument Model PI250 at a speed of 3.75 ips, resulting in a bandwidth of 1250 Hz.

Subjects

A total of five subjects were tested, ranging in age from 20 to 35 years of age. Two of the five subjects were unable to generate smooth eye movements under SVFB conditions; one was a naive subject, while the other was an experienced subject. The data from the remaining three subjects were analyzed. Of these three subjects, two were experienced eye movement subjects and the last, a naive subject. None of the subjects was able to generate smooth eye movements without the SVFB target present.

Data Analysis

The eye movement data were played out on a strip chart at 10 mm/sec (100 ms/mm) and analyzed as follows: The peak smooth-pursuit velocity was measured from these records by placing a straight edge along the eye movement records and finding the maximum slope. Also, total smooth-pursuit amplitude was measured by summing the lengths of smooth responses in one direction minus the saccadic eye movements that were present. Finally the expected error produced by the velocity of the eye and the amount of delay in the SVFB signal was calculated: (a) by assuming the SVFB target was within the fovea and (b) by calculating the maximum retinal error at each delay for each subject. This was performed by multiplying the peak velocity by the delay.

RESULTS

Figure 1 shows typical responses from the three subjects tested. The top traces show the responses of the three subjects performing smooth pursuit under SVFB with no delay. These responses show the smooth characteristic of the SVFB pursuit. Notice that the responses are approximately sinusoidal similar to others' results (Kommerell & Taumer, 1972; Heywood & Churcher, 1971; 1972). Saccades are small and infrequent. Each subject was able to sustain the smooth eye movements from several tens of seconds.

The effects of delaying the SVFB target on the subjects' ability to produce smooth eye movements varied from one subject to the next. Thus, each subject's response will be described separately.

<u>Subject MM (naive)</u>

Figure 1a shows the responses from subject MM for delays from 1 to 200 ms. The binocular records show that the initiation of smooth eye movements was conjugate and produced a sinusoidal response of frequency 0.4 Hz. Only a few saccades are found in this subject's records. When the SVFB target was delayed 50 ms, the responses remain smooth and sinusoidal but the frequency has dropped to 0.18 Hz. As the delay is increased further, the responses remain fairly smooth but the frequency of oscillation gradually decreases. At delays of 150 to 200 ms, saccades that attempt to refixate the lagging target appear; yet the smooth movement continues. The frequency dropped to 0.16 and 0.15 Hz, respectively.

Peak eye velocity also declined as delay increased. The plot of eye velocity versus delay (Figure 2a) shows a decrease in eye velocity with increased delay. The decline is gradual from 90 to 200 ms delay and more erratic from 1 to 80 ms delay. Despite the decline in peak velocity, the amount of the response composed of smooth movement remained high. The percent of the response composed of smooth movement remained above 70% on average across the 1 to 200 ms delays. This plot suggests that the smooth control of the eye did not break down into saccadic tracking even at long delays.

To provide a better understanding of how the visual system might regard the delayed SVFB target on the retina, the data were replotted with the dependent variable now retinal error. This error might be best described as inferred retinal error and represents the amount the eye would lead the

SVFB target assuming that at zero delay the SVFB target is at the center of the fovea. During fixation with no delay the retinal error with our monitors was no greater than 4 arc min. Thus, the noise for this plot would be ± 4 arc min.

The error was calculated by multiplying average peak velocity during the SVFB movement in Figure 2a by the amount of the delay. In Figure 2c, the maximum inferred retinal position error rises to 0.5 degree as the delay is increased from 1 to 100 ms. This error, produced by the combination of delay and peak eye velocity, saturates after this point and rises at a slower rate. The quality of the smooth responses remains high even as the retinal error reaches 0.7 degree, as can be seen from the average percent smooth pursuit (Figure 2b).

Subject JM (experienced)

Eye movements to delayed SVFB targets from 1 to 250 ms are shown in Figure 1b. As the delay is increased from 1 to 50 ms, the frequency of oscillation remains high at 0.36 Hz to 0.4 Hz. At delays of 100 and 200 ms, the frequency drops to the 0.33 to 0.29 Hz range. The responses remain smooth for this subject even at 100 ms delay. An increasing number of saccades are seen at delays of 100 to 200 ms. A breakdown of the smooth response can be seen at 150 ms and above.

The peak velocity during the SVFB varied as the delay increased (Figure 3a). Generally, the peak velocity declined with increase in delay except for a noticeable increase between 40 and 70 ms of delay. The percent smooth pursuit declined steadily with increase in delay except for the spike in the 40 to 70 ms interval.

The relationship between good smooth-pursuit movement, as measured by percent amplitude of smooth pursuit versus the peak velocity, showed that the eye velocities above 5°/sec provided the most smooth components (Figure 3b). Thus delays of 200 to 250 ms generated more saccades than smooth movement amplitude. However, the smooth movements were still robust even at 100 ms delays for this subject.

The amount of positional error tolerated by this subject rose as the delay increased (Figure 3c). Comparing the percentage of smooth eye component versus delay with the error versus delay shows that fairly good smooth pursuit is still produced with errors as high as 0.45 degree but performance falls off when errors are greater than this value. However, the percentage of smooth pursuit remains high until the error exceeds 0.6 degree. This drop in percentage of smooth pursuit along with the drop in peak velocity would indicate that saccades are an important part of the movement and that the smooth movements are not under control. Peak eye velocity steadily decreased as the delay was increased. These data have more variation but show the same trend as for subject MM. Furthermore, the amount of smooth movement for each response remained high throughout the range of delays tested. Plotting the error function for this subject, Figure 3c, shows that as the delay increased, the error gradually rose and saturated at 0.7° of retinal error. The change in peak velocity did not show the same strong declining trend found for subject JM. Instead the peak velocity remained high until the error reached 0.7 degree. The inferred retinal position error tended to rise as the delay increases. Finally, the percent smooth amplitude remained level regardless of the peak velocity or the error.

Subject RVK (experienced)

This last subject was much more erratic in eye-movement response to the SVFB delays as seen in Figure 1c. The now familiar sinusoidal responses are found in 1- and 50-ms records. The frequency decreases from 0.4 to 0.25 Hz when the delay is increased from 1 to 50 ms. Saccades against the smooth response are more prevalent in the short delay records. In the 50-ms-delay record, the amplitude of the smooth response has decreased from its value in the top record. These sinusoidal responses are replaced by sawtooth waveforms at delays of 100 ms and 150 ms (frequency 0.15 and 0.18, respectively). At 200-ms delay, the response was difficult to call smooth.

An examination of the peak velocity as delay is increased (Figure 4a) shows a wide swing in peak velocity. A similar erratic response is found when the percent smooth movement is plotted against the SVFB delay (Figure 4b). However, if the points at 10- and 20-ms delay are ignored, a decreasing smooth amplitude function is seen with increased delay. Good smooth responses were most likely to be seen at the high velocities (Figure 4a).

Errors greater than 0.3 degree were usually not well tolerated by this subject (Figure 4c). As the retinal error increased beyond this point the subject would lose smooth-pursuit function. These followed a reduction of eye velocity and the subject would again track smoothly until the delay produced still more error even at the lower velocity.

DISCUSSION

In general, the effect of pure delay on the generation of smooth movements using SVFB targets is to decrease the velocity of the smooth movements with increasing delay. At some value of delay, the ability of the subject to produce smooth responses deteriorates and saccadic tracking emerges. The ability of the subject to tolerate the error associated with the eye-movement velocity and delay can be rather large -- up to 0.7 degree in some subjects.

The changes in smooth velocity of the eye from SVFB targets with increasing delay perhaps tells us of some of the strategies that subjects employ to maintain smooth velocity and their control of the SVFB velocity generated. It is important to note that the lag of the target behind the eye during the smooth responses is maximum when the velocity is maximum. Yet these subjects could sustain the velocity in the presence of these positional and velocity errors. Heywood and Churcher (1972) showed that attention to peripheral targets can modify the velocity of the SVFB smooth responses. It appeared that the subjects ignored the SVFB target as it moved into the periphery as the delay increased. This inattention to the target might cause the reduction in the velocity found in these eye movements. Alternatively, as the target sweeps into the off-foveal region the motion of the target might activate a tracking response that would counter the forward motion of the eye, thus reducing the total movement to some acceptable level of slip and positional error. In addition, the retinal error that builds up with velocity and delay may compete with the ongoing smooth response, thus reducing the total velocity. Finally, these data might be showing the ability of these subjects to voluntarily control the velocity generated under these conditions by using an error toleration scheme.

If, at high delay and eye velocity, a reverse error of the target does occur, then what are these subjects pursuing? The target is lagging behind the eye and not serving as a suitable target. Perhaps it is the ability of the subject to control their attention that continues to drive the eye in the intended direction. A concerted effort to move the eyes in one direction perhaps is preceded by a shift of attention in that direction. Control of the position and direction of that attention shift has been demonstrated in other experiments. What these results show is that attention can be used to override the normal corrective responses that external retinal images can have on the oculomotor system.

A similar control of smooth pursuit was demonstrated by Zeevi and Peli (1984) in response to filtered SVFB signals.

This research also applies to the use of area-of-interest (AOI) displays that are being evaluated for use in modern simulators by the Air Force. Such displays are presently head slaved but future systems are proposed to be eye slaved. Such AOI systems might set up a condition that could initiate unwanted smooth eye movements from the pilot and provide the pilot with a situation that might lead to negative training.

Eye Movement in Response to Single and Multiple Targets

PART 2. SECONDARY VISUAL FEEDBACK

INTRODUCTION

Various studies (Heywood & Churcher, 1971; Young, 1977) have demonstrated that smooth movement can be elicited by visual means other than a real moving stimulus. For example, either the foveal after-image (Kommerell & Taumer, 1972) or an optically stabilized foveal image (Hedlum & White, 1959) can elicit smooth movement. The direction of the movement is apparently selected by the subject, who shifts attention to the left or the right of the after-image (Kommerell & Taumer, 1972).

Recently a new technique was introduced to investigate control of eye movements and acquisition of visual information. The eye position signal was either displayed together with the target or else was superimposed on a visual scene, thereby closing a secondary visual feedback (SVFB) loop (Zeevi & Peli, 1979; Zeevi, Peli & Stark, 1979). Since this SVFB situation is similar to that of an after-image, it can be expected to allow the control of smooth movement. Unlike the after-image, because of measurement imprecision and noise, the SVFB 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 (Zeevi, Peli & Stark, 1979; Zeevi & Peli, 1979; Peli & Zeevi, 1979).

The SVFB signal can also be presented during tracking of 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 to 10 degree/sec, the SVFB task does not impede the tracking performance, but rather improves it (Peli & Zeevi, 1979). It, thus, became of interest to investigate the tracking of a discontinuous target. It has been shown by Stark Vossius & Young (1962) and by Gauthier and Hofferer (1976) 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 very well and that the spatial and temporal components of the target motion can be used for saccadic position control, but that all of these factors are insufficient for a continual control of smooth eye movement. Therefore, an experiment was designed to show that secondary visual feedback can be combined with the internal model of target motion to maintain smooth tracking of the disappearing target.

Eye Movement in Response to Single and Multiple Targets

In tracking a smoothly moving target, the eye velocity is, in most cases, somewhat lower than the target velocity (Robinson, 1965; Young, 1962). 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 (Young, 1962). With SVFB, 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 is rather similar to a predictive control situation. Thus, experiments with a conditioned SVFB should provide better understanding of the smooth-pursuit control system.

METHOD

The SVFB technique was described in detail elsewhere (Zeevi et al., 1979). Displaying, to the subject, the point of gaze, in addition to a target or a visual frame of reference, provides a SVFB. While this is rather similar to the open-loop condition in a variable-feedback experiment (Young, 1962; Young and Stark, 1963), here there is also an independent point target. The two signals are displayed such that they are easily distinguishable on the screen even when superimposed. The distance between them indicates the tracking or position error to the subject (Peli & Zeevi,1979). The SVFB signal can also be manipulated electronically to give rise to interesting experimental paradigms (Figure 5). For example, a DC shift is useful in the study of eccentric fixation and peripheral saccades (Zeevi, Peli & Stark, 1979; Zeevi & Peli, 1979; Peli & Zeevi, 1979). In the following experiments, the SVFB signal was conditioned either by low-pass filtering or phase inversion. Target and SVFB signals were displayed on a dual-beam CRT system with a separate focusing and intensity control for each beam. The target beam was focused to a diameter of less than 0.1 degree, the second beam was partially focused to an effective diameter of 0.5 degree. 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 secondary visual feedback. In a second setup, the target and SVFB were generated on separate display systems and superimposed on the optical axis via a beam-splitter. Although 10 subjects with varying amounts of training participated in this study, only 5 took part in most experiments with a conditioned SVFB.

Subjects viewed the 10-degree display from a distance of 30 cm, with the head immobilized by means of a headrest and a bite bar. Only monocular movements of the right eye were recorded;

the left eye was coverd with an eye patch. Eye position was monitored with an infrared photoelectric device (Zeevi et al., 1979; Stark, Vossius & Young, 1962). To improve signal-to-noise ratio, the bandwidth was limited to 40 Hz in most experiments, giving a resolution of about 0.1 degree. Target positions and SVFB signals were sampled by a PDP-11 computer at a rate of 100 samples per channel. A variable filter (K&H Model 3323 with active and passive options) was used for SVFB low-pass filtering.

EXPERIMENTS

Foveal "Open-loop"

The subject was presented with his point of gaze using the unconditioned SVFB signal (gain = 1, eccentric bias = 0). The SVFB signal was locked on the fovea and no retinal slip was possible in any eye movement. (This is rather similar to the foveal after-image condition (Young, 1977; Yasui & Young, 1975)). 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 SVFB. Subjects were then asked to smooth out their eye movement response to the same saccadic stimulus. A very short period of training (less than 10 minutes) was needed for all 10 subjects. Examples from three subjects (Figure 6) show that each one used a different velocity, but all were able to move their eyes smoothly toward the target with almost no saccadic interruptions (Table 1). The few exceptions were mostly co-directional saccades toward the target (Figure 6b and c). 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 (Figure 7). Thus, there was no need for cumulation of the smooth movement to make it appreciable (Gauthier & Hofferer, 1976; Yasui & Young, 1975).

To compare the SVFB-controlled smooth eye movements with those elicited under the foveal after-image condition, the same experiment, with 4 of the 10 subjects, was repeated using a cross-hair foveal after-image. By and large, the performance was similar (Figure 8), but in some of the experiments, it was found and experienced subjects reported, that they could more easily effect and control the smooth movement with the SVFB. In all tasks with an after-image, fading limited the experiments to a few seconds before requiring the image to be refreshed by flickering the background illumination or by the subject's blinking.

Subjects were next required to control the velocity of movement voluntarily 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, subjects typically demonstrated ranges from a few degrees to 20 degrees per second (Figure 9).

Smooth Movement Task without SVFB

Both for comparison and as a control, subjects were required to execute smooth movements when tracking the same saccadic stimulus, but without the SVFB. This is equivalent to moving the eyes smoothly with no smoothly moving target. Although the subjects were trained in this task, only one (YO) achieved smooth movement without SVFB, and even his tracking was interrupted by 2 to 3 saccades in each direction (Figure10). The other nine subjects exhibited a typical saccadic "staircase" pattern (Figures 10b and 10c). Experienced subjects were conscious of their responses as a series of small discrete jumps, whereas novice subjects were unaware of their saccadic staircase response.

SVFB with Variable Position Error

Next, the researchers attempted to find out how far the SVFB can 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, potentially, be driven by the eye position signal in a variety of man-machine system applications. When steady-state velocity is achieved, the foveal position leads the SVFB signal with a constant error.

The eye position signal was low-pass filtered before being displayed (Figure 5). At a cutoff frequency of 4 Hz, all subjects were able to perform smooth movement without difficulty (Figure11). Despite intersubject velocity variability (Table 1), each subject exhibited a typical velocity approximately equal to that observed in the open-loop experiment 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 (Young, 1962; Young & Stark, 1963), 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 (Figures12b and12c) and observed overshoots resulted from an attempt to eliminate the positional error with respect to the secondary visual feedback loop (separation of target from the SVFB). Comparison with subject YO (Figure 12a), who can achieve eccentric fixation with smooth movements (Zeevi & Peli, 1979; Peli & Zeevi, 1979), demonstrated dynamic correction of the positional error in smooth movement.

Inverted SVFB Signal

Since the results of the variable position error experiments with a 4-Hz cutoff imply that smooth control can be achieved even with negative retinal slip, at least for short periods of time, the next investigation involved the continuous negative slip as an additional control signal. To generate negative retinal slip, the S7FB signal was inverted before being presented to the subject. Thus, the subject had to move the eye leftward to superimpose the SVFB on a target that had moved toward the right, and vice versa. This inversion was confusing, but with some training, 2 of the 10 subjects were able to perform the task with smooth movement (Figure 13), while a third subject managed to generate short episodes of counterdirectional smooth eye movement. It should be noted that the subject, superimposing the SVFB on the target, is gazing away from it and thus achieves eccentric fixation (Zeevi et al., 1979). As the subject moves from one position to another, the SVFB image slips across the retina with double the velocity of eye rotation.

Smooth Pursuits of Disappearing Targets

Subjects were presented with a sinusoidally moving target (the sinusoidal stimulus was chosen as an alternative to the triangular (piecewise-constant velocity) one, so as to avoid the sharp velocity changes involved and thereby help subjects keep control) which 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 secondary visual feedback, unconditioned except for the 40-Hz filtering. In agreement with the findings of Gauthier and Hofferer (1976) and Stark, et al., (1968), the subjects utilized an internal model of the target as a control signal after its disappearance, using a saccadic "staircase" pattern (Figure 14a). When display of the SVFB continued after the disappearance, however, subjects were able to realize smooth movement, except for occasional saccades (Figure 14b). Examination of Figure 14a 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 (Figure 14c) thus generated a sinusoidal pattern of the right frequency but with a very small amplitude. The movement, therefore, is a low-gain smooth movement which is compensated for by saccadic position corrections. With the SVFB (Figure 14d), however, the smooth movement gain is close to unity, requiring only slight and less frequent saccadic correction. The SVFB thus seems to facilitate a higher gain in the smooth-pursuit system similar to the effect of after-image on the vestibular nystagmus system (Stark et al., 1962).

DISCUSSION

The experimental paradigm used here is similar to the stabilized image conditions previously reported (Yasui & Young, 1975; Steinbach & Pearce, 1972). The simple case of centric and unconditioned SVFB 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 after-image (Heywood & Churcher, 1971; Young, 1977; Steinbach & Pearce, 1972) and with an optically stabilized image (Yasui & Young, 1975), only involuntary smooth nystagmus-like oscillations were observed, and any attempt by the subject to move the eyes by command distorted and broke down the smooth movement into a staircase pattern. Kommerell and Taumer (1972) reported different results using foveal after-images: 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 after-image. Our experiments with an after-image and the SVFB further substantiate the findings of Kommerell and Taumer.

Some important differences between our experiments with SVFB, and studies reporting experiments with after-image, should be noted. The SVFB implies that the measured eye-position signal is superimposd on an independent target or a visual scene. Three types of positional errors are generated (Figure 15) (Peli & Zeevi, 1979), and a subject can select the one appropriate to a specified task and/or strategy. The first positioned error (e) is related to the primary, built-in, feedback loop (the angular separation between gaze and independent target position). The second error (e') relates to the SVFB signal which can be considered a secondary visual target. Only, in the case of foveal after-image, this error is nullified. Any manipulation of the SVFB as depicted in Figure 5, or impression in measurement will result in e not equal to 0. This error cannot be eliminated by eye movement and, therefore, the resultant situation has been named "open loop." The third error (e") is defined by the angular separation of the independent target and the secondary target (or alternatively e" = e - e'). Selection of this error as a control signal permits, for example, a subject to stabilize an eccentric fixation on a target (Zeevi et al., 1979). Without such a reference signal, the open-loop condition generated by the fixed eccentric image results in an unstable staircase pattern (Zeevi et al., 1979; Young & Stark, 1963).

Previously, it was shown that some subjects can achieve eccentric fixation using smooth movements (Zeevi et al., 1979) but switch to primary feedback error, resulting in intermittent foveation, when the independent target is displaced abruptly (Peli & Zeevi, 1979). In this study, we have shown that with the SVFB the smooth movement control can tolerate a variable positional error (e"). With SVFB, 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 what kind of mechanism or strategy permitted this voluntary control. In the Kommerell and Taumer study (1972), the control of velocity was demonstrated only for the eccentric after-image in which the velocity was not subjected to voluntary control. Under thse 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 the smooth eye tracking (Grusser, 1980); with SVFB, this was not necessary, and it appeared as though voluntary effort was sufficient. Once initiated, the smooth movement with SVFB 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 (Wyatt & Pola, 1981).

The results with both after-image and SVFB 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 (1977) 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 (Hallet, 1978). Thus, for example, the "hypo-saccade" to a fraction of stimulus-step finds its counterpart in subjects' ability to track a smoothly moving target with only a fraction of target velocty (Steinman, Skavenski, & Sansbury, 1969).

Similarly, we have demonstrated that subjects can elicit smooth movement counter-directionally to the target movement when the SVFB is inverted. This complements the "anti-saccade" task which requires the ability to respond with an equal amplitude but opposite direction to a saccadic stimulus (Hallet, 1978). A word of caution is, however, necessary: not all the subjects could perform the inverted SVFB task, and, in some cases, extensive training was required even to achieve intermittent smooth movement. Indeed, this task served to identify those subjects who performed better in all tasks, demonstrating superior oculomotor control. It appeared that with sufficient training most subjects could execute this task. This inference is drawn from the limited success of this experiment, as well as from other studies indicating that plasticity of the human oculomotor system can be exploited effectively by training with SVFB (Zeevi & Peli, 1979; Griffin, 1976). In particular, it was shown that using the SVFB paradigm, subjects could be trained to achieve control of cyclotorsional smooth eye movements voluntarily (Baillett & Nakayama, 1978). Like smooth movement with inverted SVFB, the performance of such a novel task required both extensive training and voluntary effort. These results also clearly demonstrated the distinction between an open-loop (selection of e') and SVFB condition (selection of e"). Opening the loop using an after-image 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 SVFB condition permitted torsional smooth movement.

Foveal secondary visual feedback is used clinically in the training of patients with eccentric fixation, in conjunction with tagging of the fovea using after-images, Maxwell spots, or Haidinger's brushes (Griffin, 1976). Patients are trained to shift their fixation center back toward the fovea. We have noticed that individuals trained this way do indeed use smooth eye movements for the final alignment of their fovea on the target.

Eye Movement in Response to Single and Multiple Targets

The SVFB could also be applied to the 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 scanpath being controlled by the subject. The SVFB has obvious advantages over the after-image 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 (Zeevi, Peli & Wetzel, 1981). There appears to be a reciprocal relationship between the probability of target recognition and the scanning velocity.

PART 3. OCULOMOTOR DELAYS TO BIFURCATING SACCADIC TARGETS

INTRODUCTION

Prior to the execution of a voluntary response to a visual stimulus the eye movement output remains relatively quiescent. The sudden displacement of a previously fixated target away from the fovea provides a sufficient stimulus for the initiation of a sequence of timed events or processes that precede the saccadic response. The collective sum of these events lead to what is termed the saccadic response latency and has been studied by numerous investigators.

The type of eye movement elicited in response to movement of a visual target or scene depends, to a considerable extent, on the spatio-temporal characteristics of the stimulus. For instance, as a person reads, a pattern of eye movements is generated (Zuber & Wetzel, 1981). Following each fixation pause, the eye moves to the next fixation point by a rapid eye movement called a saccade. Similarly, when a person moves his or her eyes between two targets or during visual search and/or pattern recognition, one or more saccades may be executed. In these examples, the saccadic eye movement is under voluntary control and one is usually unable to make more than four or five saccades per second. Figure 16 illustrates a typical saccadic eye movement of 7 degrees. Following a delay of 200 to 250 ms, a rapid angular acceleration of the eyes of up to 40,000 deg/sec/sec, with peak velocities of up to 1000 deg/sec, may occur before midtrajectory. Subsequent deceleration and velocity braking towards the new fixation point often exhibits dynamic overshoot generated by the neurological control signal (Robinson, 1964; Bahill, Clark, & Stark, 1975). The saccadic duration is related to the target displacement angle and normally lasts between 20 and 50 ms (Robinson, 1964). If the target eccentricity -- the difference between the center of the fovea and the retinal target image -- exceeds about 0.3 degree, the angle subtended by the central fovea, an error-correcting saccade occurs. This secondary saccade, which further reduces the error, follows after a latency shorter than the regular saccadic refractory period.

The intent of this study is to elaborate on several aspects of changes induced in saccadic latency and decision during the processing of visual information. An attempt will be made to attribute some observed changes to cerebral hemispheric organization. Since the early photographic method of eye movement measurement by Dodge and Cline in 1901, and in nearly all succeeding studies which followed using other measurement techniques, response latency time has been found to average about 200 ms (Westheimer, 1954; Young, 1962; Robinson 1964). The saccadic latency has been shown to be sensitive to a number of other factors which either increase or decrease saccadic latency.

A knowledge of the spatio-temporal stimulus pattern can reduce or eliminate the latency time through mediation of a predictor operator (Stark, Vossius, & Young, 1962; Saslow, 1967). Hackman (1940) showed that, while individual subject results were not always consistent, his pooled results revealed a trend of decreasing latency attributable to the effects of practice and familiarity with the experimental conditions. Bartz (1962) and White, Eason, and Bartlett (1962) demonstrated that response time increased with the number of possible targets. Hackman (1940) claimed latency would decrease with a knowledge of the target's location. In contrast, Saslow (1967) found that changing the size of the stimulus set had no significant influence on response latency and attributed the increase found by White et al., (1962) to the complex sequence of target stimuli and to the complicated instructions issued to their subjects.

The effect of target displacement amplitude and intensity has been shown to increase the saccadic response latency time (Bartz, 1962; Wheeless, Boynton, & Cohen, 1966; Uneo, 1977; Uemura, Arai & Shimayaki, 1980). Response latency was also found to increase slightly when visual target displacements were greater or less than 10 to 15 degrees (Frost & Poppel, 1976). Frost and Poppel hypothesized that the observed change in response latency as a function of target eccentricity was attributable to the functionally separate modes of information processing in the central and peripheral zones of the visual field.

Neurological as well as other pathological disorders can affect response latency time. Pirozzolo and Hansch (1981) compared the response latency times of normal subjects with those of subjects with varying severity of dementia and found that the overall latency for patients with cerebral dysfunction was 158 ms longer than for a group of similar-aged normal subjects.

To elucidate some of the timed mechanisms or processes necessary prior to a saccadic response, various stimulus profile combinations involving multiple-step and pulse-step target displacements have been presented to subjects

(Westheimer, 1954; Bartlett, Eason, & White, 1961; White et al., 1962; Wheeless et al., 1966; Saslow, 1967; Becker & Fuchs, 1969; Levy-Schoen & Blanc-Garin, 1974; Carlow, Dell'Osso, Troost, Daroff, & Birkett, 1975; Lisberger, Fuchs, King, & Evinger, 1975; Taumer, 1975; Frost & Poppel, 1976; Hallett & Lightstone, 1976 a,b; Hallett, 1978; Becker & Jurgens, 1979; Heywood & Churcher, 1981; Hallett & Adams, 1980). A fundamental finding of many of these studies has shown that contrary to earlier findings by Vossius (1960), Young (1962) and Robinson (1973), the saccadic system is not limited to only serial processing of visual information by restricting the number of saccades to only one response per reaction time but can respond in such a manner that suggests preprogrammed or parallel processing of visual information. With the appropriate stimulus profile, the saccadic system can initiate a second response with a saccadic interval time shorter than a normal refractory period (Levy-Schoen & Blanc-Garin, 1974; Taumer, 1975; Carlow et al., 1975). This response often occurs if a corrective secondary saccade is necessary when primary movements greater than 10 degrees are made (Becker, 1972; Hallett, 1978). Such responses imply that the secondary saccade was in preparation while the primary saccade was already in progress and supports the hypothesis of either a packaged programmed response or parallel processing of the visual information. As Becker and Jurgens (1979) have stated, an important criterion regarding the existence of parallel processing of visual information is the critical amount of time available between the second stimulus step and the onset of the first response. Several studies using a double-step paradigm have attempted to determine the allocated time prior to response that can still influence the saccade (Wheeless et al., 1966; Lisberger et al., 1975; Taumer, 1975; Becker & Jurgens, 1979). These studies indicate that a change in response direction can be made within 50 to 100 ms from the start of a stimulus, and changes in amplitude can be made up to 100 ms. Although the critical interval times for the decision-making mechanisms have been determined with some degree of consistency among the investigators, the actual amount of time for decision making is not generally known. Furthermore, given that a change in target direction or position occurs within a critical period of time, the likelihood or probability that the change will influence the response has not been determined.

Many factors distinguish the human nervous system from that of other animals. Common to both are at least two forms of specialization: the analysis of sensory information and the control of movement. It is, however, the greater number of known specializations in humans that separates them from other life forms. Many of these specializations are lateralized in the brain so that one function may be located in one hemisphere, while another may be located in the other. The earliest evidence for the existence of these functional asymmetries between the hemispheres came from those persons who had suffered non-fatal brain damage to only one hemisphere. For example, a right-handed person who has suffered damage to the right hemisphere often loses control of the left side of the body and the ability to recognize faces. For the same type of dominant-handed person, damage to the left hemisphere often results in the loss of control of the right side of the body and the loss of speech although the ability to recognize faces is retained.

For most right-handed persons, spatial abilities are lateralized in the right hemisphere, whereas verbal skills and fine control of motor movement are lateralized in the left hemisphere (Sperry, 1974). The human nervous system is organized such that each hemisphere receives information primarily from the opposite side of the body. In the visual system the organization is somewhat different. Instead of the right eye being wholly mapped to the left hemisphere and the left eye being wholly mapped to the right hemisphere, the visual system is arranged such that the right visual field of each eye is mapped to the left hemisphere, while the left field of each eye is projected to the right hemisphere. Thus, when the eyes are fixating a central point, stimuli to the right of fixation are projected to the left hemisphere, whereas stimuli to the left of the fixated point are projected to the right hemisphere. A simplified diagram summarizing these specialized asymmetries between hemispheres is given in Figure 17.

The division of right eye visual field stimulation, and registration of this information onto the opposite hemisphere, is one of several examples of the contralateral organization of the nervous system. Stimulus information received from one side of the body is primarily sent to the opposite or contralateral cerebral hemisphere. Sensory information received by one hemisphere is then shared with the other through the interconnecting commissure fibers between the hemispheres. The interconnections between the hemispheres form the communication channels or links between them. The transfer of information through the commissure fibers was demonstrated by Myers and Sperry (1958), who were able to isolate the hemispheres of a cat by cutting the corpus callosum between them.

Eye Movement in Response to Single and Multiple Targets

The retina of each eye is functionally divided at the fovea into both right and left visual fields. When projected back to the hemispheres, the left visual field from each eye exists in the right hemisphere and the right visual field from each eye exists in the left hemisphere. Neural fibers from the temporal half of the left-eye retina and from the nasal half of the right-eye retina are represented in the right hemisphere. Neural fibers from the nasal half of the left-eye retina and from the temporal half of the right-eye retina are represented in the left hemisphere (Mountcastle, 1974).

The division of left and right retinal fields on the hemisphere does not occur for small angles away from the fovea. In the region of the macula, an area some 2 degrees about the fovea, neural connections project onto both hemispheres; consequently, single hemispheric stimulation is not possible within this area (Mountcastle, 1974).

The implications of the separation of visual fields present an attractive opportunity for the study of the mechanisms of visual information processing because either one or both hemispheres can be stimulated by presenting visual targets to one or both visual fields. An outcome of these experiments may be to relate eye movement response to questions of hemispheric lateralization and specific forms of cerebral specialization in humans. If successful, the results of this study could be compared to the visual information processing of dyslexics, who are believed (Uden, personal communication, 1982) to decode visual information in a less than useful manner when reading texts from left to right. Differences between normal subjects and dyslexics may not necessarily indicate differences between oculomotor systems but, rather, differences between the way information is being processed or organized.

Because of the specificity of function and processing of certain kinds of information that are often located in one hemisphere or the other, cerebral dominance has been used to describe these functional differences. Differences between geographic and cultural backgrounds in reading between Israelis and Arabs who read from right to left, and Americans and Europeans who read from left to right are supposedly attributable to this hemispheric specialization (Albert, 1975). The left hemisphere is thought to be language dominant and is more skilled at sequential processing and analytical information than the right or spatially dominant hemisphere, which is more skilled at synthesizing many different kinds of information. Therefore, when a person who reads from right to left starts a new line or word, only the left hemisphere is initially activated, and according to Kinsbourne (1972) the right hemisphere is inhibited, whereas those who read from left-to-right develop, with practice and time, an integrated response from both hemispheres. Thus, when a person who reads from right-to-left is told to look to the right or left, the command activates the left dominant verbal hemisphere, while the left or right spatial response activates the right spatial dominant hemisphere. The dissociation between concurrent verbal and spatial tasks was most clearly seen between left-to-right and right-to-left readers. The latter group showed a significantly greater number of initial directional errors and a higher frequency of slower responses than did left-to-right readers. Albert (1975) attributed these differences to the ways in which information was activated and integrated in both hemisphere.

In another study, response latency differences dependent on the type and hemisphere to which the stimulus was initially presented were observed (Rizzolatti, Umilta & Berlucchi, 1971). The response time for letters was significantly faster (15.5-ms difference) when stimuli were initially presented to the left field rather than to the right. The faster response can be attributed to the type of stimulus and whether or not the hemisphere to which it is initially projected is specialized for that stimulus. If it cannot be processed directly, then the stimulus information must be transferred to the other hemisphere via the commissure fibers.

The idea of crossed and uncrossed reactions to stimulation of the hemispheres is not new. Berlucchi, Heron, Hyman, Rizzolatti, and Umilta (1971) showed that motor response (represented by hand movement) to visual stimuli on the same side was significantly faster than response with the other hand. It was suggested that responses on the same side as the stimulus could be integrated within one hemisphere whereas visual stimulation of one hemisphere and motor response from the other required interhemispheric communication between the visual cortex on one side and the motor cortex on the other. Because of the involvement of hemispheric communication with crossed reactions, the response times of these are longer than those of uncrossed reactions.

In summary, the response latency time for a target stimulus is a composite of a sequence of timed events and decision-making processes. A change in response time may indicate a change in one or several of these processes. By careful selection of target stimuli the underlying decision times of these processes can be determined, as well as the possible changes occurring due to the specialized asymmetries between the hemispheres.

The existence of lateralization between the hemispheres is well known. However, since the types of stimuli used in this study contain no apparent contextual information, these specializations should have no apparent effect on the response. On the other hand, any observed differences (excluding oculomotor difficulties) between dyslexic and non-dyslexic subjects may indicate organizational differences between the way the two groups process visual information. With proper experiments, it should be possible to separate oculomotor effects from informational processing effects. The goal is, therefore, to determine if these differences can be measured through non-invasive eye movement analysis.

The experiments involved in this study are similar in certain respects to the pulse step and double step experiments of Wheeless et al. (1966) and Becker and Jurgens (1979), except that here the stimuli were double steps or anti-steps and, on many occasions, were presented with no intervening delay. These types of experiments should have important implications with regard to the processing mechanisms involved prior to saccadic eye movement response. Utilizing a technique of eye position measurement, the objective of this research effort is divided into two major questions:

1. Is there a significant difference in response time between single hemispheric and bihemispheric stimulation, and if so, to what can it be attributed?

2. Is there a preferred eye movement response, and if so, then what factors can be used to offset this?

METHODS

Two alternate display systems were used in these experiments: the narrow-field display (NFD) and the wide-field display (WFD). The NFD was a Hewlett-Packard Model 1300X-Y display CRT (P31 phosphor). Point target stimuli subtending a visual angle of 5 arc minutes were deflected 3, 5, or 7 degrees to either side of a center target, or bifurcated symmetrically. The display was viewed from a distance of 65 cm.

Subsequently, it was found advantageous to develop a wide-field perimeter display system. The WFD consisted of 21 computer-controlled green-light-emitting diode (Fairchild FTV 310) targets spaced 5 degrees apart, each subtending a visual angle of 3.7 minutes of arc when observed from the normal viewing distance of 1 meter. Targets were mounted flush along the meridian of a flat, black-painted surface of a semicircular arc of 100 degrees and radius 1 meter.

Unlike the NFD system, which required the experimenter to select and trigger target stimuli manually, the WFD was completely controlled by a specially designed digital hardware display controller that interfaced to a DEC PDP 11/34 computer. One program was used to create the stimuli sequential pattern files; and another was used to read the file, load the contents into the display controller interface, present the stimuli, sample the eye movement monitor (EMM) output signal, and store the results for later analysis.

In all instances visual stimuli were randomized for type -- single- or dual-target stimuli, direction displacement, and time course. Targets were binocularly observed in the dark while an infrared reflectance technique was used for continuous measurement of the horizontal movement of the left eye. To be assured that the eye movement records obtained from each subject were not contaminated with extraneous motion artifact, several precautions were taken to reduce the effects of head and body movement during the experimental sessions.

A head movement mount was constructed to minimize involuntary head movement and to reduce fatigue. The head movement mount consisted of a padded head yoke with adjustable chin rest, bite bar, and pedestal. Attached to the head movement mount by adjustable clamps and slide rods are a pair of infrared photodetectors and an infrared emitter (part of the eye movement monitoring system described later). The entire head movement mount system was fixed to a 6-mm-thick aluminum plate which, in turn, was rigidly held to a sturdy table. The bite bar was tightened securely to the stem of a swivel ball-and-socket joint, which allowed for roll, pitch, and yaw movement of the head while positioning it properly against the head yoke. The base of the swivel ball and socket joint connected to an adjustable shaft in the head mount pedestal and allowed for height adjustment of the head. Once the head assumed the proper, as well as comfortable, position in the head mount system, both the head angle and height were locked in place.

To further reduce the head movement caused by a lowering of the jaw over the course of an experiment, an adjustable padded chin rest was raised from beneath to support the jaw and thus prevent fatigue. Further body movement was minimized by seating the subject in an adjustable padded chair with lower back support.

Horizontal eye position was measured by a differential infrared reflectance technique. A DC-driven, infrared light emitting diode (LED) light source at 940 nanometers (Texas Instruments TIL33) was used to illuminate the left eye. The infrared radiant output power from the LED was approximately 2.25 milliwatts/centimeter^2 when driven at the normal current of 50 milliamps. A pair of phototransistors (Texas Instruments LS-400) separated by 20 mm were mounted on each side of the infrared emitter and aimed slightly below and to opposite sides of the iris-sclera borders (the limbus) of the left eye. The distance between the photodetectors and the eye varied between 10 and 15 mm depending on the length of the eyelashes. With this type of eye movement system, accurate positional measurements were limited to 15 degrees. The phototransistors are part of a balanced bridge circuit configuration. As the eye moves horizontally, photodetector signals proportional to the amount of infrared light reflectance from the eye are differentially summed and amplified to produce an analog voltage proportional to eye position. A first-order low-pass filter with a cutoff frequency of 1 KHz was placed at the output of the eye movement monitor. At nominal gain settings, typical system noise was less than 2 mV (RMS). Common-mode noise rejection was adjustable to 90 dB down. Monitor gain was adjustable from less than 1 to 180; full scale output voltage was restricted to 1 volt. Horizontal linearity of the system was limited to approximately 15 degrees and was largely dependent on the placement of the infrared emitter and phototransistors but could be minimized during a three- or five-point calibration procedure. Horizontal sensitivity was typically 67 mV per degree. Vertical sensitivity was negligible. Instrumentation parameters over which the experimenter had control were the output gain, phototransistor bridge balance and DC-level output. Incorporated into the eye movement monitor was a stimulus marker circuit. When desired, this circuit could sum a 5- or 15-ms (switch-selectable) saturated pulse with the movement output whenever a stimulus occurred. Under certain circumstances, the marker circuit could provide information on direction and type of stimulus. The analog output of the eye movement monitor was sampled by the laboratory peripheral system (LPS), a 12 bit analog-to-digital converter, at rates not less than 100 points/sec and stored on disk for later analysis. A diagram showing the experimental setup for the WFD setup is given in Figure 18.

Procedure

Fifteen subjects, mostly students, participated in various phases of these experiments. Prior to the experimental run, subjects were seated and comfortably positioned directly in front of the display's center target; the EMM was adjusted; and the room lights darkened. Subjects were instructed to respond to the different target types in a rapid and spontaneous manner. Each subject, over the course of the experimental sessions, was presented with a minimum of 100 stimuli. Sessions lasted less than 1 hour, and attempts were made to schedule a subject's sessions at the same hour of the day on subsequent visits.

Data Analysis

For each categorical type of stimulus, the saccadic latency and response direction were measured on a computer graphics display terminal using the Digital Equipment Corporation program SPARTA. The accuracy of saccadic latency measurement was limited by the sampling rate of the eye movement signal to + 10 ms.

Classification of Stimuli

Visual stimuli were classified according to their initial projection of visual information to one or both hemispheres. Stimuli consisted of single hemispheric or bihemispheric stimuli, examples of which are shown in Figure 19. Single-target stimuli were used to assess any significant left-right response differences or response time dependency on eccentricity and to serve as a comparative reference for the other types of stimulus response.

Bifurcating dual-target stimuli involved either bidirectional (bihemispheric) or unidirectional situations. Bidirectional stimuli were either symmetric, equal displacements, or asymmetric unequal but opposite displacements. The final class of targets consisted of delayed bifurcation (double-step) representations of unidirectional and bidirectional stimuli where one of the two targets was delayed. Targets were delayed in either direction by 10-ms intervals up to 120 ms, and by 20-ms intervals from 140 to 220 ms. The greatest delay was 250 ms. The type of stimuli that could be presented on each display was dependent on the sophistication of the display controller. Because the NFD controller was manually controlled by switches, stimuli were limited to symmetrical bifurcations and single-target stimuli. The digitally designed display controller, on the other hand, presented none of these limitations and, as a consequence, could present any stimulus pattern desired including highly repeatable inter-target delay intervals.

The response data for each subject were analyzed with the aid of a computer graphics display terminal in conjunction with the SPARTA data analysis program. For each response at least two pieces of information were recorded: the saccadic eye movement response latency time and the direction of movement. When appropriate, the amplitude of the response was also measured. If the movement was unique or novel indicating false alarms, blinks due to the stimuli, or smooth movements, these occurrences were noted and their locations recorded in the file for later examination.

RESULTS

The results of this study have been organized so as to include both population and, when sufficient data exist, individual subject results. Throughout the subsequent sections, the NFD results will be presented first, followed by the results from the WFD. This method of presentation will continue until the utility of the manual NFD controller is exceeded by the added usefulness of the computer-driven controller. Only recently, a new NFD was constructed, motivated by questions pertaining to some result differences between the displays and a need to study the narrow field from 1 to 10 degrees with the same type of stimuli patterns offered by the WFD. These results will also be included.

The single-target results are presented first and serve as a baseline reference for other results obtained throughout this study. The sample population results are always given. When appropriate, the individual subject results are included as well. Within this section, the data are examined for directional latency differences between left and right single-target response, as this measure provides further information concerning asymmetries and directional biases.

The response time results for bifurcating dual targets are then presented, with special emphasis on the gross differences between these and the single-target response data. Within the same body of bifurcation data, the response direction results are then presented; and the concept of the preferred and reluctant response direction is developed. From this point on, the results are exclusive to the WFD or to the later-developed NFD, both of which have identical point-source stimuli. The response results for delayed bifurcating targets are subsequently examined with the intention of addressing (a) how the response time is affected by the delay between the two targets, and (b) how the same delay affects the response direction. To refine the analysis of results further, the effects of lateralization, hemispheric organization and stimulus complexity (number of bits of information) on processing, and latency time for single hemispheric bifurcations are also included. With these responses, special emphasis is placed on both the response latency and the selected target (inner or outer). The intent is also to determine whether there is an innate or acquired dominant directionality of decoding of visual information.

Finally, to rectify some of the uncertainties related to differences between the NFD and WFD, the results from the wide field are compared to those obtained from the newly constructed NFD for several subjects. These results clarify the significant differences between the original NFD and the WFD.

Throughout the following sections, it will be necessary to estimate a response mean and a standard deviation for descriptive purposes, as well as for performing statistical comparisons between the mean using the t test. The most commmonly used measure to describe the response times will be to state the sample mean, followed by plus or minus one sample standard deviation. Whenever a statistical comparison is made between two sample means, the differences between them will be considered significant if the attained level of significance for the computed t value is less than the 0.05 level; otherwise the differences between the means are not significant.

Single Target Response Time

Narrow Field Display. The single-target mean response time obtained from 10 subjects (representing a total of 518 left and right displacements on the NFD of 3, 5, and 7 degrees) was 254 (±76) ms. The mean was calculated without regard to the possible existence of left and right directional differences within subjects and between the left-right sample population means. The single-target response mean times varied widely among the 10 subjects who participated in the NFD experiments and were somewhat longer than those reported by other investigators. Subject means ranged from 200 to 300 ms (Table 2). The superposition of such a range of subject-specific response times gave rise to the wide-lobed distribution of Figure 20. Thus, intersubject variability poses a problem in pooling subjects' data and requires the application of normalization and nondimensionalization, as will be introduced later.

The distribution of response times can often reveal something of the nature of the internal processes governing the generation of single events in response to the experimental conditions and/or to the stimuli. Had there, for example, been skewing towards the shorter response times this could have been an indication of spatial or temporal prediction of target appearance. The appearance of the single-target response histogram leads to the conclusion that the randomization of stimuli was sufficient to minimize prediction.

Among the 10 subjects, the differences between left and right direction response times ranged from 7 to 52 ms. In all cases, the response time was invariably faster to the right than to the left.

Further analysis revealed that the differences between left and right response times were significant in only three of these subjects. If the response variances of several subjects had been less, more subjects might have shown significant differences between left and right response time. Of the three subjects whose results were significant, two exhibited differences of less than 27 ms, while the third subject showed a left and right response time difference of 43 ms. Similar findings were obtained when the differences between left-right response direction of three groups formed from the 10 subjects were examined. The first group consisted of the three subjects who showed significant left-right response direction differences. The second group consisted of the remaining seven subjects who individually showed no significant left-right response differences. The third group was a collection of all 10 subjects. In each of the three groups, the differences between left-right response direction were highly significant (Table 3). Response was always faster to the right than to the left. Not surprisingly, the greatest difference between response direction occurred in group one, which was composed of those subjects who individually showed significant differences. When the results of group two were considered collectively, they showed a significant difference of 25 ms between left-right response. When the responses of both groups were lumped together, the difference between left-right response assumed an intermediate value of 27 ms between the two groups.

Normalization. To overcome the difficulties arising from intersubject variability, the individual response latency times of each subject throughout this study were normalized with respect to that subject's single-target mean response times. The normalization of subject data permitted the comparison of results between displays and, when appropriate, could eliminate the individual differences between subjects' response times. For its intended purpose, the normalization of individual data incurrred no loss of sensitivity regarding the analysis or interpretation of the results, because the primary interest here was the change in response time relative to the single-target response mean, as it occurred when the complexity of the stimulus was changed.

Whenever the differences between the left and right response means were statistically significant at the 0.05 level, the responses of that subject were normalized by the corresponding single-target response mean in the same direction. If the differences between them were not significant, the left and right single-target responses were combined into a single response mean.

The previous set of experiments were repeated and further elaborated upon using the WFD. Target displacements to the left and right were either 5, 10 or 15 degrees. Five subjects participated in these experiments, and of these, subjects MB and BL were NFD subjects some 8 to 10 months earlier.

Wide Field Display: The combined left and right single-target mean response time was 211 (±39) ms, some 43 ms faster than for the NFD experimental group and 20 ms faster for the two subjects who had participated before. The frequency histogram distribution of the single-target response times for all five subjects resembles the distribution results obtained from the NFD and are given in Figure 21.

The response time differences between the two displays (as shall be later established) were likely caused by distinguishing factors between the two displays rather than by any significant differences between the two sample population groups. Support for this conclusion was offered by the observed differences in the results obtained from the two subjects who participated in experiments using both displays. One contributing factor may have been that the increased response time associated with the NFD was due to the extra accommodative or vergence control necessary for clear single-target vision because of the shorter viewing distance. Another factor involved here may also be the effect of target eccentricity on response latency time. In preliminary experiments, an attempt was made to quantify the change in single-target response latency time with increasing target eccentricity from 5 to 50 degrees. In that study, the results from three subjects showed that response time varied as a function of target eccentricity, and, furthermore, the response rate of change was dependent on the magnitude of the target displacement angle. From 15 to 50 degrees response latency time increased at the rate of approximately 1 ms per degree of target displacement. A slight decrease in response latency time was observed when target displacement increased from 5 to 15 degrees. Finally, the most significant factor may have been the effect of target luminance on response latency time.

The individual mean response times of the five subjects from the WFD are given in Table 4. Subjects' response latencies extended from 182 to 239 ms and the standard deviations were, in each case, less than 35 ms, a value considerably smaller than the preceding NFD results. The significant differences that were observed between left-right response in the NFD experiments also existed in four of the five subjects in the WFD experiments. Surprisingly, however, the direction associated with faster mean response was opposite to the previous results. Of the two subjects who participated in both experiments, only BL showed faster response to the right, a finding consistent with the NFD experimental results. With the other subject, MB, differences in response direction were always significant on both experiments; however, response became faster to the left with the WFD.

Upon examination of the left-right response differences between the NFD and WFD groups, it was apparent that, on the average, response differences from the WFD group were roughly half the value of their NFD counterparts. The greater difference between left and right direction latency response on the NFD may in fact be attributable to a statistical effect caused by a limited sample size. The reduction of the response variance associated with the WFD is indicative of the greater number of samples taken from the sample population, leading to a convergence of the variance. In each of these parameters, the sample size, the sample mean, and the sample standard deviation all have an effect on the size of the confidence interval about the mean and ultimately on the size of the allowable differences permitted for acceptance testing between the mean.

Response to Bidirectional Stimuli

Narrow Field Display: A significant difference of 125 ms was measured between the single and bifurcating-target sample population means. Mean response time increased from the single-target response time of 254 (± 79) ms to the bifurcation response time of 379 (± 160) ms, a change equivalent to a 49-percent increase over the single-target mean response. The extent of the bifurcation response time increase varied widely among the 10 subjects and ranged from 304 to 544 ms corresponding to increases in response from 38 to 87 percent over the single-target response means. In each case, the increase in response time caused by the bifurcating stimulus was highly significant (Table 2).

The population frequency distribution of the normalized response data collected from the 10 subjects is shown for single- and bifurcating-target response in Figure22. Comparing the two distributions, the bifurcation response exhibits much more extensive variability due to the larger response variance. The probability of a prolonged response latency was far greater when the stimulus involved a mapping onto both hemispheres rather than a single or unidirectional bifurcation. In no case was there ever a response to a bifurcation that was faster than the fastest single target response. Similarly, there was never a single-target response longer than the longest bifurcation response. The differences between bifurcation- and single-target response were significant at each displacement angle, implying that the differences were not attributable to effects of eccentricity but, instead, to direction processing necessitated by the difference between the stimuli.

Response Direction to Bidirectional Stimuli: A consistent subject-specific preferred response direction to bidirectional stimuli was observed in all subjects. Individual biases toward a preferred direction ranged from 54 to 100 percent. The occurrence of preferred subject response to the right was more frequent with the NFD subject group than it was for the WFD subject group. Preferred response to the right occurred in 6 out of the 10 NFD subjects, whereas only one of the 5 WFD subjects had preferred response to the right.

The influence of handedness did not appear to be a sufficient factor in predicting preferred response direction because of the remaining eight subjects whose preferred response was to the left, all were right-handed except one. An agreement between the preferred response direction and the direction of shortest single-target mean response time occurred in 10 of the 15 subjects. Of the four NFD subjects who had preferred response to the left, their single-target response times were all faster to the right, and the left-right differences were significant in only one case. With one exception, the speed of response and the preferred response direction were in agreement in four of the five WFD subjects and in three of these cases, the differences between left-right responses were significant. Of this group only BL showed a significant difference between left-right response; that is, the response was faster to the left while preferred response direction was to the right.

Similar results showing differences between left-right responses have been reported by others (Rayner, 1978; Hallett & Adams, 1980; Hallet, 1978). Recently however, Pirozzolo and Rayner (1980) showed that right-handers had a significantly shorter response latency to the right than to the left and that left-handers showed no asymmetry in response latency for single-targets. They attributed these differences to the apparent asymmetry of sensory-motor organization between the left and right hemispheres.

In the present study, only one of the subjects was left-handed, and it was observed that this individual's mean response to single target stimuli was shorter by 26 ms to the right than to the left when tested on the NFD. Of the two subjects who participated in both the NFD and WFD experiments, only BL's results were consistent with the notion that preferred response direction and the direction of the shortest single target response mean were related and remained unchanged between the two displays. The other subject, MB, showed an unalterable preference to the right regardless of direction of shortest single-target mean response time. In this case, response was shorter to the right with the NFD but just the opposite when later tested on the WFD.

Responses to Delayed Bidirectional Stimuli: The response to a stimulus can often be influenced by both internal and external interventions. In the case of bidirectional stimuli, the instruction to the subject regarding specific response performance, or the decision of the subject to modify response voluntarily, will often affect response direction as well as response latency time, changing them from their characteristic values. In these experiments, it was decided not to confound the results with the involvement of higher level control through instructions, and thus to modify subjects' response to bidirectional stimuli by introducing only a variable intertarget interval time between the appearance of the dual targets. The same five subjects participated in these experiments, and all experiments were conducted on the WFD.

In addition to the delayed stimuli presented to each subject, a certain number of single- and non-delayed bifurcating targets were also included as part of the stimuli sequences. The purpose of these non-delayed stimuli was twofold. First, the preferred response direction needed to be established for each of the five subjects, and second, their bifurcation response times needed to be determined. The single-target mean response times were used to normalize the response latencies and eliminate the single-target response time differences between subjects. The sample population results and the individual subject response means are all given in Table 4. These results, as well as the percentage of responses in each direction to the bifurcating target, were already given in some detail in the previous sections.

It was advantageous to consider the bifurcation response direction in terms of the preferred and reluctant response directions, because it eliminated the predominant left or right response directional differences between subjects and allowed a convenient method of examining both group and individual directional response data.

The preferred response direction was defined as the direction for which the probability of response to a bifurcating stimulus was greater than 0.5. The counterpart of the preferred response was termed the reluctant response direction and, as such, was defined as the less probable response direction of the two choices for a bifurcation stimulus.

When the data are presented, however, they are given in terms of whether the appearance of the first target leads or lags the appearance of the second target in the preferred direction.

The response time due to a bifurcating stimulus was nearly 40 ms greater than the single-target mean response time (Figure 23). The increase in response time from 212 (±39) ms was statistically significant; however, the 18-percent increase was less than the amount obtained from the

NFD. The normalized response time increased dramatically for small delays to either side of the now delayed bifurcation response, then it decreased as the delay increased beyond 40 ms. With larger delays, the response time nearly equaled that of the single-target mean response.

In both directions, the greatest change in normalized response occurred within the period of 90 ms. The amount of change was similar in both directions and the differences between identical interval times were less than 8 percent and were not significantly different, as shown in Figure 24.

The probability of response in the preferred or reluctant direction was dependent on the relationship between the interval of time between the appearance of both targets and the direction of the initial target displacement (Figure 25). Response in the preferred direction was more likely when the direction of the initial target displacement and the preferred response direction coincided. Response in the preferred direction continued even though the initial target displacement was in the reluctant direction, if the intertarget interval time was less than 80 ms. Beyond this range, the majority of responses were in the reluctant direction.

These results suggest (as have those of Wheeless et al., 1966; Hallett, 1978; Becker & Jurgens 1979) the possible existence of a critical interval of time necessary for the directional decision process. Within the decision interval time, however, there is a persistent probabilistic bias of response towards the preferred direction. The influence of this bias diminishes rapidly as the intertarget interval time exceeds the time allocated for the directional decision process.

The data for Figure 27 were replotted in Figure 26 to show the asymmetry of directional response to bidirectional stimuli as a function of the intertarget interval time. The region of greatest change in the probability of response in the preferred direction occurred when the intertarget interval time was less than 80 to 90 ms. Beyond this interval, which included the critical interval of time for directional decision, the probability of response asymptotically approached the limits of probability as determined by the direction of the initial target displacement.

The apparent asymmetry of the response toward the preferred direction is offset by an amount that corresponds to directional decision. If the data were expressed as the majority of responses in both the preferred and reluctant directions, then the probabilities of response would reach a minimum when equal and would be symmetric about this intertarget interval time. This point occurs when the preferred target lags the initial target displacement by approximately 50 ms.

A more extensive set of experiments was carried out with subject BL to determine the change of response time with delay and to estimate the critical decision interval time.

The procedure was similar to those of previous experiments. Targets were displaced to the left or right 5, 10, and 15 degrees and were either single, bifurcating, or delayed bifurcating stimuli. To create a large sample size about the region of interest, only three delay times of 30, 60 or 120 ms were used. The results for BL are summarized in Table 5 and are quite consistent with previous performance. A difference of 34 ms was measured between the single-target response mean and the bifurcation response mean, an increase of 19 percent. Response time increased still further but unequally when the delay was increased. The greatest increase in response latency occurred when the initial target displacement was in the reluctant direction. The effects of delay were inconsequential after 30 ms when the intitial target displacement was in the preferred response direction.

With no delay between bifurcating targets, 20 out of 21 responses, or 95 percent, were to the left. The percentage of response in the preferred direction decreased with increasing lag time between the initially appearing reluctant target and the preferred target. Nearly half of the responses were in the reluctant direction when the preferred target lagged by approximately 60 ms. At this value, the response time increased by 58 ms over the single-target response mean, an increase of 32 percent.

Response to Unidirectional Stimuli: For projection of unidirectional bifurcating stimuli to either the right or left cerebral hemisphere, the mean response time did not vary significantly from that of the single-target response mean time. Five subjects participated in these experiments, and all had prior experience with the experimental paradigm and apparatus. Targets consisted of random presentations of either single, dual bidirectional, or dual unidirectional stimuli displaced from 5 to 15 degrees in both directions. Target separation ranged from a minimum of 5 degrees to a maximum of 30 degrees. Minimum target separation occurred when unidirectional target combinations of 5 to 10 or 10 to 15 degrees were given. Maximum target separation occurred when targets were bifurcated left and right 15 degrees. With each subject, the unidirectional mean response time was not significantly different from the bidirectional mean response.

Although each subject had a left or right preferred response direction to the bifurcating stimulus, subjects, without exception, responded to the inner target of a unidirectional target pair. Only 5 percent of the responses were to the outer target. In four out of five subjects, the percentage of responses to the outer target was 3 percent lower than for the intertarget. These results are given in Table 6.

To investigate the response to unidirectional stimuli further, a delay paradigm similar to the delayed bifurcating stimulus paradigm was implemented. Since the probability of response to the inner target was always near 1.0 and since no significant increase in response time occurred, the outer target of a unidirectionally delayed target always appeared before the inner target. Delays were between 10 and 200 ms, and the targets were displaced from 5 to 20 degrees, with separations between them varying from 50 to 15 degrees.

The differences between left and right unidirectional stimuli were not significant when the delay values were the same. The results of these response times at each delay are given in Table 7. The left and right responses at each delay were combined and were then statistically compared to the single-target response mean of 206 (± 31) ms. Significant differences between the single and delayed unidirectional response were found only within a narrow range of delays between 60 and 120 ms. On either side of these values, response decreased toward the single-target response mean. The maximum difference found between single-target and delayed unidirectional response was 22 ms, an increase of 11 percent over single target mean response (Figure 27).

The probability of response to the inner target, the preferred response, is given in Figure 28. The crossover point, where the probability of response to the outer target is 0.5, occurs at approximately 100-ms delay. The critical unidirectional crossover delay value is roughly twice the delay value necessary for the equivalent probability of response to the reluctant direction with bidirectional stimuli.

Response to Repeated Bifurcating Stimuli: A consistent finding for the three subjects tested was their inability to reduce the extra response time when bifurcating targets were presented in succession. Subjects MB, BL, and JM participated in these experiments, which were performed on both the new NFD and the WFD. The bifurcation mean response times were compared under two types of stimulus presentation. The first method presented bifurcating stimuli as they had been presented throughout this study; that is, a certain number of bifurcating stimuli were randomly presented among a majority of single-target stimuli. The second method presented 20 consecutive bifurcating stimuli to subjects without inclusion of single target stimuli.

The results from each subject are given separately for each display (Table 8). The experiments with repeated bifurcations resulted in a greater variability. The differences between the mean values of these latencies and those generated by non-repetitive bifurcations were not statistically significant at the 0.05 level. This finding implies that knowledge of a bifurcating event does not affect the processing time; therefore, in future experimental sequences involving bifurcating stimuli, a greater number can be included without affecting the experimental paradigm.

Comparison of Differences Between the New Narrow Field and Wide Field Displays: To explain the response latency differences between the NFD and WFD displays, two hypotheses were proposed. The first considered the differences between the target displacements. The second considered the effect of distance between the subjects and the display; that is, the hypothesis was that the level of accommodation and vergence could affect the response time to some extent. To resolve these issues, and to investigate further the effects of intertarget separation, a second NFD was constructed. The new NFD was identical in every respect to the WFD except the targets were spaced 1 degree apart when observed from a distance of 1 meter. Three subjects (MB, BL, and JM) were tested for single- and bifurcating-target response on both the new NFD and WFD. Responses to target displacements of ±3, ±5 and ± 7 degrees were compared to tagret displacements of ± 5, ±10, ±15 degrees. The order of stimulus presentation was the same in both experiments, and an efforts was made to collect the data within the same day. The data for MB and BL were collected over a period of two days. The results of these experiments are given in Table 9.

The new NFD single-target response times were on the average 9 ms faster than the WFD response times. The differences were not significant when tested at the 0.05 level, however. The new NFD bifurcation response times were, on the average, 19 ms slower than the WFD bifurcation response times. In only one subject, JM, were the differences significant.

On the average, response times for the bifurcating targets were 10 percent greater for the new NFD than for the WFD, but still about 13 percent less than for the original NFD result.

DISCUSSION

The intent of this research was to investigate, through the continuous measurement of eye position the allocation of time necessary for the processing of visual information and decision making by comparing the response time for single-target stimuli to the response means of other novel stimuli. In pursuit of this task, visual stimuli were presented to subjects which exploited the organization of the visual pathways to the cerebral hemispheres and the communication between the hemispheres via the interconnecting hemispheric nerve fibers.

Throughout this study, the single-target mean response time was used as a reference against which the response means of the other, more complicated stimuli were compared.

The single-target response mean of 252 ms obtained from target displacements of 3, 5, or 7 degrees was considerably slower than the frequently reported average of 200 ms obtained for much larger displacements (Westheimer, 1954; Bartz, 1962; Robinson, 1964). Single-target response latencies obtained from the wide-field display were 40 to 50 ms less than of the NFD and were more consistent with the previous investigators' results. To resolve these differences, several hypotheses were proposed, and a series of short experiments were run to test these hypotheses. The effect of target displacement was considered to be a factor in increasing the response time. Bartz (1962) found that the response time was greater to the left and right at 5 degrees than at 10 degrees, and it increased steadily from then on to 40 degrees. Similar results were obtained by White, Eason, and Bartlett (1962); however, they did not measure latency for displacement angles of less than 10 degrees. Frost and Poppel (1976) offered an explanation for the change in latency for small displacements of 10 to 15 degrees versus larger displacements and hypothesized two modes of information processing in the central and peripheral fields. Central field processing was considered to be mediated by the visual cortex, whereas the peripheral field was mediated by the superior colliculus. The transition from one mode to another occurs about 10 to 15 degrees from the fovea on the retina.

To resolve the differences, a set of experiments were conducted with a display similar to that of the WFD, but with the targets separated by 1 degree and a viewing distance of 1 meter. The results provided two valuable observations. First, the response times for the smaller target displacements were not statistically different from those obtained from the WFD, yet they were approximately 11 percent slower. Also consistent with previous investigations was the steady increase in latency with target eccentricity. Since target displacement angles were under 20 degrees in this study the two-mode processing of spatial information would not seem a significant factor alone in explaining the large difference between NFD and WFD results.

A second consideration was the difference in viewing distance between the two displays. At the NFD viewing distance of 0.65 meter, the level of accommodation and vergence necessary to maintain clear single target vision was expected to be greater than when the same target was viewed at 1 meter. As a result, the latency time should be slower. A method to resolve this question would involve measuring the response latency times for the same target displacement angles at various levels of viewing distances. If the hypothesis were true, then, as the viewing distance increased, there should be a decrease in response time. The question would still remain regarding the resolution of the response into its constituent components of accommodation and vergence.

Physical limitations on the size of the NFD CRT prevented moving it back to a distance of 1 meter and replicating the original experiment at 3, 5, and 7 degrees. The alternative was to replicate the experiment using the new NFD discussed earlier. Again, the issue has not yet been fully resolved since the increase in response was not significantly different from the WFD results; however, a small but statistically contributing increase in response time resulted from the displacement of the targets at the nearer distance of 0.65 meter.

The effect of target luminance was shown by Wheeless et al. (1966) and by Ueno (1977) to be a significant factor affecting response latency time. Response time was shown to decrease and reach an irreducible or asymptotic latency as the luminance level was increased to well above threshold. Wheeless showed that for every half log luminance change up to two log luminance levels above foveal threshold, response time decreased 20 ms. Based on this finding, the 40- to 50-ms difference in response time between the NFD and WFD would necessitate at least a one log unit difference in luminance level above the foveal threshold. A further property, which was observed by Wheeless and which seemed to agree with the results obtained here, was the increase in response time variance associated with the lower levels of target luminance due to the narrow-field CRT display. The spread of the Wheeless' response data was shown to decrease as the level of luminance was increased. A similar result was found in these experiments when the response variances from the NFD were compared to the variances from the WFD when the number of samples were nearly the same.

An effect that may have further increased the response time for bifurcating targets on the NFD was a very slight, but observable, reduction in target intensity as the number of targets was increased from one to two. In all likelihood, the decrease in target intensity contributed to a further increase in response time for bifurcating targets.

In future experiments involving CRT-type displays, the Z-axis should be modulated to maintain equal luminance levels under all target conditions. The ability to maintain equal target luminance under different stimulus target patterns was not a problem with the discrete display.

For one subject the response latency time was measured at both the normal luminance level and at a considerably reduced level. Between the two luminance levels, single-target response time increased by 29 ms, or 15 percent, from the higher to the lower luminance level. For the same shift in luminance level, the bifurcation response time increased by 26 ms, or 11 percent. At the lower level of luminance, response variances for the single targets were less than at higher levels; whereas, the bifurcation response variances for the bifurcating targets were greater than these response variances at the higher levels of luminance.

In nearly all of the subjects who participated in these experiments, an asymmetry between left and right single-target response latency times was observed. A consistent trend in all of the CRT NFD subjects was faster reponse to the right than to the left. This finding was consistent with the results of Rayner (1978), who attributed the differences to the highly practiced left-to-right movement associated with the reading process and to handedness and hemispheric function. A majority of WFD subjects showed faster response to the left than to the right. The differences between left and right response were less than the directional differences associated with the NFD group and may be due to a larger sampling.

Over an 18-month period, consistency of single target response latency time has been observed in two subjects. Periods ranging from several days to more than 2 months elapsed before the same person was asked to participate again as a subject. The repeatability of results suggests that a subject's response can be characterized by an underlying response-time distribution. Since the exact nature of this distribution is unknown, one must be satisfied for the moment with a statistical model of it. The statistical model is a representation of the probability density function with the response latency time representing the outcome of a random variable for a specific stimulus. For most purposes, it has been adequate to describe a subject's response with a statistical mean and standard deviation.

The frequency histogram distributions derived from the response latency data of all experiments were similar in appearance, all of them showing skewness towards the longer response latency times. A small number of extreme outliers at the longer times may be attributable to fatigue, boredom, or to a momentary lack of attentiveness. The shape of the distribution also reveals, to a certain extent, changes in response intent, cancellation of movements, and reprogramming of response direction toward another target. A more symmetrical bifurcation response distribution may infer less importance to the previously mentioned influences on the response. In addition, the fact that significant skewing does occur and is directed away from the shorter response latencies implies an inability to reduce the response time, given that the predictor operator is not active. Therefore, it cannot be concluded that the response distributions are truly normal; thus, a more appealing underlying distribution should be sought. When extreme values in response data are to be expected, it is often possible to set arbitrary upper and/or lower limits on the normal distribution without adverse effects on its statistical usefulness. The central limit theorem shows that a normal frequency distribution occurs when the effect being observed results from averaging the observations from a whole series of variables. If, however, the effect being observed is due in part to the smallest and largest number of variables, another distribution may be more appropriate. Three such continuous density functions are the two-parameter gamma, log normal, and Weibull distributions. These distributions are not defined for predictive responses. What distinguishes these distributions from one another is the behavior of their tails. The tails of these three distributions all decrease rapidly. For large t, the tail of the gamma is dominated by

$$e^{-ca}$$

the log normal by

$$e^{-c(\log a)}$$

and the Weibull by

$$e^{-ca}.$$

All three go to zero faster than any power of a, but the log normal decreases more slowly.

The responses of each subject in this study were normalized with respect to their single-target mean response. The normalization of response data achieved several desired features. The normalization of subject response time eliminated the significant differences between their single-target response means and emphasized, instead, the differences between single and bifurcation response. Thus, the single-target normalized response mean is always located at one. The shape of the distribution remains unchanged other than being scaled either up or down in order to maintain an integrated area of one under the curve. Because the data are being normalized with respect to a parameter of time, the resulting value becomes a unitless quantity that can also be expressed as a percentage change.

There are several disadvantages to using the preceding normalization technique, and these can be best illustrated with an example. The difficulties with the normalization technique arise when the differences between several pairs of numbers are the same size, but the numbers themselves are different. The smallest pair of numbers will have the largest ratio between them, while the largest pair of numbers will have the smallest ratio between them. In this case, the normalization procedure obliterates the equivalence of differences between the pairs of numbers. It is impossible, therefore, to expect equivalence between their ratios if the differences between the numbers are the same. For the ratios to be equal, the differences between a pair of numbers must be greater as the factor to which the value is being normalized becomes larger.

The difference between normalization of data by division or by subtraction is further illustrated by the analysis of results of subject responses to two different levels of target luminance. In each case the difference between single and bifurcation responses was 37 and 35 ms for high and low levels of luminance, respectively. The difference of 2 ms hardly seems significant. When the same data were then analyzed by divisional normalization, the response change was 20 and 16 percent for high and low levels luminance, respectively. Because the response time increased with the decreased luminance level, the percentage change in response also decreased.

In this study, the responses to crossed and uncrossed stimuli and the effects of hemispheric lateralization in the sense of spatial and verbal hemispheric dominance should not have been the sole factor for explaining the significant response differences between unidirectional and bidirectional stimuli. The point-target stimuli used in these experiments were different from many other types of stimuli used to investigate asymmetries in cerebral function and provide no information that would favor processing by the specialized properties of either hemisphere. Therefore, any asymmetries shown in these experiments may represent a more basic, underlying form of specialization that could be referred to as visual hemispheric dominance.

A basic finding of this study was the significant increase in response latency to symmetrically bifurcating targets. At first, this finding may not seem startling because various studies have shown that as the number of stimuli increase, response time increases at a rate proportional to the log number of bits of stimulus information (Hick, 1952; Welford, 1968). Such a measure fails, however, to capture the quintessence of the spatial-temporal structure of the stimulus as it relates to the organizational properties of the visual system. As a consequence, it cannot accurately predict response latency for certain types of stimulus patterns. The mean response to bidirectional stimuli was always significantly longer than the mean response to unidirectional stimuli. The increase in response time, therefore, may not be related to the number of targets present but to the participation of the hemispheres. An elaboration of this idea will be forthcoming.

Eye Movement in Response to Single and Multiple Targets

An indication of the lack of apparent plasticity in the system in response to bidirectional stimuli was provided by a preliminary investigation into the effects of repeated bifurcation. If the response time for these stimuli could be reduced, then it might be an indication of plasticity existing at the level of oculomotor control involved here. In these experiments, no significant differences nor consistent tendencies were found between the response latency times for randomly appearing or continually appearing bifurcating targets. Such a result implies that the pathways involved in the bifurcation response are an innate or stereotypic characteristic of the response process, which is thus constrained by the physiological organization of the system. The effects of repeated bifurcation with temporal or spatial prediction have yet to be explored. It is well known, however, that the response latency for predictable single-target stimuli can be reduced or eliminated completely (Dallos & Jones, 1963; Stark, Vossius, & Young, 1962). However, it is not known if the same operator can eliminate the extra delay when the visual stimulation involves both hemispheres. Not only should future experiments consider temporal prediction but spatial prediction as well since a knowledge of the probable location of a target should increase target detectability and decrease response time. In all likelihood, a knowledge of target location may obviate intervention of the higher centers of control.

Although the differences between the responses to continuous and randomly presented bifurcations were not significant, some of the trends that occurred in some subjects deserve further attention. One avenue of interest is to consider the interaction between the hemispheres via the commissure fibers as a communication channel. Interference acting on these channels either through internal sources or via limitations of its own channel capacity could affect the response latency or direction of response.

The unequal response latency changes that were observed between single- and bifurcating-target response between the NFD CRT display and the WFD were most likely due to the same effects that influenced single-target response. The additional increase in bifurcation response time and increased variance associated with the CRT NFD were probably related to a further decrease in target luminance when dual targets were displayed. Although a luminance reduction of at least 50 percent might be expected when two targets are displayed, the persistence of the phosphor maintains the luminance of the targets at a slightly higher level.

A more representative measure of the change in response times to single and bifurcating stimuli is likely given by the new NFD and WFD results. The conclusions that can be drawn from the CRT NFD are similar for the most part to those obtained from the other two displays.

The sudden displacement of a target off the fovea initiates a sequence of timed processes that occur prior to the eye movement response and involve various decisions that must be made to place the eye accurately at the new target position. The events preceding eye movement have been summarized and sequentially ordered along a time line recently by Young (1981). The oculomotor system requires various pieces of information before the execution of a response can occur; namely, the determination of the response direction followed by the magnitude of the response. The ability to modify the directional decision and the magnitude of response is allowed, but only if these changes occur within certain intervals of time along the event sequence.

The results here have shown that over a small group of subjects, response to bidirectional bifurcating stimuli adds an additional 30 to 60 ms of extra processing time to the response latency. A significant factor for this increase is believed to be the involvement of both hemispheres in the response process. When the same number of targets were unidirectionally bifurcated onto only one hemisphere, response time was equivalent to single-target response latency. In both these cases, a directional decision, as well as a magnitude estimate, needed to be made prior to execution of movement. The unidirectional bifurcating case involves a somewhat different decision since the information required by the system for a unidirectional bifurcation is no longer a decision of either right or left but one of selecting either the inner or outer target.

A preferential response direction to bidirectional and unidirectional bifurcating targets was observed in all subjects. The asymmetry of response was strongly biased toward either the left or right or was directed toward the inner target.

The left or right directional preference was not influenced by asymmetrical displacements between the targets. It would seem reasonable though that, given the choice between extreme displacement of a target in the preferred direction versus small target displacement in the reluctant direction, the response would be to the smaller of the two.

Eye Movement in Response to Single and Multiple Targets

The trade-off between the cost of a movement in terms of extra programming of an intermediate saccade to reach an extreme outer target versus the closer target in the reluctant direction was not fully explored. The minimum target displacement at the time was limited to only 5 degrees, and no targets completely utilized the full 50-degree span of the display. Consequently, only asymmetrical differences up to 15 degrees were investigated.

The effect of target luminance and differential luminance between targets was not investigated. The influence of target luminance would seem to have more effect on detection, but to what extent is not known. There was a tendency for the CRT NFD subject group to have a preferred response to the right, while the WFD subjects showed display preference in the opposite direction. The influence of target displacement magnitude and the effect of distance seemed to have little effect on response or directional preferences based on experiments between the WFD and the new NFD. The luminance levels may have played an important role in influencing the preferential direction. Even with the apparent lower levels of target luminance, the fact remains that the directional response biases were strong under both conditions. It would seem unlikely, therefore, that for such a small change in target luminance level between the two displays such a dramatic turnaround would occur in preferred response direction. To resolve the differences between the two groups may require further experimentation on the effects of target luminance.

The preferential response direction was not always related to handedness. It should be mentioned that a complete test for handedness was not performed; thus, the conclusion drawn concerning cerebral dominance to preferred response direction is tentative. The most interesting results were provided by those subjects who indicated a certain handedness but whose preference was in the opposite direction. This observation occurred more often for those who were subjects on the WFD.

There seemed to be a relationship between the speed of response and the preferred response direction. Again, exceptions to this observation were easily found. Such a result might suggest two internal independent timers which, upon detection of a stimulus, begin their time-out sequence for directional decisions. Whichever timer finishes first could determine the response direction. Thus, if one timer runs slightly faster than the other, response in that direction might be expected more often. Such an idea has been suggested by

Becker and Jurgens (1979), who proposed a saccadic model generator with two independent timers, either of which can be inhibited by the other.

Of those subjects whose preferred response and speed of response were in opposite directions, it would seem reasonable to expect that if the independent timer hypothesis was correct, then one would have expected a greater effect on the preferential target response direction due to asymmetrical target displacements than was observed. This was not the case, however, since extreme displacements were not tested here. Based on experiments performed here, responses away from the preferred target direction would not have been expected until the asymmetries between the targets reached at least 50 degrees.

The most effective way found to manipulate the response direction was by introducing a delay between the appearance of two targets. The added delay between the targets not only changed the response direction but significantly affected the response latency time in both response directions. The observed differences between simultaneous bifurcation and delayed bifurcation may be related to the differences between parallel processing and sequential processing of visual information. In the serial mode, the interplay between targets in the opposite direction caused the greatest increase in response latency, but only if the delay between them was less than the window of time allowed by the decision process.

The unidirectional bifurcation response to the inner target did not agree with the results of Findlay (1982), who showed an eye-position response to an intermediate target position. According to his results, the influence of target size and shape seemed to have an effect on the positional response of the eye. The targets used in these experiments were point sources and were considerably smaller than his. Eye movement accuracy when reported here for either inner or outer target was within the range of positional error tolerated by the saccadic system.

Two conditions were necessary to offset the preferential response direction. The first condition involved the direction of the initial target displacement; the second involved the critical period of time between the appearance of each target. A response in the reluctant direction required that the initial target be displaced in the reluctant direction and that the minimum delay time before the appearance of the second target in the preferred direction be greater than 50 ms. The delayed step/anti-step paradigm of this experiment was similar to the approach used in the pulse overshoot experiments of Becker and Jurgens (1979). In their experiments, pulse widths were varied between 50, 100, 150 and 200 ms. Results from five subjects showed that response to the initial angle of the pulse or to the final angle response of the step was based solely on the pulse width.

The results obtained in the present study were by and large consistent with the scheme of Young (1981), who provided estimates of the amount of time for decision making prior to the generation of a saccade. He observed that directional decision occurred within the first 50 ms. From 50 to 70 ms, the magnitude of the saccade can be modified, and from 70 to 100 ms, the magnitude can still be modified, but it can be decreased only if it is in the same direction as the saccade. From 100 to 150 ms, the saccade could be cancelled so as to compute the next saccade. If not, from 150 to 200 ms, the expected error would be computed, and if the error was expected to exceed the foveal dead zone of 0.3 degree, the system would initiate parallel processing for the generation of the corrective saccade. At 200 ms, if parallel processing was initiated, the response latency would be extended another 100 ms, according to Young.

The limits of the decisions times in the present study were similar to those of other studies if the probability of preferred response was set at 0.5. At this value, the response time for simultaneous bifurcating bidirectional stimuli increased approximately 40 ms, whereas no increase was observed for unidirectional bifurcating stimuli. For one subject, the critical delay time for a probability of response greater than 0.5 toward the reluctant target was approximately 80 ms. Becker and Jurgens (1979) estimated 100 ms. The amount of time allowed for selection was approximately 100 ms and is consistent with the time obtained by Becker and Jurgens (1979) for amplitude changes. It seems, based on these results, that more time is allowed for a change in amplitude than for a change in direction, and the order of these processes is first the directional decision, followed by selection.

The existence of a preferred response for both unidirectional and bidirectional bifurcating stimuli allows the probabilities of their respective functions to be presented together. If the assumption is made that their probability curves are identical, then the only difference between them is the amount of delay separating their critical decision times. Thus, one probability of preferred response curve could be used to describe both processes, provided that the appropriate delay shift was included between the two responses. The combined probability curves, in conjunction with the normalized response latency curves, completely describe the response for step, step-step, and anti-step stimuli when based on the premise that an asymmetry of response exists. When dual or multiple targets are presented simultaneously, the preferred response predominates, as well as preferred selection of the inner target. When the delay is further increased, such that the preferred target lags the appearance of the reluctant target, the probability of response toward the preferred direction decreases and may even be exceeded by the probability of response in the reluctant direction. If the delay lag time is still within the interval defined by the critical delay time, then the probability of changing response toward the preferred direction is less than 0.5. However, if the probability of selection of the preferred inner target is still greater than 0.5, this response still dominates. Thus, for dual target stimuli, the complete response can be described by the preferred response probability curves and the appropriate response latency curve. The probability of preferred response can be described by three distinct regions where the probability of each process within the region determines the likelihood of a response. Intertarget interval times, excluding the region between the critical delays, demonstrate two regions of greater probability of preferred or reluctant response, depending on increasing or decreasing amounts of extra delay between the targets. The center region is dominated by changes in selection between preferred inner and reluctant outer targets where the chance of influencing a change in direction in this region is less than 0.5.

The similarity between the probabilities of preferred response curves for both unidirectional and bidirectional bifurcating targets suggests that the underlying distributions of the critical delay times may be similar, other than a shift in delay time, and may further suggest a close relationship between the two processes. One possibility might be in the form of a single probability of preferred reponse curve which could be displaced by the appropriate amount upon stimulation of either one or both hemispheres. Additional data points are needed before such a scheme could be accurately assessed.

Of the two dyslexic subjects tested, both showed a considerably lower percentage of responses to their preferred direction than did non-dyslexic subjects (less than 64 percent versus 88 percent). The mean response time for the symmetrically bifurcating dual targets for dyslexic subjects was 33 ms longer than that for non-dyslexic subjects. A considerably higher percentage of responses to the outer target was observed when unidirectional stimuli were presented to the two dyslexic subjects than when presented to non-dyslexics, and the percentages differed for each side. Another observation was the increase in the percentage of responses in the preferred direction with from two to six symmetrically bifurcating targets. The increase in the number of bifurcating targets had no effect on the frequency of preferred direction for non-dyslexic subjects. When six targets were presented to the dyslexic subjects, the percentage of preferred direction responses was similar to that for non-dyslexics. Clearly, there are measurable observable differences between dyslexics and non-dyslexics that deserve further attention. Although a sample of two is too small for hard conclusions to be drawn, these results do indicate some interesting possibilities concerning the way information may be processed. The reduced percentage of preferred direction responses may indicate less directional asymmetry between the hemispheres. The unidirectional response for the dyslexics showed an increased percentage of responses to the outer target pair and unequal percentages between left and right responses. This observation may indicate an asymmetry of sequential decoding of visual information not found in non-dyslexic subjects. These results may suggest other strategies for reading improvement programs for dyslexic subjects and further suggest that having these subjects read in the usual way may not be the most effective or efficient method for learning.

The single-target response latencies obtained in these experiments were consistent with the values obtained from previous investigations. The effect of reduced target luminance can have a dramatic influence on both the mean, which tended to increase, and the standard deviation, which showed increased variability.

Over long intervals of time, subjects showed an amazing consistency in their response times and preferred response directions. For short periods of time, response-time performance was sensitive to such factors as fatigue and alertness, but response preference was consistent and insensitive to these factors. Thus, it appears that whereas motor function performance can be affected by the state of the observer, the sensory factor remains relatively immune from these effects. This observation may, in fact, be a manifestation of the innate asymmetries of the functional organization of the hemispheres.

It is not clear yet whether the differences between left-right response latency motor asymmetries can be related to the preferential asymmetries. In future experiments, a more concerted effort should be made to firmly establish left or right cerebral dominance and to determine the degree of dominance. The data are inconclusive and, in fact, a strong preferential response direction does not necessarily indicate asymmetry between left-right motor responses. For the same group of subjects, the relationship between contextual and context-free stimuli should be explored. Contextual stimuli should be favored by one hemisphere or the other, depending on the presented form. Thus, for spatial-type stimuli, response should be faster when they are presented to the left field; with alpha characters or numbers, response should be faster when they are presented to the right field. Since, in these experiments, a context-free stimulus was used, neither hemisphere should have been favored. Since single-target left-right response latency differences may be a better indicator of oculomotor asymmetries, these differences may not be a good predictor of directional preference. Perhaps, then, preferred response may be due to a visual hemispheric dominance. Differences between context-free preferred response and the preferred response to contextual stimuli may indicate an overriding influence that high levels of specialization may impose on the lowest level of preferred response direction as investigated here. Future experiments should consider this by changing the contextual information of the targets while examining the changes in response.

A basic finding of these experiments was the relationship between the number of stimuli presented and the response latency time. The crucial factor determining response time is not in the number of targets shown but in their spatial distribution over both hemispheres. Bidirectional bifurcating targets which stimulate both hemispheres simultaneously show significant increases in response times over single- or multi-target stimulation of only one hemisphere. Unidirectionally bifurcating targets which stimulate only one hemisphere do not increase the response time. The differences between the latencies are believed to be attributable to the participation of either both hemispheres or of only one hemisphere during the response process. To clarify whether the increase in response latency is due to the participation of both hemispheres and not to the directional decision, an experiment should be performed that would involve only one hemisphere but would necessitate a directional decision similar to that of the bidirectional experiment above. Such an experiment might involve a simultaneous lateral displacement and vertical bifurcation of a single target. If the hypothesis is correct, then for a similar decision involving the choice of moving either up or down, no increase in the response latency time should be observed if only one hemisphere is stimulated. To avoid stimulation of both hemispheres, the lateral displacement of the vertically bifurcating targets should be sufficient to avoid the macular region.

The increase in response time associated with the bidirectional stimuli may offer another explanation for the increase in response latency time for single-target, small-angle displacements. Within the macular region, an area less than 3 degrees around the fovea, neural fibers from each field project onto both hemispheres. Any small displacement of a single target may have an effect similar to that for bidirectional stimuli of larger amplitude; it may, however, take even longer to respond, because the system needs to determine which mapping represents the true target position. Under these conditions, a greater number of corrective fixations might be expected.

The way in which dual targets are presented can significantly affect the amount of time necessary to process the information and the response. In general, targets that were presented simultaneously had shorter latencies than did targets that were presented serially. The increase in response times for sequentially appearing bidirectional stimuli was quite sensitive to even the shortest delay intervals. Thus, it seems that small differences between the appearance of targets can significantly alter the manner in which the information is to be processed. Simultaneous presentation of the targets may mean or infer parallel processing in the sense that the system has all the necessary information for performing a simultaneous analysis. The reduced processing time may also be a direct result of the asymmetry between the directional responses. Because the system possesses both directional and selection biases, the amount of time necessary for a decision is reduced. Of course, the response can be influenced by other information but only for a critical period of time. After that, the system accepts no further suggestions. A change in target information within a certain critical period of time requires a sequential mode of processing the information. Post-target information can be modified by new information but only up to a certain critical period of time. To gain further insight into the differences between sequential and simultaneous presentation of target information, the sensitivity of the simultaneous response should be explored for delays less than the ones used in these experiments.

CONCLUSIONS

In this study, a technique of eye-position measurement and analysis was used to investigate the allocation of time necessary for processing visual information, by comparing the mean response latency time of single targets to the response means of other novel stimuli. In all cases, stimuli were visual, context-free, point-source targets that were randomized for type, order of appearance, and time course.

The brain has two hemispheres that are not functionally symmetric. The organization of the visual system is such that the right visual field of each eye is mapped onto the left hemisphere, whereas the left visual field of each eye is mapped onto the right hemisphere. This organization is consistent with that of the rest of the body wherein the right hemisphere receives information primarily from the left side of the body and the left hemisphere receives information primarily from the right side of the body.

Although the two hemispheres may have specialized properties for processing certain kinds of information, they can communicate with each other through connecting fibers that link the two.

In these experiments, the separation of the visual fields is exploited so that stimuli can be selectively presented to either one or both hemispheres. If targets are presented to both hemispheres, then the interactions between them can be studied. If the same number of targets presented to both hemispheres are now presented to only one, then one can determine if the system responds differently. It was shown that eye movement measurement can be used to quantify these differences and that these differences, measured by the eye movement response, can reflect to a certain extent the functional organization of the system. The primary dependent measures in these experiments were the initial saccadic response latency time, the direction of response, and, when applicable, the magnitude of the response.

An asymmetry in single-target, left-right response latency times was observed in nearly all subjects. There was a tendency for the CRT NFD subject group to respond to the right faster than to the left, whereas most subjects in the WFD group showed faster responses to the left. These differences were not thought to be attributable to any significant differences between the sample populations, but rather, to the characteristic differences between the display types.

In all cases, there was a significant increase in response latency time when targets were presented to both hemispheres simultaneously. The increase in response time was greater using the CRT NFD than the WFD display. The additional increase in response time using the CRT display was thought to be due to changes in target luminance level. No significant response latency differences were observed between single-target response latency and dual-target, single hemispheric response latency. Thus, the significant increase in response latency time is not due to the number of targets presented to an observer but rather, to the stimulation of both hemispheres. Dual targets presented simultaneously to an observer showed consistent subject-specific preferred responses. Dual targets presented simultaneously to both hemispheres showed preferred responses to the left or right 88 percent of the time. Dual targets presented simultaneously to one hemisphere showed prefered selection of the inner target 95 percent of the time. The response biases did not appear to be influenced by asymmetries between the targets nor were they necessarily related to handedness. Preferred responses could, however, be offset by introducing a time delay between the appearance of the two targets. The probability of preferred response and the response latency time were both influenced by the length of the delay.

Delayed bihemispheric stimulation produced changes in response latency that were similar in both directions, and the response latency increased still further when targets were presented sequentially rather than simultaneously. The delay, furthermore, had pronounced asymmetrical effects on the probability distribution of the response direction. Delayed dual-target, single-hemispheric stimuli showed a similar, but shifted, probability distribution curve. The response time changed only when the appearance of the preferred inner target lagged behind that of the outer target. The directional response and/or selection of a target is therefore conditional on both the initial target displacement and the elapsed time before the apppearance of the second target. When the second target appears in the opposite visual field and is in the preferred direction, then the critical period of time separating these two targets is approximately 50 ms if the response is to be in the preferred direction. If, on the other hand, the second target is in the same visual field as the first but is the inner target of the two, then the critical period of time for response to the inner target is roughly twice that of a directional decision, or approximately 100 ms.

These studies have shed light on the timing of events prior to the execution of a saccade. The single and bihemispheric paradigms have also proven useful in studying the mechanisms and organization of visual information processing.

PART 4. BIFURCATING STEP RAMP STIMULI

INTRODUCTION

A previous section of this report discussed the presence of an added delay in fixating a target when multiple targets are presented to the subject simultaneously. As was pointed out in that section, the saccadic latency increased by 40% when a single target was split into two or three targets on each side of the visual field. This part of the report deals with a similar yet less thorough examination of these same stimulus conditions on smooth-pursuit latency.

Most investigations of smooth pursuit have examined the latency to a single target velocity, both using step-ramp and plain-ramp stimuli (Rashbass, 1961; Lisberger, Evinger, Johanson, & Fuchs, 1981). In these reports the latency of the smooth-pursuit system is 120 to 180 ms. This latency increases to 200 to 280 ms when a step ramp stimulus is used (Rashbass, 1961; Heywood & Churcher, 1981; Bahill, Iandolo & Troost, 1980). Although such information from laboratory conditions tells us much about the characteristics of smooth pursuit, in most normal occuring conditions there is not usually only one target that moves in one direction but rather many targets moving in several directions. Pilots are faced with such decisions on a continuing basis and must move to the new target rapidly so as not to lose this target in their visual field. How humans process these sometimes conflicting stimuli and the delay in reactions to these stimuli are the subject of this part of the report.

As humans scan their environment, they use both saccadic and smooth eye movement control systems to bring objects of interest onto the fovea of the eye. Once they have detected a moving object, if they do not fixate that object and continue to track it, they may lose sight of it, especially if it is small and dim. When faced with multiple targets of interest to track, the human may take much more time than is ideal to choose and follow the moving object that is most important to the task at hand. By displaying to the subject multiple moving targets and measuring the latency to track the target, it may be possible to understand eventually how humans decide and scan the visual environment about them. This information can be used to optimize human scanning behavior. The first step in this process involved looking at a small sample of subjects' responses to step-ramp bifurcating stimuli. This reprecents only a first step and more work is needed to confirm the results obtained in this study.

Eye Movement in Response to Single and Multiple Targets

METHODS

The eye-movement monitors were clipped to the subject's glass frames and adjusted for maximum linear range. The subject places his head in a head-and-chin rest to minimize head movements. Each experiment was preceded by a calibration of the monitors. During the experiment, bifurcating ramp, step-ramp and bifurcating step stimuli were presented to the subject.

The presentation of the bifurcating stimuli always began with the stimuli in the center of the screen. After a variable delay of between 0.5 and 5 seconds, the single target split into two horizontally displaced targets separated by a predetermined, but randomized, amplitude. These step separations from center position were 2.5 to 5.0 degrees. If the trial was to be a bifurcating step, the targets would remain separated for 2 seconds and then return to the central position. If a ramp-step were to be presented, both targets would immediately move towards the center postion at a predetermined randomized velocity; a ramp stimulus would start in the center and then split into two spots moving away from the center. The target velocities were 2.0 and 5.0 deg/sec, but only the 5 deg/sec data was analyzed. After a ramp duration of 4 seconds, the beam would return to the center position.

Eye movements from the right eye were recorded using a PDP 11-34 computer. The data were sampled at 200 Hz and stored on disk for off-line analysis. The data were subsequently played back onto a strip chart recorder and latencies were determined by hand. The speed of the recorder was 40 mm/sec, allowing a resolution of 25 ms/mm. This data was averaged and a t-test was performed to indicate significance.

Three subjects, ranging in age from 18 to 35, were used in these experiments. No overt ocular pathology was present and subjects had a full range of oculomotor movements. Two subjects were experienced in eye movement experiments and one was naive.

RESULTS

Average smooth pursuit latencies were 10 to 36% longer during bifurcating smooth pursuit conditions than under the single target experiment (Table 10). However, the increase in latency was not significantly different from our single target responses for ramp stimuli. The bifurcating ramp responses showed more variability than the single target control. In some cases double that of the control condition. However, the latency of the saccades that occur to refixate the moving target was significantly increased in all three subjects when compared to the control experiment using a single target.

The schematic diagram in Figure 29 shows the relative changes that took place when single and double targets were presented to the subjects. The values used to show these differences were taken from the average response values from our population in Table 10. The two noteworthy comparisons are the small change in smooth pursuit latency and the very large change in refixation saccade latency. This saccadic latency change is aproximately 130 ms. Similar changes were found during bifurcation saccadic data in part 3 of this report.

Although not examined very closely, we have noticed that smooth movements which take place following these saccades are in the same direction as the saccade regardless of the direction in which the smooth movement was moving prior to the saccade. It is as if there is a single directional command is sent to both smooth and saccadic systems to move the eyes in a coordinated direction.

DISCUSSION

The present experiments show a small change in the latency of smooth pursuit to bifurcating targets. This change was only slightly significant in one subject. The change seen in all subjects may reflect more the bifurcation paradigm than the effects of the system itself. Approximately 30-40 ms would be needed for the single target to appear as two separating targets to the visual system given the velocity of the target and the size of the CRT spot. If this delay is incorporated into the previously defined latencies, the increased delay that we find here represents no change in latency.

A previous section described the increased saccadic latencies to bifurcating targets. A similar increase in refixation saccadic latencies are also found when multiple smooth moving targets are presented to the subject. Many of the same issues - directional preference and slightly increased latency - are seen in these saccadic responses.

An exhaustive study of smooth-pursuit reaction to these ramp-step stimuli was not possible to the extent that saccadic responses were investigated. However, the mode of interaction that these two systems undergo as a result of these stimuli is of much interest. Most normally occurring visual stimuli are multiple combinations of smooth and rapid movement in which both systems are called upon for response. Understanding how these systems interact in normal situations can help predict the limits of target detection and acquisition for pilots.

Future research on such issues should examine smooth-pursuit function in as much detail as was done here for the saccadic system. Then one should examine how these two systems interact and form strategies that optimize the tracking of multiple objects in the field of view.

BIBLIOGRAPHY

Albert, M.L. (1975). Cerebral dominance and reading habits. Nature, 256, 403-404.

Bahill, A.T., Clark, M.R., & Stark, L. (1975). Dynamic overshoot in saccadic eye movements is caused by neurological control signal reversals. Experimental Neurolology, 48, 107-122.

Bahill, A., Iandolo, J., & Troost, T. (1980). Smooth pursuit eye movements in response to unpredictable target waveforms. Vision Research, 20, 923-931.

Bailliet, R., & Nakayama, K. (1978). Training of voluntary torsion. Investigative Ophthalmology, 17, 303-314.

Bartlett, N.R., Eason, R.G., & White, C.T. (1961). Latency of ocular fixation upon the second of two successive stimuli. Perceptual Motor Skills, 13, 259-268.

Bartz, A.E. (1962). Eye-movement latency, duration and response time as a function of angular displacement. Journal of Experimental Psychology, 64, 318-324.

Becker, W. (1972). The control of eye movements in the saccadic system. Bibliotheque Ophthalmologica, 82, 233-268.

Becker, W. & Fuchs, A. (1969). Further properties of the human saccadic system, eye movements and correction saccades with and without visual fixation points. Vision Research, 9, 1247-1258.

Becker, W. & Jurgens, R. (1979). An analysis of the saccadic system by means of double step stimuli. Vision Research, 19, 967-983.

Berlucchi, G., Heron, W., Hyman, R., Rizzolatti, G., & Umilta, C. (1971). Simple reaction times of ipsilateral and contralateral hand to lateralized visual stimuli. Brain, 94, 419-430.

Carlow, T., Dell'Osso, L.F., Troost, B.T., Daroff, R.B., & Birkett, J.E. (1975). Saccadic eye movement latencies to multimodal stimuli. Intersubject variability and temporal efficiency. Vision Research, 15, 1257-1262.

Dallos, P.J., Jones, R.W. (1963). Learning behavior of the eye fixation control system. IEEE Transactions on Automatic Control, AC-8, 218-227.

Dodge, R., & Cline,T.S. (1901). The angle velocity of eye movements. Psychological Review, 8, 145-157.

Findlay, J.M. (1982). Global visual processing for saccadic eye movements. Vision Research, 22, 1033-1045.

Frost, D., & Poppel, E. (1976). Different Programming modes of human saccadic eye movements as a function of stimulus eccentricy = indications of a functional subdivision of the visual field. Biological Cybernetics, 23, 39-48.

Gauthier, G.M., & Hofferer, J.M. (1976). Eye tracking of self-moved targets in the absence of vision. Experimental Brain Research, 16, 121-139.

Griffin, J.R. (1976). Theray for amblyopia. In Binocular Anomaies Procedures for Vision Therapy. pp. 195-232, Professional Press, Chicago, IL.

Grusser, O.J. (1980). Work with sigma-optokinetic movement. In Neurosciences Research Program Bulletin, 18, 549.

Hackman, R.B. (1940). An experimental study of variability in ocular latency. Journal of Experimental Psychology, 27, 548-558.

Hallett, P.E. (1978). Primary and secondary saccades to goals defined by instructions. Vision Research, 18, 1279-1296.

Hallett, P.E., & Adams, B.D. (1980). The predictability of saccadic latency in a novel voluntary oculomotor task. Vision Research, 20, 329-339.

Hallett, P.E., & Lightstone, A.D. (1976a). Saccadic eye movements toward stimuli triggered during prior saccades. Vision Research, 16, 88-106.

Hallett, P.E., & Lightstone, A.D. (1976b). Saccadic eye movements to flashed targets. Vision Research, 16, 1107-1114.

Hedlum, J.M., & White, C.T. (1959). Nystgmus induced by visual feedback. Journal of the Optical Society of America, 49, 729-730.

Heywood, S. & Churcher, J. (1971). Eye movements and the after-image, I: Tracking the after-image. Vision Research, 11, 1163-1168.

Heywood, S. & Churcher, J. (1972). Eye movements and the after-image, II: The effects of foveal an nonfoveal after-images on saccadic behavior. Vision Research, 12, 1033-0143.

Heywood, S., & Churcher, J. (1981). Saccades to step-ramp stimuli. Vision Research, 21, 479-490.

Hick, W.E. (1952). On the rate of gain of information. Quarterly Journal Experimental Psychology, 4, 11-26.

Kommerell, G., & Taumer, R. (1972). Investigations of the eye tracking system through stabilized retinal images. Bibliotheque Ophthalmologica, 82, 288-297.

Kinsbourne, M. (1972). Eye and head turning indicates cerebral lateralization. Science, 176, 539-541.

Levy-Schoen, A., & Blanc-Garin, J. (1974). On oculomotor programming and perception. Brain Research, 71, 443-450.

Lisberger, S.G., Fuchs, A.F., King, W.M., & Evinger, L.C. (1975). Effect of mean reaction time on saccadic response to two-step stimuli with horizontal and vertical components. Vision Research, 15, 1021-1025.

Lisberger, S.G., Evinger, L.C., Johanson, G.W., & Fuchs, A.F. (1981). Relationship between eye acceleration and retinal image velocity during foveal smooth pursuit in man and monkey. Journal of Neurophysiology, 46, 229-249.

Mountcastle, V.B. (1974) Medical Physiology. (13th ed.) St.Louis: C.V. Mosby Co.

Myers, .E., & Sperry, R.W. (1958). Interhemispheric Communication through the corpus callosum. Mnemonic carry-over between the hemispheres. Archives of Neurology and Psychiatry, 80, 298-303.

Peli, E., & Zeevi, Y.Y. (1979). Multiple visual feedback loops in eye movement control. XII Internaltional Conference on Medical and Biological Engineering, Jerusalem, Israel.

Pirozzolo, F.J., & Hansch, E.C. (1981). Oculomotor reaction time in dementia reflects degree of cerebral dysfunction. Science, 214, 349-351.

Pirozzolo, F.J., & Rayner, K. (1980). Handedness, hemispheric specialization and saccadic eye movement latencies. Neuropsychologia, 18, 225-229.

Rashbass, C. (1961). The relationship between saccadic and smooth tracking eye movements. Journal of Physiology, 159, 326-328.

Rayner, K. (1978). Eye movement latency for parafoveally presented words. Bulletin of the Psychonomic Society, 11, 13-16.

Rizzolatti, G., Umilta, C., & Berlucchi, G. (1971). Opposite superiorities of the right and left cerebral hemispheres in discriminative reaction time to physiognomical and alphabetical material. Brain, 94, 431-442.

Robinson, D. (1964). The mechanics of human saccadic eye movement. Journal of Physiology, 174, 245-264.

Robinson, D.A. (1965). The mechanics of human smooth pursuit eye movement. Journal of Phyisiology, 180, 569-591.

Robinson, D. (1973). Models of the saccadic eye movement control system. Kybernetik, 14, 71-83.

Saslow, M.G. (1967). Effects of components of displacement - step stimuli upon latency for saccadic eye movement. Journal Optical Society of America, 57, 1024-1029.

Sperry, R.W. (1974) Lateral specialization in the surgically separated hemispheres. In Schmitt, F.O. and Worden, F.G. (eds.) The Neurosciences Third Study Program. Cambridge, MA: MIT Press.

Stark, L. , Vossius, G., & Young, L.R. (1962). Predictive control of eye tracking movements. IRE Transactions on Human Factors in Electronics, HFE-3, 52-57.

Steinbach, M.J., & Pearce, D.G. (1972). Release of pursuit eye movements using after-images. Vision Research, 12, 1307-1311.

Steinman, R.M., Skavenski, A.A., & Sansbury, R.V. (1969). Voluntary control of smooth pursuit velocity. Vision Research, 9, 1167-1171.

Taumer, R. (1975). Three reaction mechanisms of the saccadic system in response to a double jump. In Lennerstrand, G. and Bach-y-Rita, P. (eds.) Basic Mechanisms of Ocular Motility and their Clinical Implications. Oxford: Pergamon Press.

Uden, P.O., personal communication, 1982.

Uemura, T., Arai, Y., & Shimayaki, C. (1980). Eye-head coordination during lateral gaze in normal subjects. Acta Otolaryngolica, 90, 191-198.

Ueno, T. (1977). Reaction time as a measure of temporal summation at suprathreshold levels. Vision Research, 17, 227-232.

Vossius, G. (1960). Das system der Augenbewegung. Zeitschrift fur Biologie, 112, 27-57.

Welford, A.T. (1968) Fundamentals of Skill. London:Methuen and Co. Ltd.

Westheimer, G. (1954). Eye movement responses to horizontal moving visual stimulus. Archives of Ophthalmology, N.Y. 52, 932-941.

Wheeless, L.L. Jr., Boynton, R.M., & Cohen, G.H. (1966). Eye movement responses to step and pulse-step stimuli. Journal of the Optical Society of America, 56, 956-960.

White, C.T., Eason, R.G., & Bartlett, N.R. (1962). Latency and duration of eye movement in the horizontal plane. Journal of the Optical Society of America, 52, 210-213.

Wyatt, H.J., & Pola, J. (1981). Slow eye movements to eccentric targets. Investigative Ophthalmological Visual Science, 21, 477-483.

Yasui, S., & Young, L.R. (1975). Perceived motion as an effective stimulus to pursuit eye movement system. Science, 190, 906-908.

Young, L.R. (1962). A sampled data model for eye tracking *movements.* ScD. Dissertation, MIT Cambridge, MA.

Young, L.R. (1981). The sampled data model for foveal dead zone for saccades. In: B.L. Zuber (ed.) *Models of Oculomotor Behavior and Control.* Boca Raton, FL: CRC Press, Inc.

Young, L.R. & Stark, L. (1963). Variable feedback experiments testing a sampled data model for eye tracking movements. *IEEE Transactions on Human Factors in Electronics, HFE-4,* 381-451.

Young, L.R. (1977). Pursuit eye movement - what is being pursued? In Baker & Berthoz (eds.), *Control of Gaze by Brain Stem Neurons, Developments in Neuroscience,* (Vol. I, pp. 29-36), Amsterdam: Elsevier North Holland Biomedical Press.

Zeevi, Y.Y., & Peli, E. (1984). Smooth eye-movement control with secondry visual feedback. *Journal of the Optical Society of America,* in press.

Zeevi, Y.Y., & Peli, E. (1979). Latency of peripheral saccade. *Journal of the Optical Society of America, 69,* 1274-1279.

Zeevi, Y.Y., Peli, E., & Stark, L. (1979). Study of eccentric fixation with secondary visual feedback. *Journal of the Optical Society of America, 69,* 669-675.

Zeevi, Y.Y., Peli, E., & Wetzel, P. (1981). Visual information processing during tracking of the point of gaze. *Journal of the Optical Society of America, 71,* 1555.

Zuber, B.L., & Wetzel, P.A. (1981). Eye movement determinants of reading rate. In *Models of Oculomotor Behavior and Control.* Boca Raton, FL: CRC Press, Inc.

Task	Direction	Subject / parameter	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)
		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)
		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)
		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)
		Intersaccadic velocity	6.0 ± 2.3 (20)	0.3 ± 0.2 (20)	0.3 ± 0.2 (15)

TABLE I: Number of saccadic interruptions and intersaccadic velocity in smooth movement task. Data pooled from experiments with 3 and 40 Hz low-pass filtered 2 VFB. Mean ± SD (number of segments)

Table 2. Summary of narrow field display response data

SINGLE TARGET RESPONSE										BIFURCATION RESPONSE							
SUBJECT	HANDEDNESS	LEFT		RIGHT		DIFFERENCE		COMPUTED t	LEVEL OF ATTAINED SIGNIFICANCE	MEAN ± SD	DIFFERENCE	COMPUTED t	LEVEL OF SIGNIFICANCE	PERCENT INCREASE OVER SINGLE TARGET RESPONSE	RESPONSES LEFT	RESPONSES RIGHT	% PREFERRED RESPONSE
1	R	305	N - 23 ± 38	273	N - 18 ± 83	32	NS	1.645	0.1433	545 ± 299	255	4.104	0.0004	87	11	13	54
2	R	233	N - 27 ± 38	226	N - 26 ± 42	7	NS	0.636	0.5276	330 ± 39	101	10.898	0.0000	44	22	6	79
3	R	242	N - 22 ± 57	226	N - 26 ± 29	16	NS	1.1607	0.2549	299 ± 52	65	4.865	0.0000	28	18	2	90
4	L	244	N - 26 ± 34	218	N - 25 ± 26	26	SIG	3.0760	0.0035	343 ± 66	112	3.079	0.0035	49	16	11	59
5	R	320	N - 25 ± 50	295	N - 26 ± 78	25	NS	1.3420	0.1866	400 ± 106	93	4.160	0.0002	30	5	22	81
6	R	323	N - 27 ± 19	267	N - 26 ± 38	56	NS	1.4491	0.1430	405 ± 202	111	2.509	0.0166	37	18	8	69
7	R	245	N - 26 ± 42	226	N - 27 ± 30	18	NS	1.8020	0.0781	322 ± 51	87	7.897	0.0000	37	2	26	93
8	R	304	N - 28 ± 76	261	N - 26 ± 41	43	SIG	2.6399	0.1160	455 ± 215	172	2.639	0.0117	61	6	25	81
9	R	230	N - 27 ± 66	218	N - 30 ± 77	12	NS	0.6453	0.5214	302 ± 130	159	6.220	0.0000	71	0	29	100
10	R	233	N - 30 ± 34	206	N - 29 ± 41	27	SIG	2.7574	0.0079	304 ± 46	84	2.760	0.0079	38	1	29	97
SAMPLE POPULATION		267	N - 251 ± 85	240	N - 257 ± 58	27	SIG	4.2605	0.0000	379 ± 160	125	12.09	0.0000	49	99	171	80

ALL RESPONSE TIMES ARE GIVEN IN MILLISECONDS

Table 3 Narrow field display left-right response difference

NUMBER OF SUBJECT	DIRECTION	RESPONSE MEAN ± S.D.	LEFT-RIGHT DIFFERENCE	t	p	DIFF. SIG/NS
10	LEFT RIGHT	$x = 267 \pm 85$ ms N = 261 $\bar{x} = 240 \pm 58$ ms N = 257	27 ms	4,[illegible]603	0,000	SIG
7	LEFT RIGHT	$\bar{x} = 271 \pm 95$ ms N = 177 $\bar{x} = 245 \pm 63$ ms N = 177	26 ms	2,9283	0,004	SIG
3	LEFT RIGHT	$\bar{x} = 260 \pm 60$ ms N = 84 $\bar{x} = 228 \pm 44$ ms N = 80	32 ms	3,9853	0.000	SIG

REJECT THE HYPOTHESIS THAT $\bar{x}_L = \bar{x}_R$ if $p < 0.05$ OTHERWISE

ACCEPT THE HYPOTHESIS THAT $\bar{x}_L \neq \bar{x}_R$

Table 4. Wide field display response data

SINGLE TARGET RESPONSE								BIFURCATION RESPONSE							
SUBJECT	HANDEDNESS	LEFT	RIGHT	DIFFERENCE		COMPUTED t	LEVEL OF ATTAINED SIGNIFICANCE	MEAN±SD	DIFFERENCE	COMPUTED t	LEVEL OF SIGNIFICANCE	ENT INCREASE ER SINGLE T RESPONSE	RESPONSES LEFT	RESPONSES RIGHT	% PREFERRED RESPONSE
11 GC	R	N = 105 227 ± 33	N = 105 239 ± 35	12	SIG	2.[illegible]410	0.0088	281 ± 41	48	3.999	0.0021	21	10	2	82
12 IM	R	N = 108 201 ± 34	N = 105 205 ± [illegible]	4	NS	0.8972	0.3706	227 ± 96	25	0.898	0.3884	12	11	1	92
13 BL	R	N = 99 193 ± 26	N = 98 183 ± 36	10	SIG	2.2937	0.0231	220 ± 36	32	2.735	0.0194	17	9	2	82
14 MB	F	N = 9[illegible] 224 ± 31	N = 100 233 ± 32	9	SIG	2.0195	0.0448	271 ± 66	43	2.115	0.0581	17	2	9	82
15 JM	R	N = 98 198 ± 48	N = 100 216 ± 42	19	SIG	2.9044	0.0041	251 ± 49	44	3.008	0.0109	21	12	0	100
SAMPLE POPULATION		N = 507 206 ± 38	N = 507 215 ± 41	7	SIG	2.8730	0.0042	250 ± 51	39	5.594	0.0000	18	44	14	88

ALL RESPONSE TIMES ARE GIVEN IN MILLISECONDS

Table 5. Response to delayed bifurcating targets

SUBJECT (BL): PREFERRED RESPONSE DIRECTION - LEFT

TARGET DISPLACEMENT: LEFT AND/OR RIGHT: 5 , 10 AND 15 DEGREES

DELAY TIMES BETWEEN TARGETS: 0, 30, 60 AND 120 MSEC

LEADING TARGET DIRECTION AND DELAY			PREFERRED RESPONSE
R 30 ms	N = 28	$\bar{x}$ = 233 ± 31 ms	86 % LEFT
R 60 ms	N = 21	$\bar{x}$ = 240 ± 55 ms	48 % LEFT
R 120 ms	N = 23	$\bar{x}$ = 196 ± 37 ms	13 % LEFT
L 30 ms	N = 25	$\bar{x}$ = 211 ± 37 ms	100 % LEFT
L 60 ms	N = 29	$\bar{x}$ = 187 ± 35 ms	97 % LEFT
L 120 ms	N = 25	$\bar{x}$ = 184 ± 29 ms	100 % LEFT
0 ms	N = 21	$\bar{x}$ = 216 ± 25 ms	95 % LEFT
SINGLE TARGET			
	N = 16	$\bar{x}$ = 182 ± 37 ms	-

Table 6 Unidirectional bifurcating stimuli -- percent response to delayed inner target

DELAY	STIMULUS FIELD	SUBJECTS				TOTALS	% RESPONSE TO INNER TARGET	COMBINED % RESPONSE TO INNER TARGET
		1	2	3	4			
10 ms	LEFT	5/5	6/6	6/6	5/5	22/22	100	100
	RIGHT	5/5	6/6	5/5	5/5	21/21	100	
20	LEFT	4/5	5/5	6/6	4/4	19/20	95	95
	RIGHT	3/4	5/5	5/5	4/4	17/18	94	
40	LEFT	1/5	5/5	5/5	5/5	16/20	80	82
	RIGHT	2/6	7/7	7/7	5/5	21/25	84	
60	LEFT	1/6	6/6	6/6	5/6	19/24	78	83
	RIGHT	3/5	6/6	5/6	5/5	19/22	86	
80	LEFT	2/6	5/5	2/5	5/5	14/21	67	70
	RIGHT	1/6	5/5	5/6	6/6	17/23	74	
100	LEFT	0/6	7/7	3/6	5/6	15/25	60	53
	RIGHT	0/4	3/5	3/6	3/5	9/20	45	
120	LEFT	0/5	5/5	1/6	5/6	11/22	50	37
	RIGHT	0/5	1/6	0/4	4/6	5/21	24	
140	LEFT	0/5	2/6	0/5	2/5	4/21	19	20
	RIGHT	0/6	1/6	1/6	3/5	5/23	22	
160	LEFT	0/6	4/6	0/6	2/6	6/24	24	12
	RIGHT	0/7	1/7	0/6	1/6	2/26	8	
200	LEFT	0/5	2/6	0/6	0/6	2/23	9	10
	RIGHT	0/4	1/6	0/5	1/4	2/19	11	
0		15/19	17/17	20/20	20/20	72/78	95	

DELAY: OUTER TARGET LEADS . INNER TARGET BY THE INDICATED AMOUNT THE INNER TARGET IS THE PREFERRED TARGET.

Table 7 Change in response time as a function of inner target delay

LEFT RIGHT DELAYS	COMBINED MEAN ± S.D.	COMBINED MEAN SINGLE TARGET DIFFERENCE	t	ρ	ACCEPT AT 0.05 LEVEL
0 ms	$N = 76, \bar{x} = 201 \pm 32$ ms	-5.3 ms	1.2910	0.1993	N.S.
10	$N = 44, \bar{x} = 208 \pm 25$	1.7	0.4093	0.6837	N.S.
20	$N = 39, \bar{x} = 216 \pm 30$	10.2	2.0032	0.0507	N.S.
40	$N = 45, \bar{x} = 206 \pm 30$	-0.4	0.0921	0.9269	N.S.
60	$N = 46, \bar{x} = 219 \pm 35$	12.5	2.2747	0.0268	SIG
80	$N = 44, \bar{x} = 222 \pm 41$	16.0	2.5033	0.0155	SIG
100	$N = 45, \bar{x} = 226 \pm 42$	19.8	3.0595	0.0035	SIG
120	$N = 43, \bar{x} = 229 \pm 7$	22.4	10.6377	0.0000	SIG
140	$N = 44, \bar{x} = 218 \pm 39$	11.7	1.8892	0.0646	N.S.
160	$N = 50, \bar{x} = 208 \pm 37$	1.6	0.2805	0.7800	N.S.
200	$N = 42, \bar{x} = 228 \pm 48$	4.4	0.8726	0.3877	N.S.
SINGLE TARGET $N = 302, \bar{x} = 206 \pm 31$					

FOUR SUBJECTS

Table 8 Comparison of response latency times for random appearance and consecutive presentation of bifurcating targets

SUBJECT	TYPE OF BIFURCATION PRESENTATION	DISPLAY TYPE	RESPONSE MEAN ± S.D.
MB	RANDOM	NFD	N = 27, $\bar{x}$ = 281 ± 43 ms
	CONSECUTIVE	NFD	N = 19, $\bar{x}$ = 284 ± 51 ms
	3 ms DIFFERENCE	t = 0.209, p = 0.8357, N.S.	
	RANDOM	WFD	N = 23, $\bar{x}$ = 264 ± 28 ms
	CONSECUTIVE	WFD	N = 20, $\bar{x}$ = 269 ± 50 ms
	5 ms DIFFERENCE,	t = 0.390, p = 0.6994, N.S.	
BL	RANDOM	NFD	N = 53, $\bar{x}$ = 232 ± 35 ms
	CONSECUTIVE	NFD	N = 19, $\bar{x}$ = 240 ± 43 ms
	8 ms DIFFERENCE,	t = 0.729, p = 0.4723, N.S.	
	RANDOM	WFD	N = 27, $\bar{x}$ = 226 ± 32 ms
	CONSECUTIVE	WFD	N = 19, $\bar{x}$ = 240 ± 43 ms
	22 ms DIFFERENCE,	t = 1.261, p = 0.2194, N.S.	
JM	RANDOM	NFD	N = 26, $\bar{x}$ = 307 ± 45 ms
	CONSECUTIVE	NFD	N = 18, $\bar{x}$ = 284 ± 83 ms
	23 ms DIFFERENCE,	t = 1,072, p = 0.2944, N.S.	
	RANDOM	WFD	N = 27, $\bar{x}$ = 274 ± 55 ms
	CONSECUTIVE	WFD	N = 16, $\bar{x}$ = 291 ± 78 ms
	17 ms DIFFERENCE,	t = 0.766, p = 0.4511, N.S.	

REJECT THE HYPOTHESIS $\bar{x}_N = \bar{x}_C$ IF $p < 0.05$, otherwise
ACCEPT THE HYPOTHESIS $\bar{x}_N \neq \bar{x}_C$

NFD: DISCRETE NFD

Table 9. Comparison of new narrow field and wide field display response data

SUBJECT	TYPE OF STIMULUS	DISPLAY TYPE	RESPONSE MEAN ± S.D.
MB	SINGLE TARGET	NFD	N = 50, $\bar{x}$ = 214 ± 28 ms
	BIFURCATION	NFD	N = 27, $\bar{x}$ = 281 ± 43
	67 ms DIFFERENCE	t = 7.303, p = 0.000, SIG	
	SINGLE TARGET	WFD	N = 37, $\bar{x}$ = 222 ± 27
	BIFURCATION	WFD	N = 23, $\bar{x}$ = 264 ± 28
	42 ms DIFFERENCE	t = 5.727, p = 0.000, SIG	
	SINGLE TARGET	NFD	
	SINGLE TARGET	WFD	
	8 ms DIFFERENCE	t = 1.345, p = 0.1825, N.S.	
	BIFURCATION	NFD	
	BIFURCATION	WFD	
	17 ms DIFFERENCE	t = 1.679, p = 0.1001, N.S.	
BL	SINGLE TARGET	NFD	N = 98, $\bar{x}$ = 180 ± 34
	BIFURCATION	NFD	N = 53, $\bar{x}$ = 232 ± 35
	52 ms DIFFERENCE	t = 8.801, p = 0.000, SIG	
	SINGLE TARGET	WFD	N = 50, $\bar{x}$ = 189 ± 29
	BIFURCATION	WFD	N = 27, $\bar{x}$ = 226 ± 32
	37 ms DIFFERENCE	t = 5.000, p = 0.000, SIG	
	SINGLE TARGET	NFD	
	SINGLE TARGET	WFD	
	9 ms DIFFERENCE	t = 1.682, p = 0.0953, N.S.	
	BIFURCATION	NFD	
	BIFURCATION	WFD	
	6 ms DIFFERENCE	t = 0.768, p = 0.4457, N.S.	

Table 10: Bifurcation Response Latency Summary

Stimulus Conditions	Mean / Std. Dev.	Observations	Significance
Single target			
STEP (saccadic)	214.6 ±35	31	----
RAMP (smooth)	95.2 ±36	95	----
(saccadic)	254.2 ±41	62	----
Bifurcation			
STEP (saccadic)	295.9 ±85	27	0.001
RAMP (smooth)	176.4 ±69	78	none
(saccadic)	358.1 ±43	47	0.001

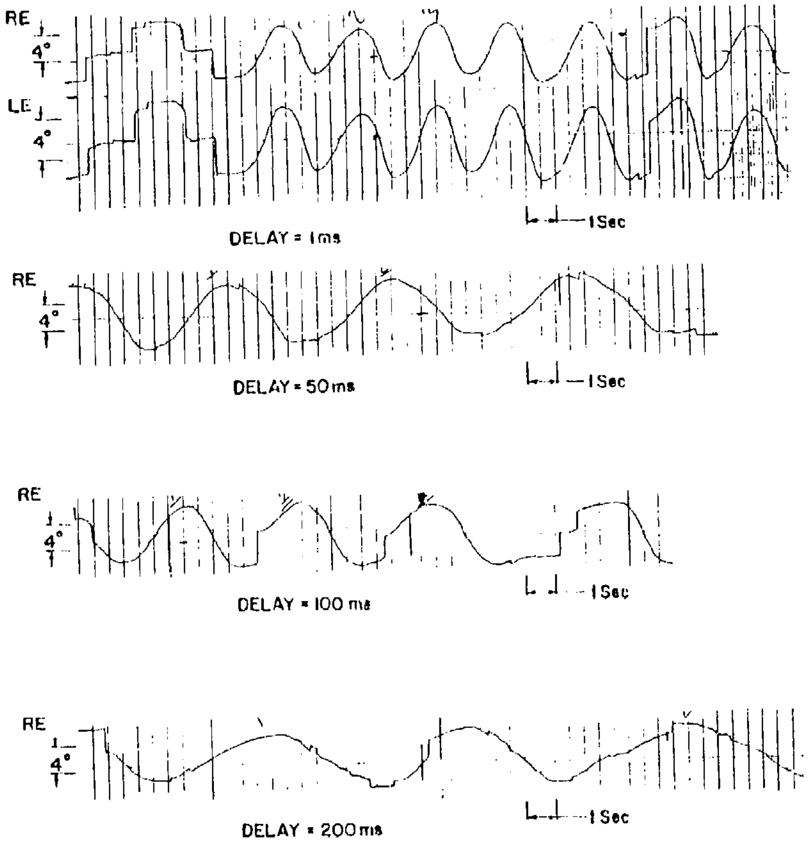

RE
4°
LE
4°
1 Sec
DELAY = 1ms
RE
4°
DELAY = 50ms
1 Sec
RE
4°
DELAY = 100 ms
1 Sec
RE
4°
DELAY = 200ms
1 Sec

Figure 1a

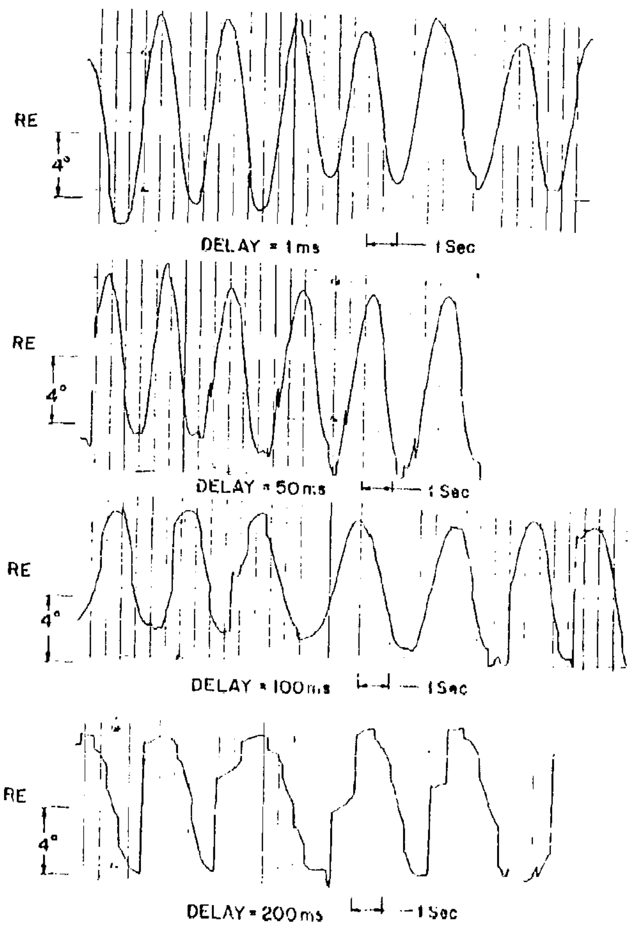

RE
4°
DELAY = 1 ms
1 Sec
RE
4°
DELAY = 50 ms
1 Sec
RE
4°
DELAY = 100 ms
1 Sec
RE
4°
DELAY = 200 ms
1 Sec

Figure 1b

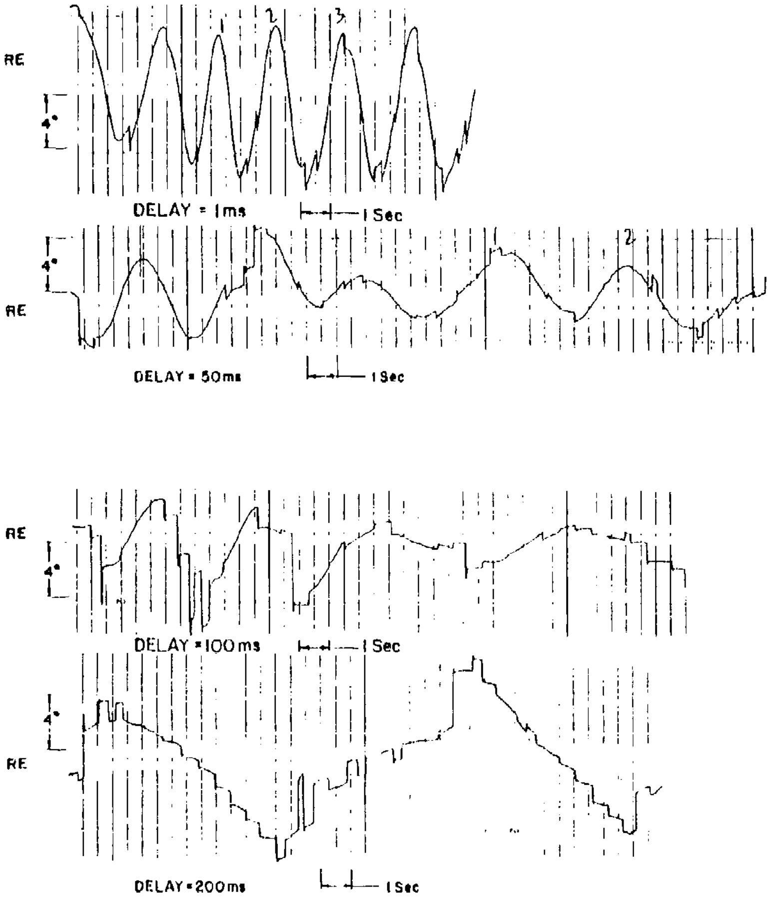

RE
4°
1
2
3
DELAY = 1ms
1 Sec
4°
RE
2
DELAY = 50ms
1 Sec
RE
4°
DELAY = 100ms
1 Sec
4°
RE
DELAY = 200ms
1 Sec

Figure 1c

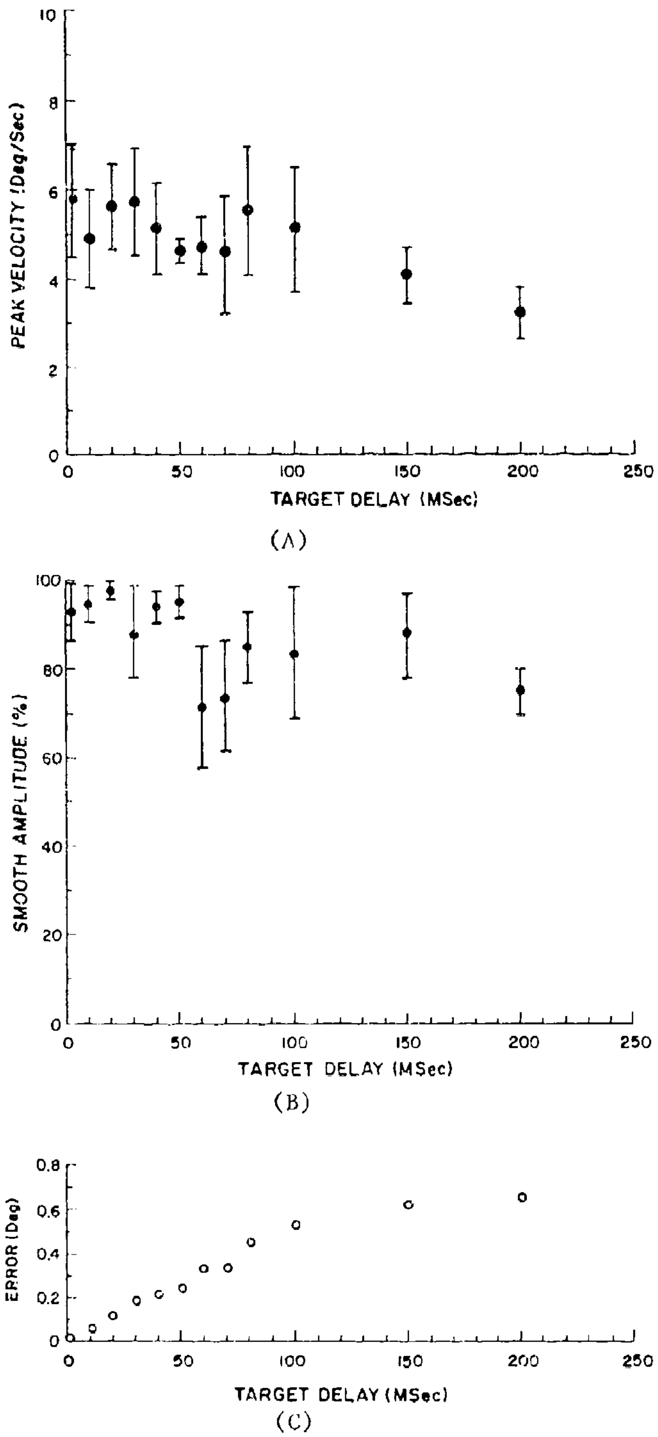
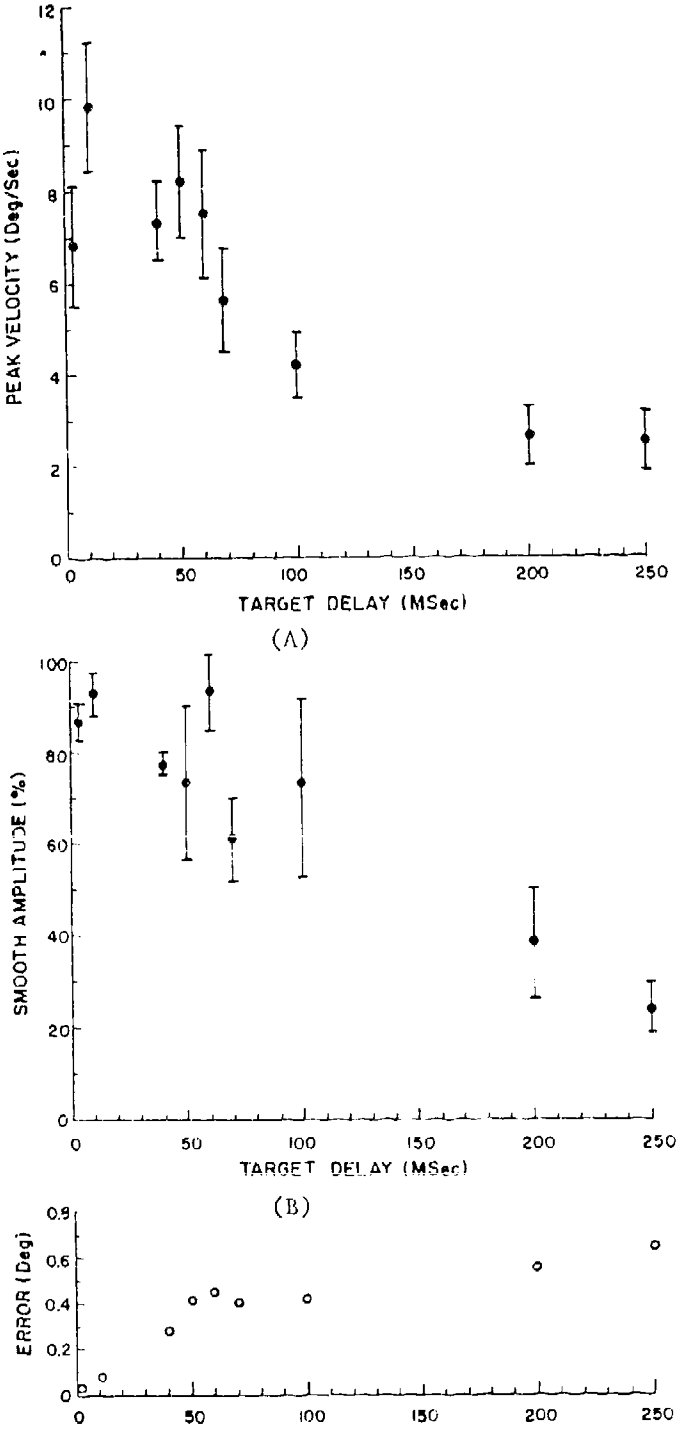
PEAK VELOCITY (Deg/Sec)
10
8
6
4
2
0
0
50
100
150
200
250
TARGET DELAY (MSec)
(A)
SMOOTH AMPLITUDE (%)
100
80
60
40
20
0
0
50
100
150
200
250
TARGET DELAY (MSec)
(B)
ERROR (Deg)
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
TARGET DELAY (MSec)
(C)

Figure 2

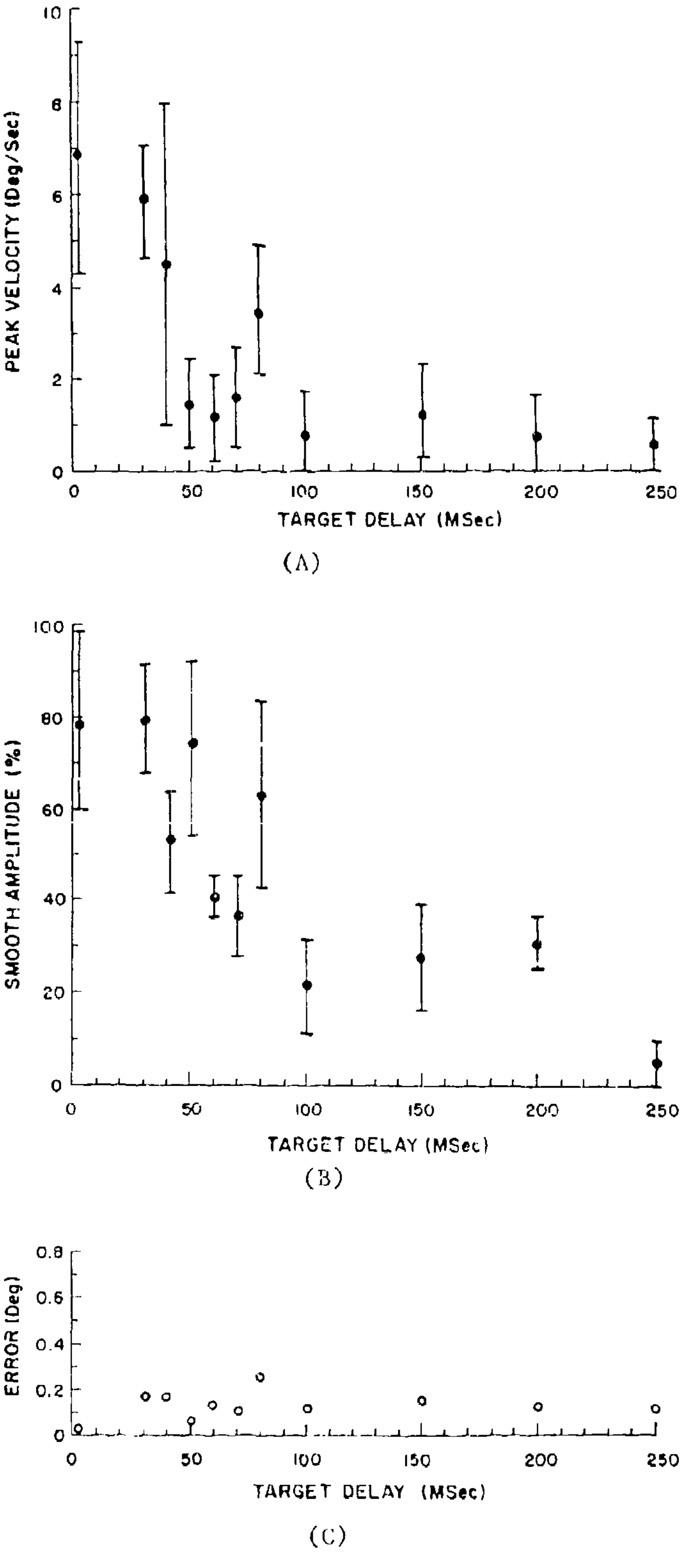

PEAK VELOCITY (Deg/Sec)
12
10
8
6
4
2
0
0
50
100
150
200
250
TARGET DELAY (MSec)
SMOOTH AMPLITUDE (%)
100
80
60
40
20
0
0
50
100
150
200
250
TARGET DELAY (MSec)
ERROR (Deg)
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
TARGET DELAY (MSec)

(A)

(B)

(C)

Figure 3


10
8
6
4
2
0
PEAK VELOCITY (Deg/Sec)
0
50
100
150
200
250
TARGET DELAY (MSec)
100
80
60
40
20
0
SMOOTH AMPLITUDE (%)
0
50
100
150
200
250
TARGET DELAY (MSec)
0.8
0.6
0.4
0.2
0
ERROR (Deg)
0
50
100
150
200
250
TARGET DELAY (MSec)

(A)

(B)

(C)

Figure 4

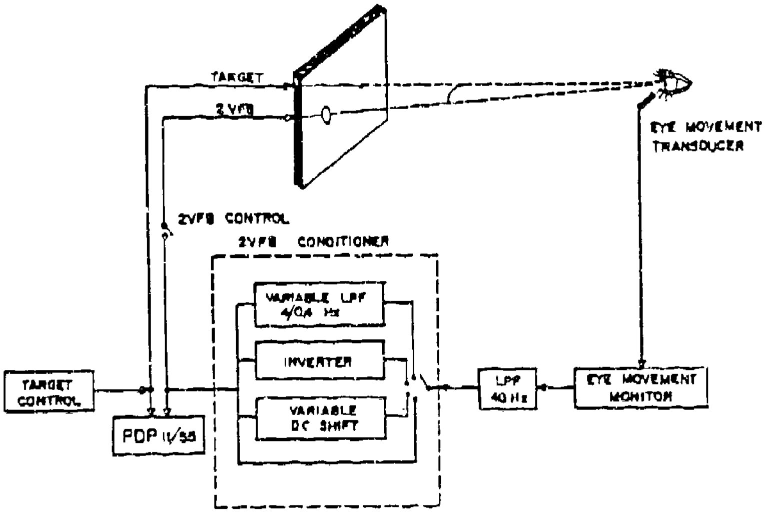

TARGET
2 VFB
EYE MOVEMENT
TRANSDUCER
2VFB CONTROL
2VFB CONDITIONER
VARIABLE LPF
4/0.4 Hz
INVERTER
VARIABLE
DC SHIFT
TARGET
CONTROL
PDP 11/55
LPF
40 Hz
EYE MOVEMENT
MONITOR

Figure 5

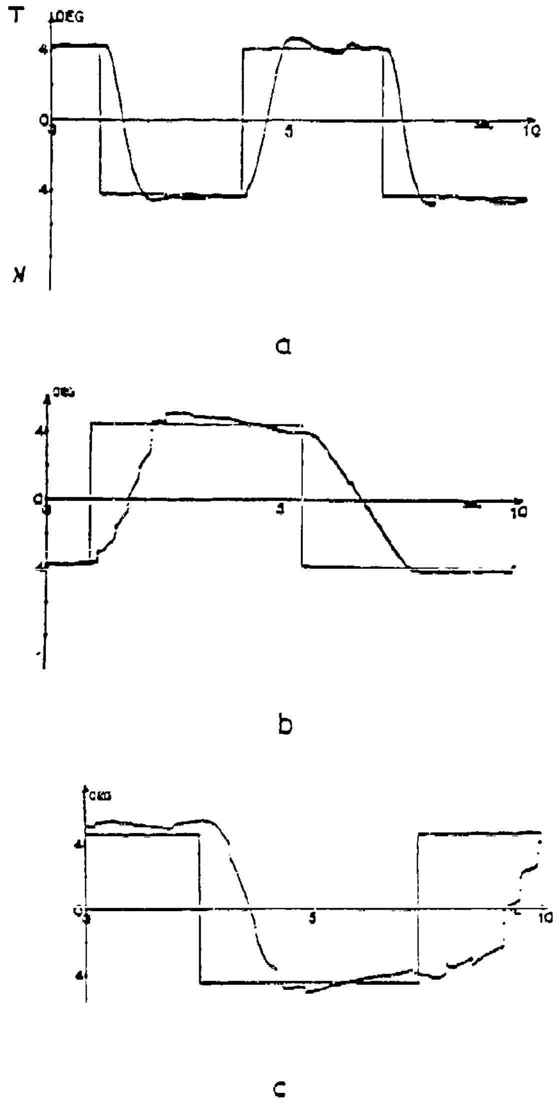


Figure 6

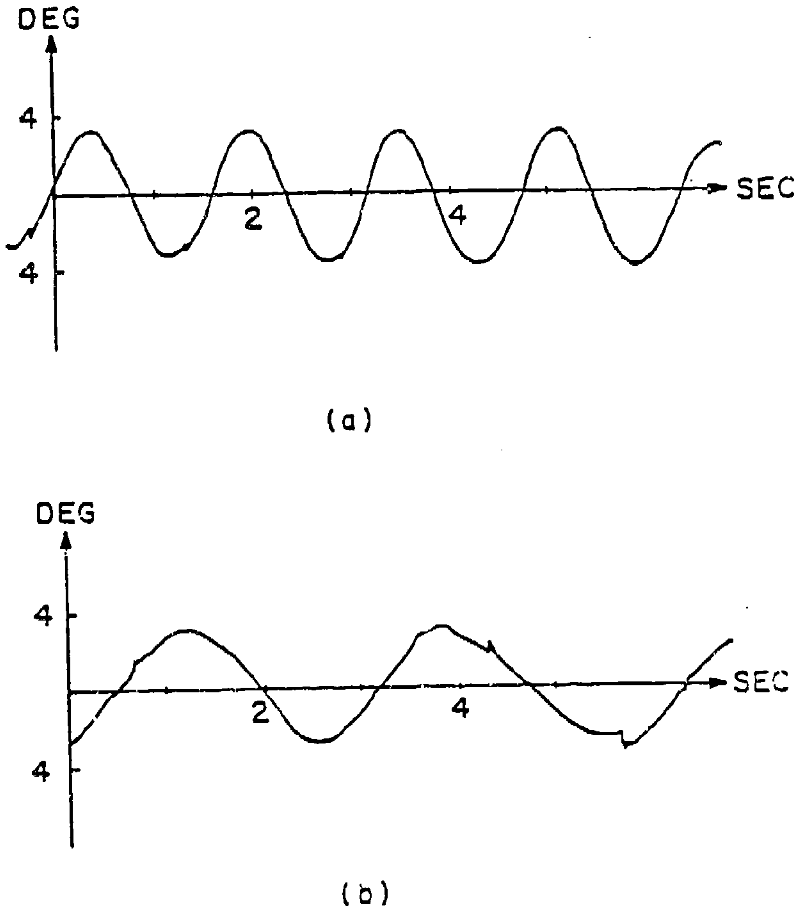


Figure 7

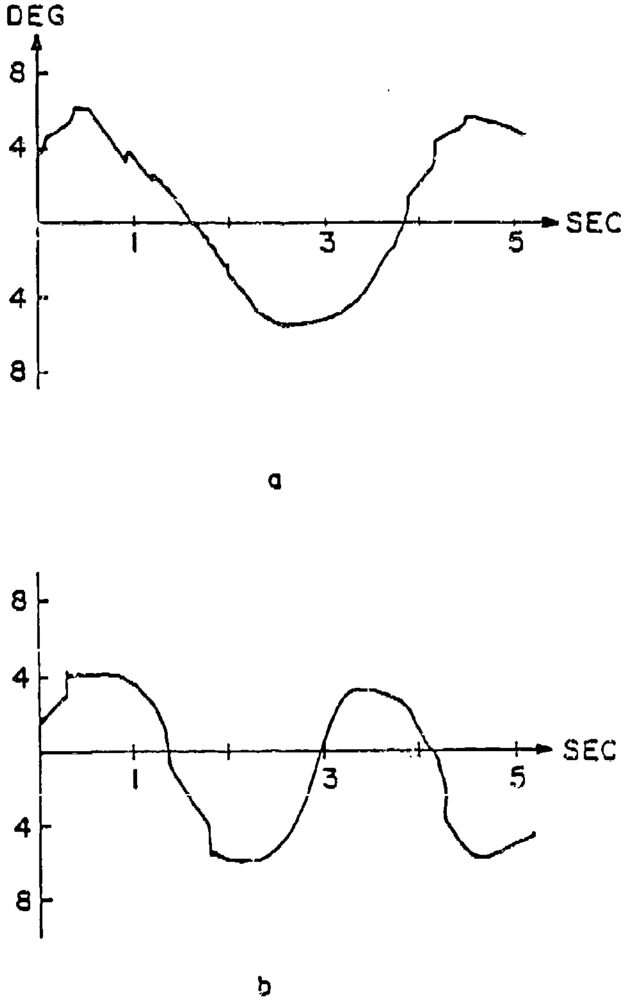
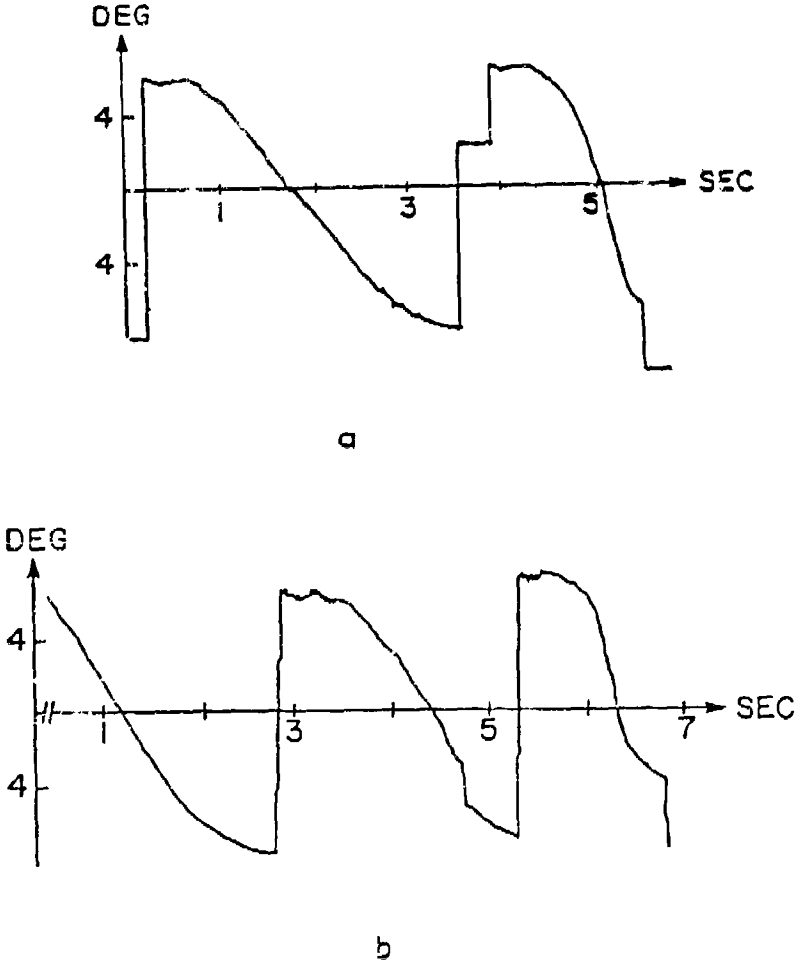


Figure 8



a

b

Figure 9

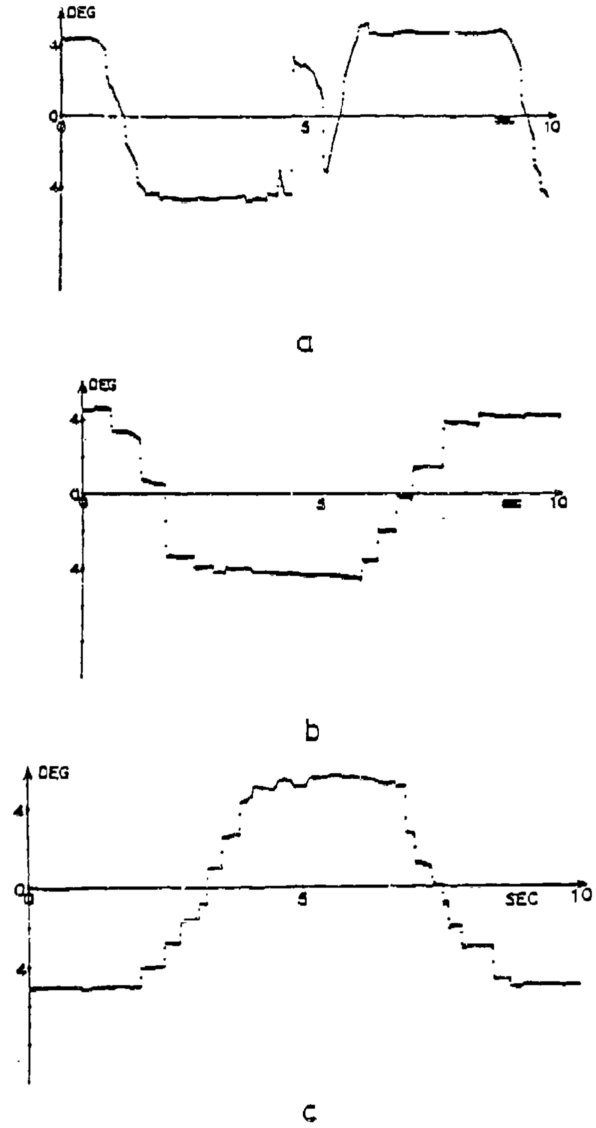


Figure 10

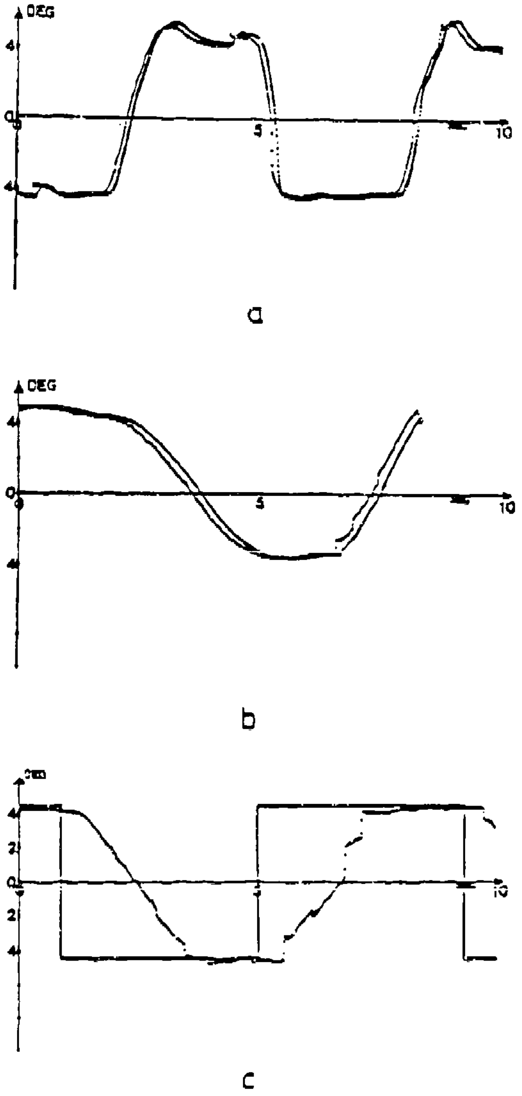


Figure 11

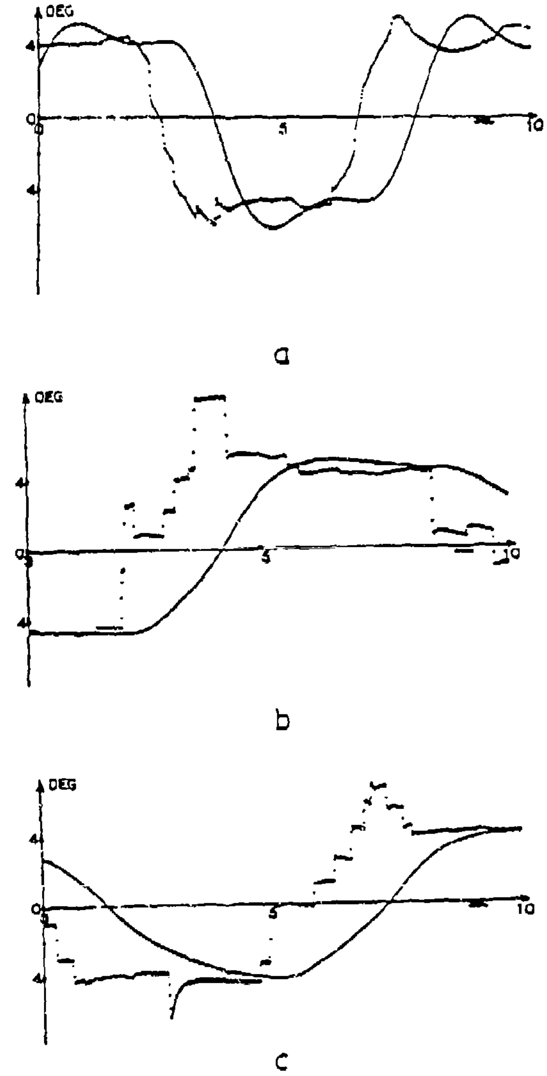


Figure 12

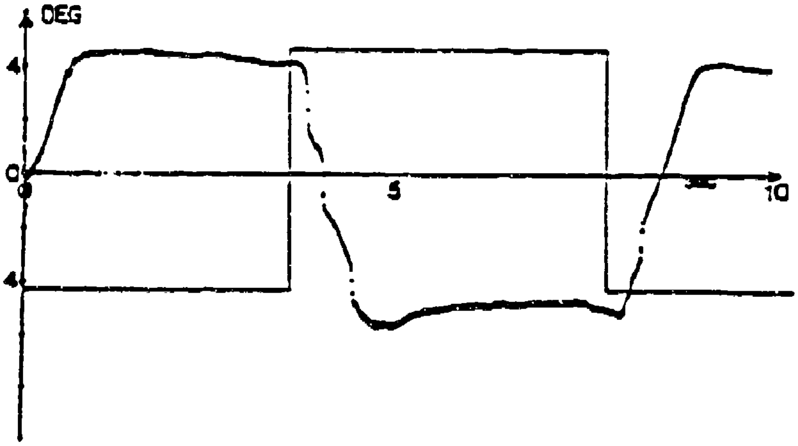


Figure 13

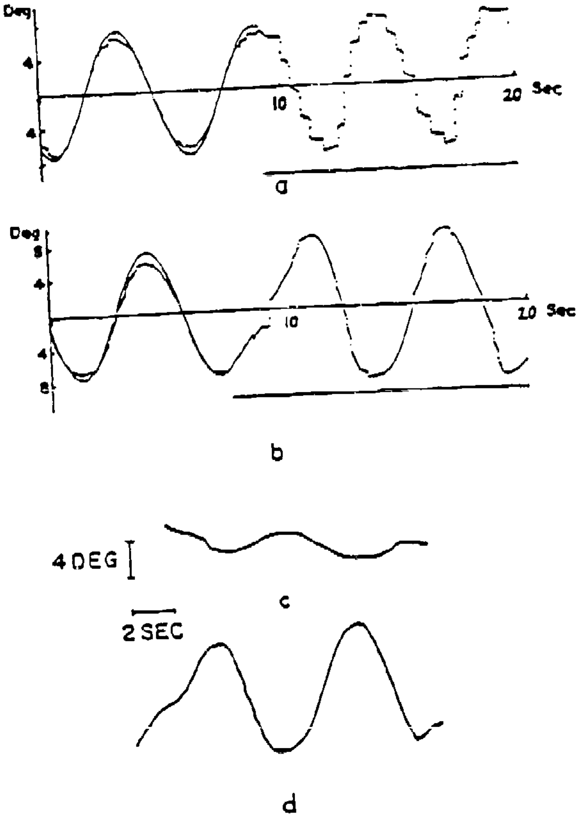


Figure 14

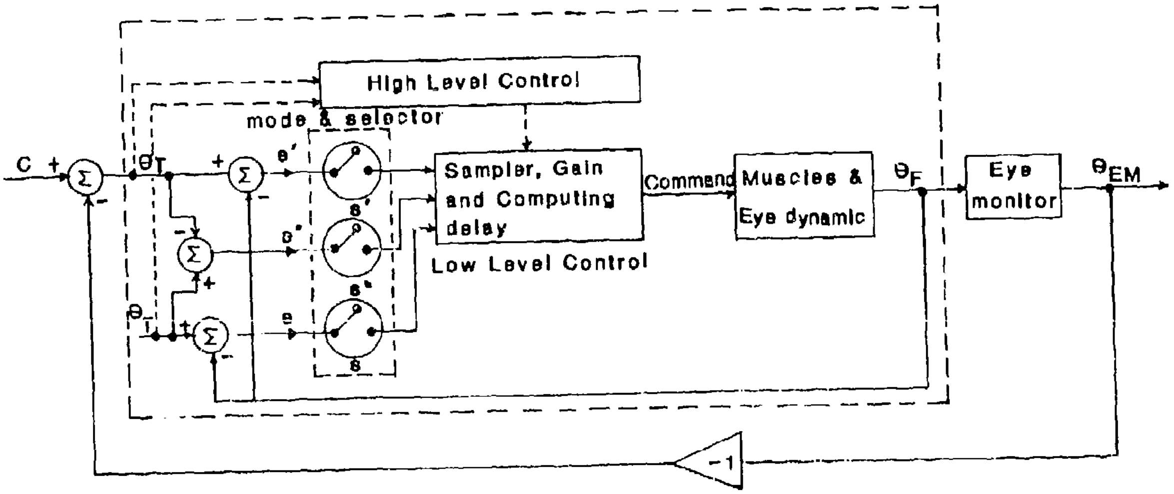

High Level Control
mode & selector
C
+
-
Σ
θT
+
-
e'
s'
-
+
e''
s''
θI
+
-
e
s
Sampler, Gain and Computing delay
Low Level Control
Command
Muscles & Eye dynamic
θF
Eye monitor
θEM
-1

Figure 15

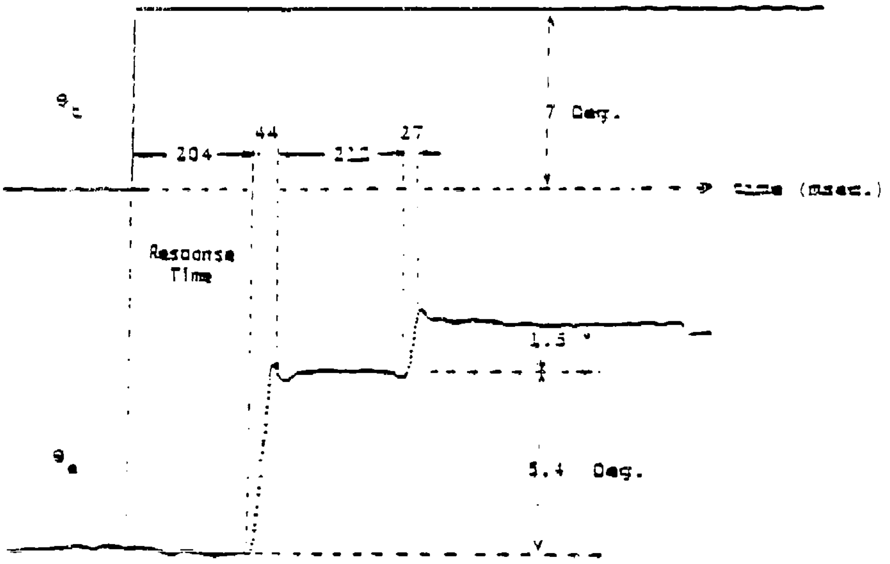


Figure 16

STEP TARGET DISPLACEMENT AND SACCADIC EYE MOVEMENT RESPONSE

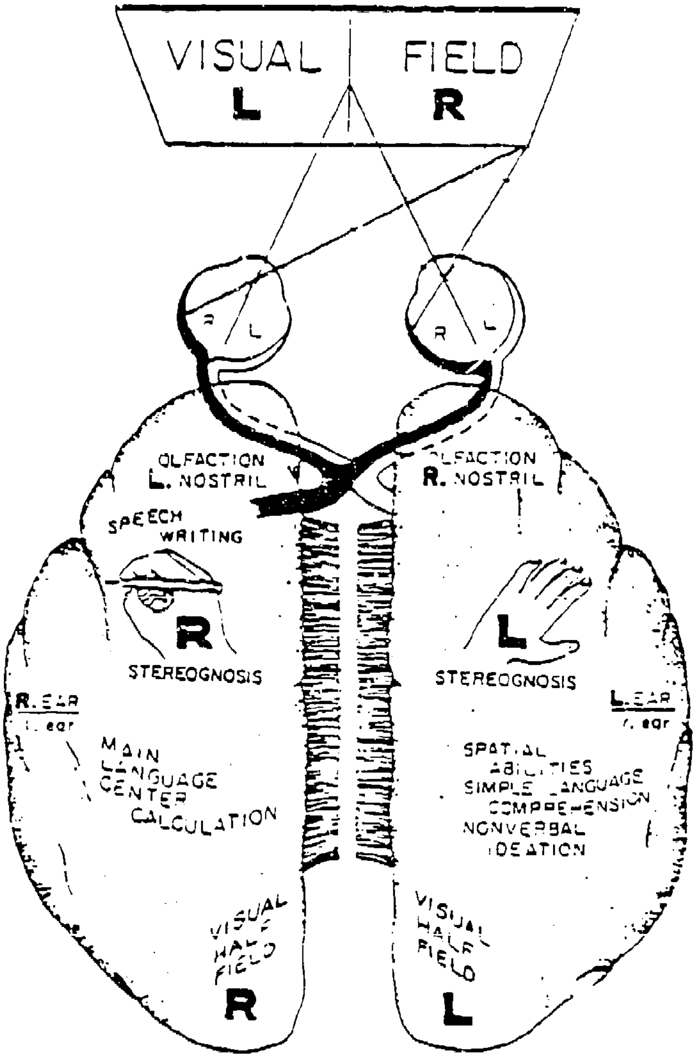

VISUAL
FIELD
L
R
R
L
R
L
OLFACTION
L. NOSTRIL
OLFACTION
R. NOSTRIL
SPEECH
WRITING
R
STEREOGNOSIS
L
STEREOGNOSIS
R. EAR
l. ear
L. EAR
r. ear
MAIN
LANGUAGE
CENTER
CALCULATION
SPATIAL
ABILITIES
SIMPLE LANGUAGE
COMPREHENSION
NONVERBAL
IDEATION
VISUAL
HALF
FIELD
R
VISUAL
HALF
FIELD
L

Figure 17

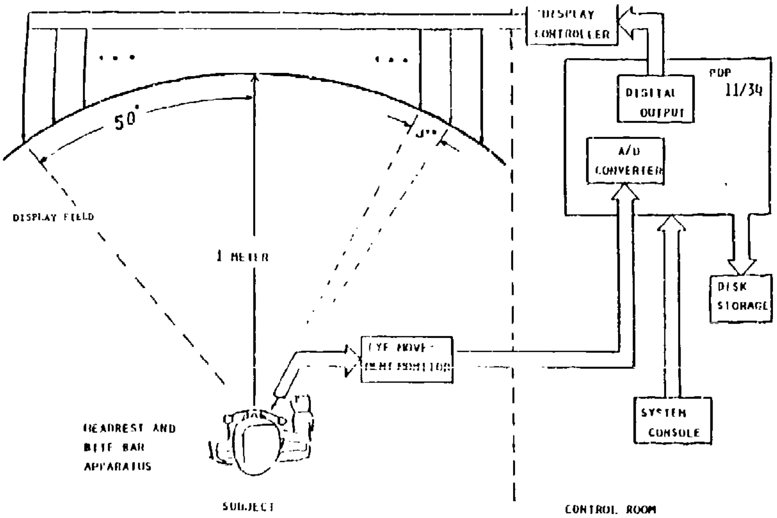


DIAGRAM OF THE EXPERIMENTAL SETUP

Figure 18

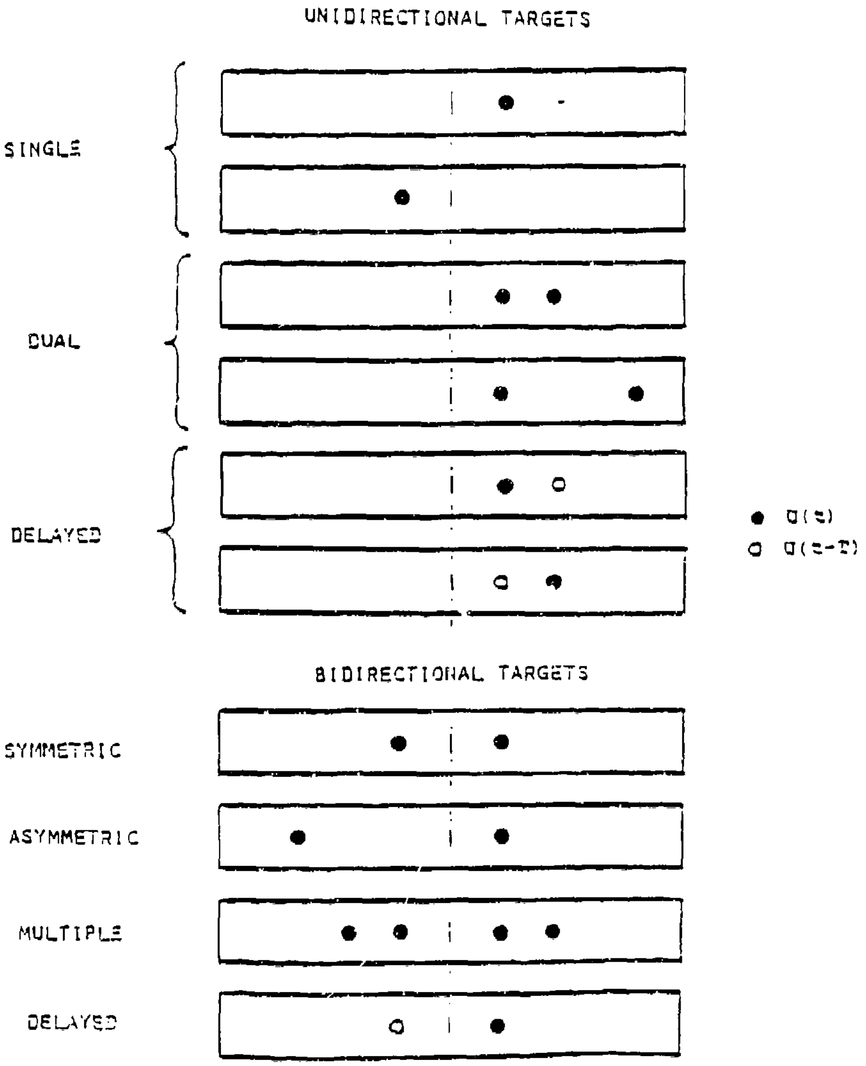

UNIDIRECTIONAL TARGETS
SINGLE
DUAL
DELAYED
● U(t)
○ U(t-T)
BIDIRECTIONAL TARGETS
SYMMETRIC
ASYMMETRIC
MULTIPLE
DELAYED

Figure 19

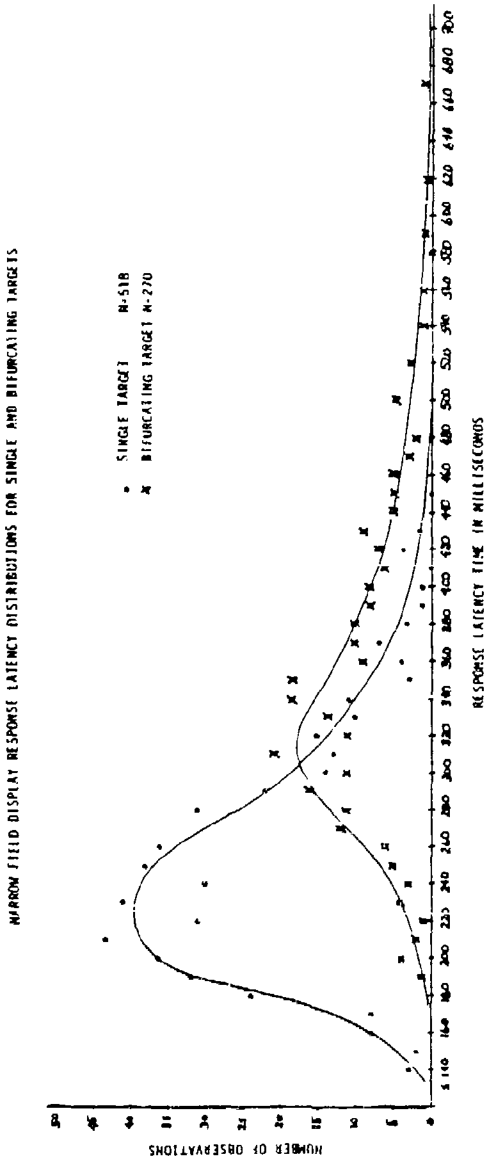
 NARROW FIELD DISPLAY RESPONSE LATENCY DISTRIBUTIONS FOR SINGLE AND BIFURCATING TARGETS
• SINGLE TARGET N=518
x BIFURCATING TARGET N=270
NUMBER OF OBSERVATIONS
0
5
10
15
20
25
30
35
40
45
50
RESPONSE LATENCY TIME IN MILLISECONDS
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
420
440
460
480
500
520
540
560
580
600
620
640
660
680
700

Figure 20

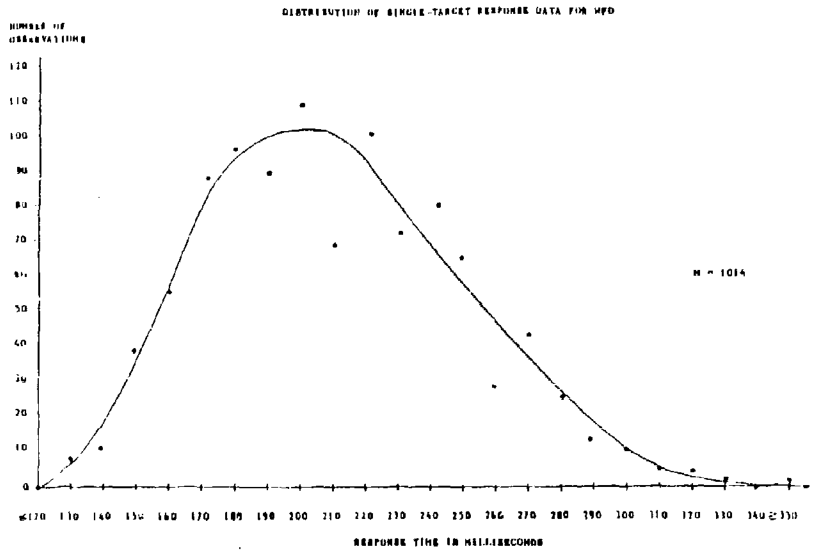

DISTRIBUTION OF SINGLE-TARGET RESPONSE DATA FOR MFD
NUMBER OF OBSERVATIONS
120
110
100
90
80
70
60
50
40
30
20
10
0
N = 1014
≤120
130
140
150
160
170
180
190
200
210
220
230
240
250
260
270
280
290
300
310
320
330
340
≥350
RESPONSE TIME IN MILLISECONDS

Figure 21

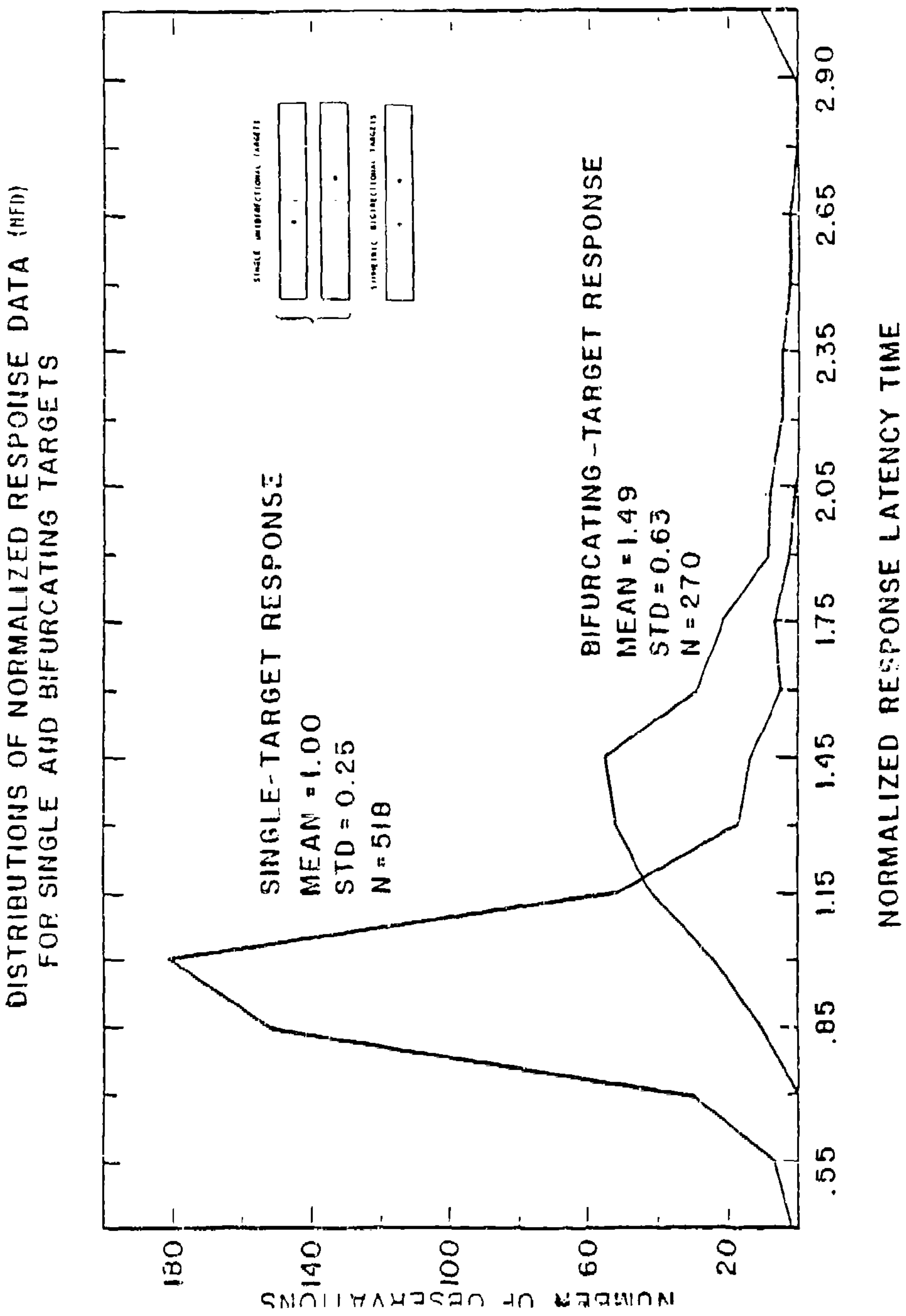
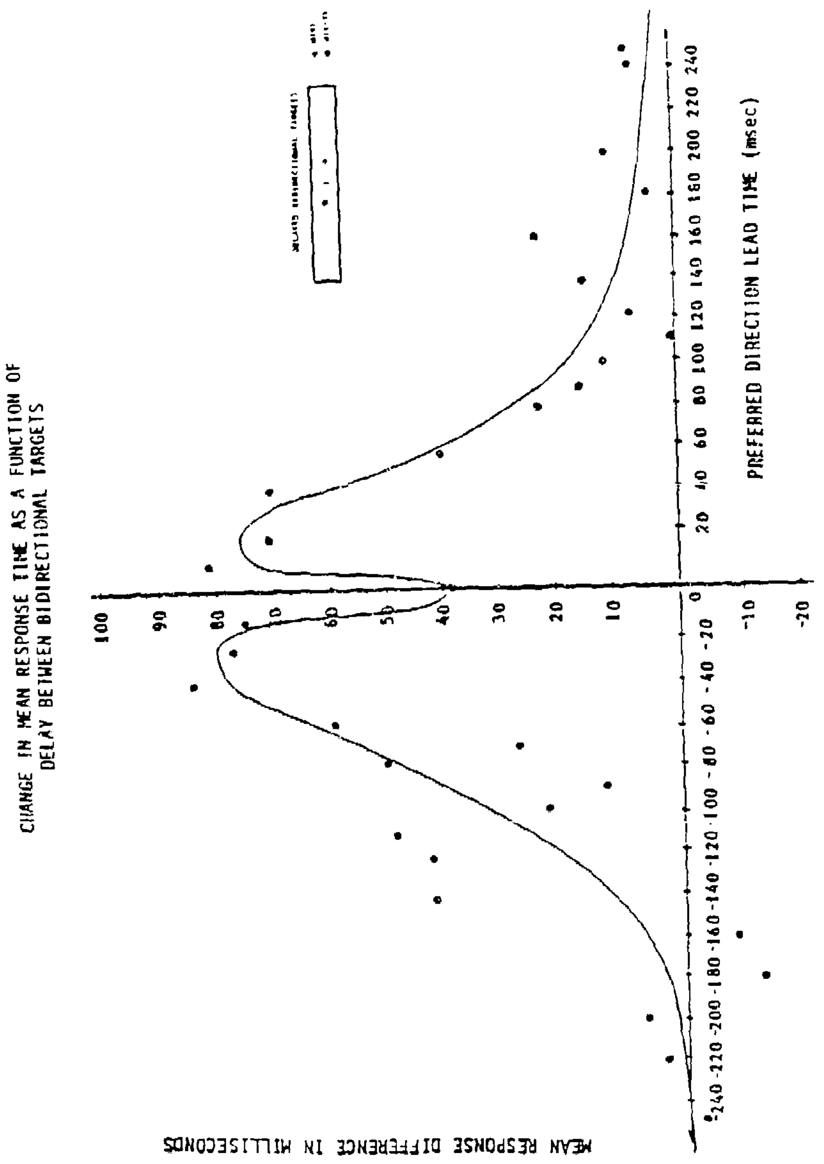

DISTRIBUTIONS OF NORMALIZED RESPONSE DATA (NFD)
FOR SINGLE AND BIFURCATING TARGETS
SINGLE-TARGET RESPONSE
MEAN = 1.00
STD = 0.25
N = 518
BIFURCATING-TARGET RESPONSE
MEAN = 1.49
STD = 0.63
N = 270
SINGLE UNIDIRECTIONAL TARGETS
SYMMETRIC BIDIRECTIONAL TARGETS
NUMBER OF OBSERVATIONS
180
140
100
60
20
NORMALIZED RESPONSE LATENCY TIME
.55
.85
1.15
1.45
1.75
2.05
2.35
2.65
2.90

Figure 22



CHANGE IN MEAN RESPONSE TIME AS A FUNCTION OF DELAY BETWEEN BIDIRECTIONAL TARGETS
MEAN RESPONSE DIFFERENCE IN MILLISECONDS
PREFERRED DIRECTION LEAD TIME (msec)
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-240 -220 -200 -180 -160 -140 -120 -100 -80 -60 -40 -20
20 40 60 80 100 120 140 160 180 200 220 240

Figure 23

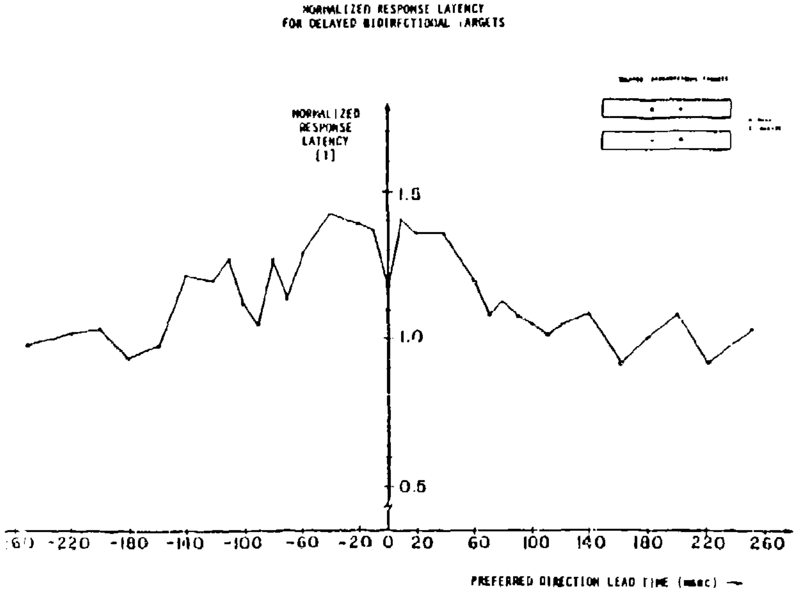

NORMALIZED RESPONSE LATENCY
FOR DELAYED BIDIRECTIONAL TARGETS
NORMALIZED
RESPONSE
LATENCY
(1)
1.5
1.0
0.5
-220
-180
-140
-100
-60
-20
0
20
60
100
140
180
220
260
PREFERRED DIRECTION LEAD TIME (msec) →

Figure 24

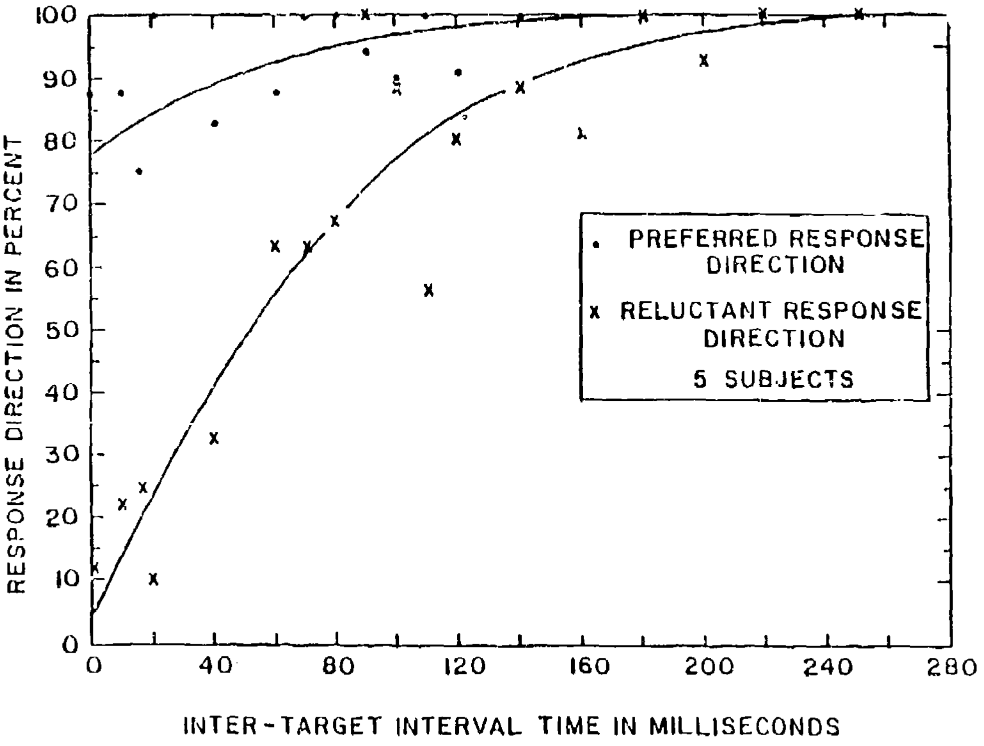

100
90
80
70
60
50
40
30
20
10
0
RESPONSE DIRECTION IN PERCENT
0
40
80
120
160
200
240
280
INTER-TARGET INTERVAL TIME IN MILLISECONDS
• PREFERRED RESPONSE DIRECTION
x RELUCTANT RESPONSE DIRECTION
5 SUBJECTS

Figure 25

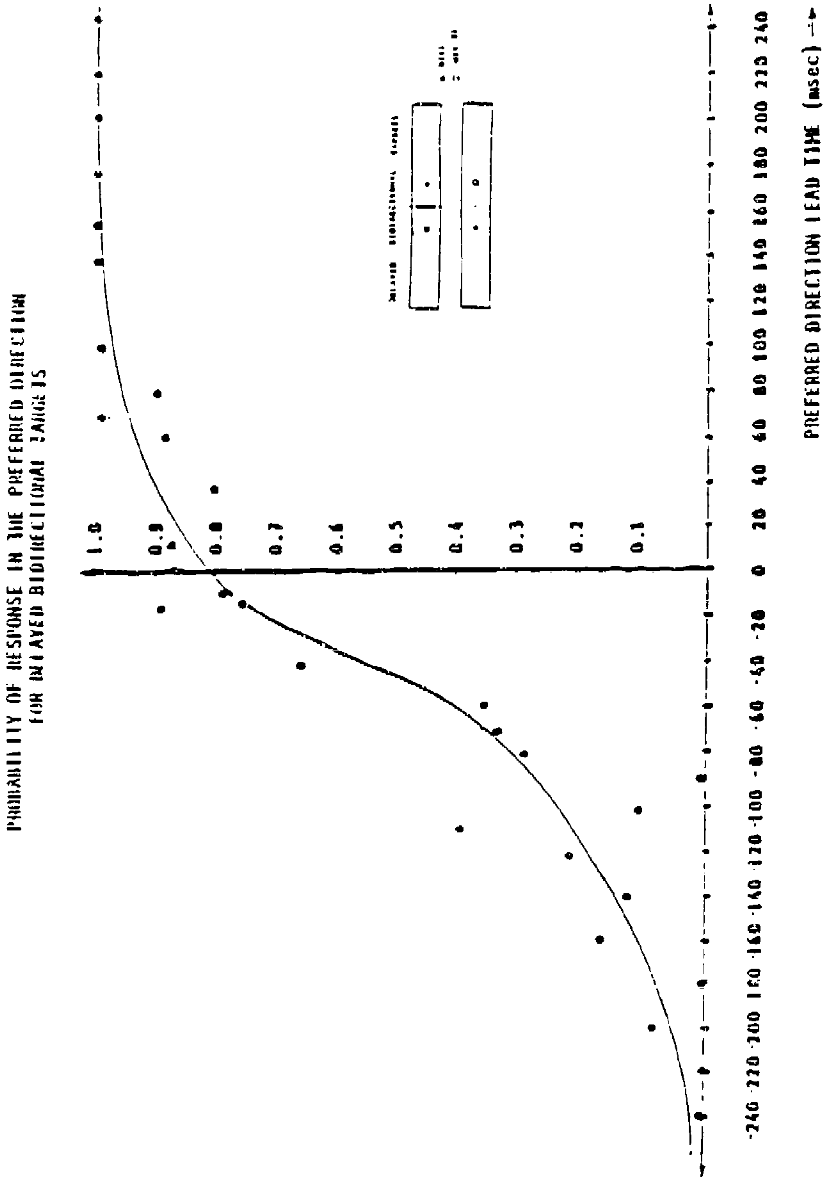

PROBABILITY OF RESPONSE IN THE PREFERRED DIRECTION
FOR DELAYED BIDIRECTIONAL TARGETS
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
-240 -220 -200 -180 -160 -140 -120 -100 -80 -60 -40 -20 0 20 40 60 80 100 120 140 160 180 200 220 240
PREFERRED DIRECTION LEAD TIME (msec) →

Figure 26

CHANGE IN MEAN RESPONSE TIME AS A FUNCTION OF
UNIDIRECTIONAL INNER TARGET DELAY TIME

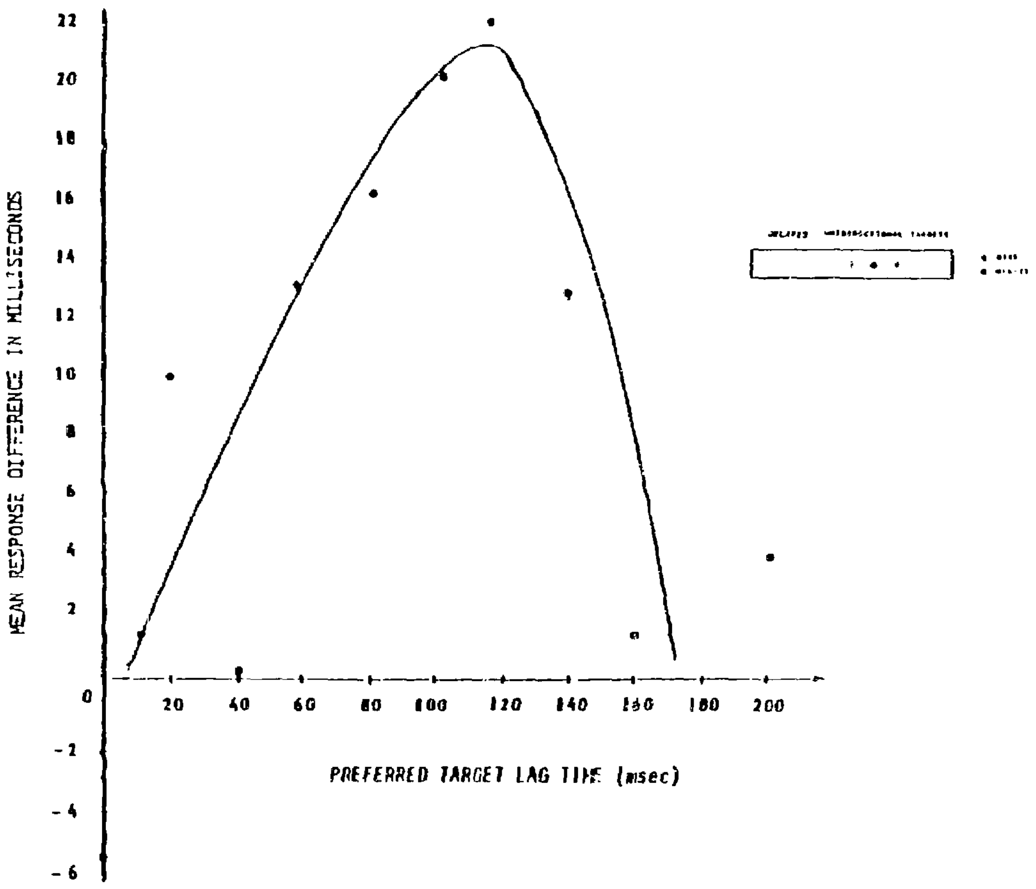


Figure 27

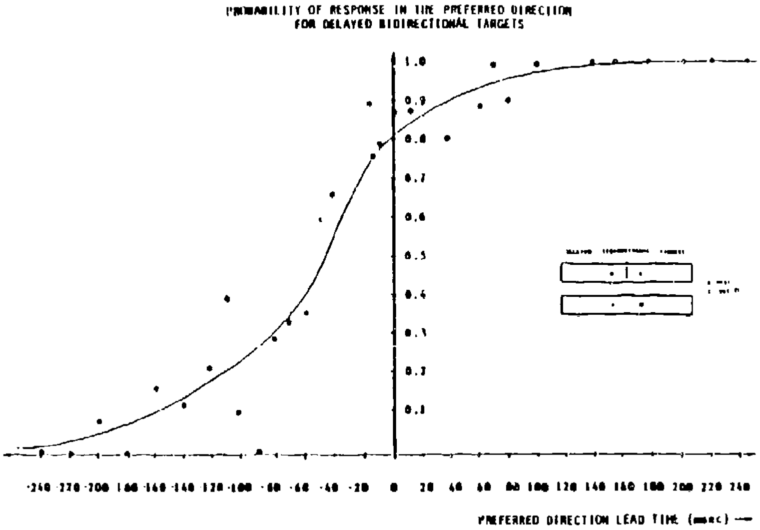

PROBABILITY OF RESPONSE IN THE PREFERRED DIRECTION
FOR DELAYED BIDIRECTIONAL TARGETS
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
-240 -220 -200 -180 -160 -140 -120 -100 -80 -60 -40 -20 0 20 40 60 80 100 120 140 160 180 200 220 240
PREFERRED DIRECTION LEAD TIME (msec) →

Figure 28

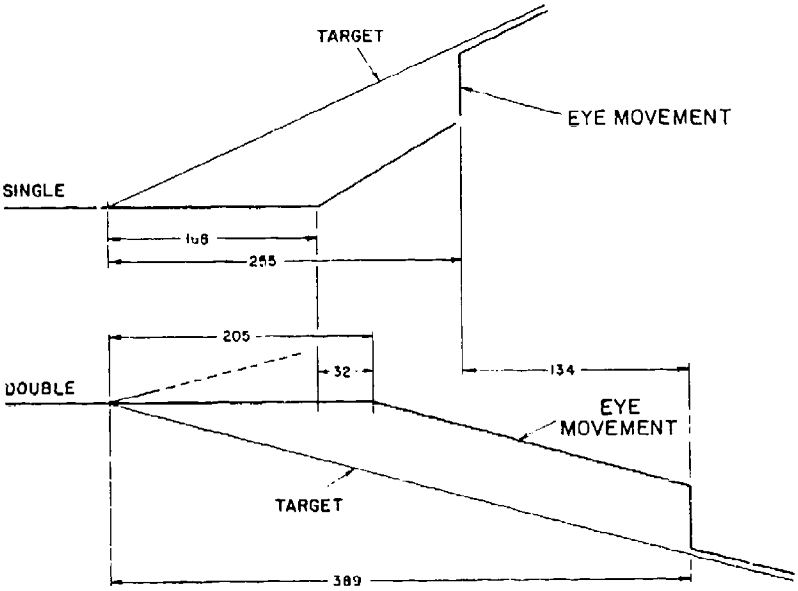

TARGET
EYE MOVEMENT
SINGLE
168
255
205
32
134
DOUBLE
EYE MOVEMENT
TARGET
389

Figure 29