THE PROGRAMMING STRATEGY
OF THE SACCADIC EYE MOVEMENT CONTROL SYSTEM

Thesis by

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To My Parents

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ABSTRACT

The purpose of this work is to learn more about the properties of and relationships between the stages of information processing in programming a saccadic eye movement.

The transient and the steady-state behavior of the saccadic programming system were studied using a double-step target movement and a long sequence of random-walk target movements, respectively. Then, the performance of the saccadic system in response to a more complex stimulus pattern which requires acuity discrimination was studied.

The results of the double target-step experiment suggested the following hypotheses.

The information processing in the programming of a saccade consists of detection, direction computation and magnitude computation. If the new target-step arrives before the direction computation of the previous saccade is complete, this saccade will be cancelled. The partial program concerning the direction of the saccade is kept in a buffer memory; if the direction of the new saccade is not in a direction similar to the old one, this partial program will have to be erased,which takes an extra 40-80 msec of processing time.

There is a stage in which the direction of the saccade cannot be reprogrammed but the magnitude can still be shortened. In other words, the magnitude computation seems to finish after the direction computation. Although the magnitude computation requires the results of the direction computation, it seems to start before the direction computation finishes.

If the new target-step arrives when the computation of both direction and magnitude are complete, two full saccades will be observed. The results suggested that the second saccade can start to be programmed before the first saccade is executed, but there is an approximately 100 msec refractory period following the programming of the first saccade.

When the saccadic system tracks a long sequence of random walk target movements, the percentage of target-steps that elicit saccadic responses is lower than the corresponding percentage in the double target-step situation. A third order effect was identified, which might be responsible for there being fewer saccades observed in the steady-state situation when the target rate is not too high. At a high target rate, such as 10 to 20 target-steps per second, a perceptual smearing phenomenon was observed. The size of this smearing region may define a threshold for a strong and consistent stimulus for the saccadic system at the high rate.

The results from the acuity discrimination experiment suggested that the same discrimination system is used by the saccadic programming system and the psychophysical acuity system. Like the single-spot stimulus, the new acuity information which arrives early enough can be used to reprogram the saccade. When a saccade is too late to be reprogrammed, the second saccade in response to the new target information can be processed in parallel with the first one.

TABLE OF CONTENTS

I. INTRODUCTION

The function and control of human eye movements have been of central interest to many researchers for many years. There are several different types of eye movements. During fixation tiny tremor eye movements, slow drift eye movements, and quick jerk-like eye movements can be observed. The tiny tremor eye movements, which sometimes oscillate at high frequency, contribute to our vision by keeping a retinal receptor from habituating to a stationary stimulus. It has been shown that vision actually fades out when an image is stabilized on the retina through an optical arrangement. The contribution of the slow drift and quick jerk-like eye movements is less clear, and no consensus exists among researchers.

In addition to fixational eye movements, there are two types of voluntary eye movements: conjugate eye movements and disjunctive eye movements. In a disjunctive eye movement, both eyes move in opposite directions cooperatively to keep the retinal image of an object in fusion. In conjugate eye movements, both eyes move in the same direction. The conjugate eye movements consist of two components: smooth pursuit and saccadic eye movements. Smooth pursuit eye movements can be used to follow a smoothly moving target when its speed is not too high. Saccadic eye movements are jerk-like eye movements. The maximum speed of a saccadic eye movement can reach 400-500 degrees/sec. The saccadic eye movements are the eye movements normally observed when we are reading, scanning a picture, or searching for something.

The control of the saccadic eye movements attracts researchers from the fields of neurophysiology, control system engineering analysis, psychophysics and ophthalmology. The system engineering approach was first employed by Fender and Nye (1961) and a sampled-data control model was subsequently proposed by Young and Stark (1962). This initial model has been modified several times (Young, Forster, Van Houtte, 1968; Becker, Fuchs, 1969; Robinson, 1968, 1973). In the neurophysiological approach, a great deal has been learned from the correlation of measurements of eye movements with electrophysiological stimulation and recording. The activities of motorneurons during eye movements are well understood. Some knowledge about the role of brainstem, cerebellum and superior colliculus on the control of saccadic eye movements was also obtained from these studies. In addition, psychophysical and clinical studies also contribute to our understanding of this subject.

When a saccadic eye movement follows a target movement, there is about 200 msec latency between the onset of the target movement and the initiation of the saccade. The brain processes which correspond to this 200 msec latency still have not been identified. During this latency period the input visual target information has to be processed and the final commands for the motorneuron of the eye muscles have to be generated, but how are these processes done? This problem is too complex to be tackled by the neurophysiological approach at this stage. This thesis addresses this problem using psychophysical and control system engineering approaches. The purpose is therefore to obtain some understanding of the brain processes involved in the control of saccadic eye movements and to provide some suggestions for the neurophysiological studies.

Using engineering jargon, the transient and the steady state behavior of brain processes were studied for various input target rates. From this work, an information processing model for the brain processes is proposed.

One often tends to make a comparison between the human brain and some man-made information processing system. The human brain can be viewed as a computer with tremendous capability but very slow speed. It is interesting and instructive to study how the brain reacts to the situation when the information rate of the visual input exceeds its processing rate. The same situation often occurs in man-made real time information processing systems. Does the brain use a buffering technique to cope with this situation? This question is discussed at the end of Chapter VI.

So far, almost all of the studies of saccadic eye movements have used the movement of a single spot as the stimulus. In response to this type of stimulus, only detection is necessary in the input processing. In Chapter VII I investigate what effect more complex stimulus will have on the control of the saccadic eye movements. The complex stimulus used is a Landolt C-like target, with an arbitrary gap orientation. With this type of stimulus, a discrimination process has to follow the detection process in order to program the saccadic command.

II. THE PHYSIOLOGY OF SACCADIC EYE MOVEMENTS--A REVIEW

2.1 Anatomy and Physiology of Extraocular Muscles

The human eyeball is a globe consisting of a gelatinous mass, a lens and retinal layers. It is surrounded by a white, opaque connective tissue, called the sclera, except for the front part which is transparent and called the cornea. It is housed in a bony socket called the orbit. The orbit is of conic shape with its apex pointing into the head.

There are three pairs of extraocular muscles--lateral and medial recti, superior and inferior recti, superior and inferior oblique (Fig. 2.1). All these muscles except the inferior obliques and the superior obliques originate from the membranous structure at the apex of the cone, called the annulus of Zinn. For all the recti, the muscle fibers go directly to the eyeball. The connection is made to the sclera after going through Tenon's capsule, which covers most of the eyeball except for the cornea. The superior obliques arise from the lesser wing of the sphenoid bone, then go through a pulley called the trochlea, before they are connected to the sclera just behind the equator, posterior to the center of rotation of the eye. The inferior obliques originate from a shallow depression in the anterior portion of the floor of the orbit and connect directly to the sclera just below the lateral rectus.

Activity of each of these three pairs of extraocular muscles causes the retinal axis to move in plane. However, the three planes

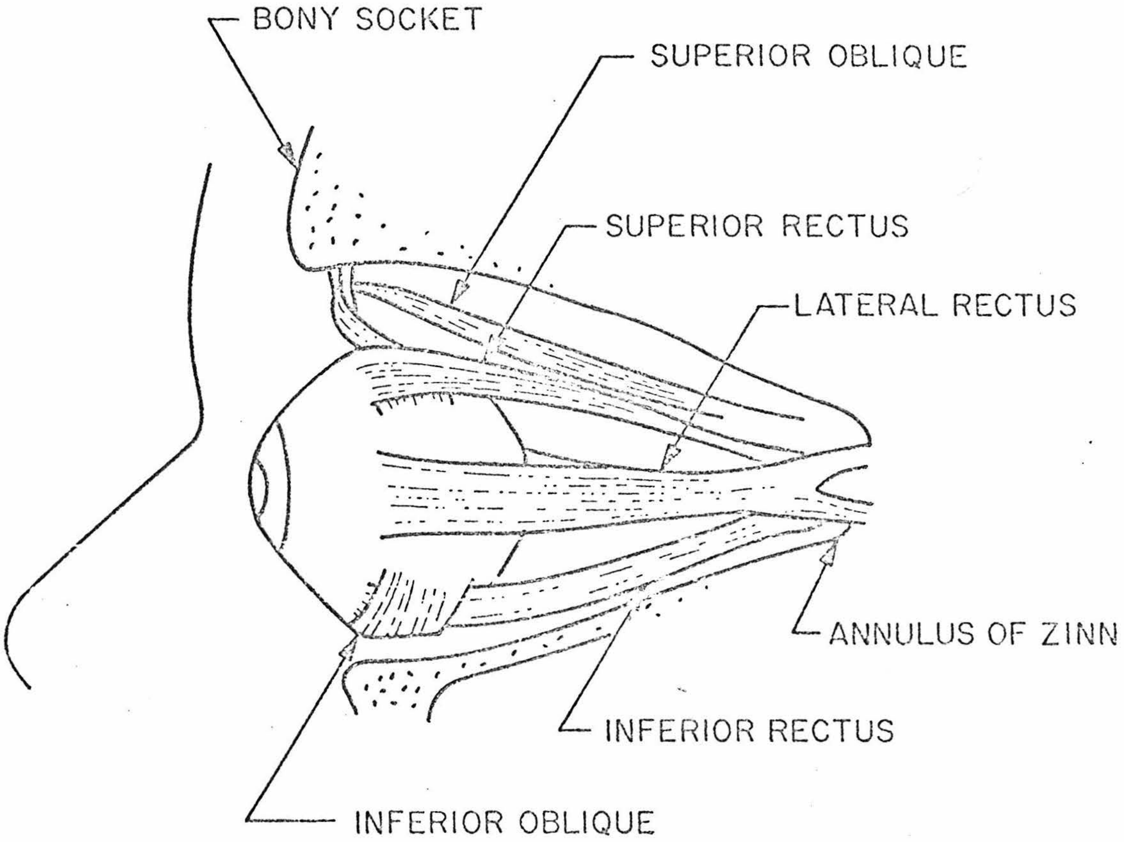


Fig. 2.1. The extraocular muscles
(Redrawn from Cogan)

are not orthogonal to one another (Fig. 2.2). The plane containing the medial and lateral recti is approximately parallel to the floor of the orbit and coincides with the horizontal plane of the globe when the eye is in the primary position. The plane containing the superior and inferior recti is vertical to the floor of the orbit but makes an average angle of 23 degrees with the anteroposterior axis of the head. The plane containing the superior and inferior oblique muscles makes an average angle of 51 degrees with the anteroposterior axis of the head.

The function of the lateral and medial recti pair is to rotate the eyeball in a horizontal plane and has very little secondary effect. The effect of the superior-inferior recti pair and the superior-inferior oblique pair is complex and depends on the initial eye position because of their non-orthogonal arrangements. Only when the eye is rotated outward 23 degrees does the contraction of the superior rectus or the inferior rectus purely elevate or depress the gaze position. And when the eye is rotated outward 39 degrees, the effect of the superior and the inferior oblique muscles is pure cyclorotation. To change fixation along a path on a plane other than the horizontal plane requires combinations of all pairs of muscles so that the side effects can be appropriately cancelled.

Within each pair of muscles, the reciprocal innervations for the two sets of muscles were shown by Sherrington (1893). To the first order of approximation, this reciprocal relationship of a pair of oculomotor muscles is independent of the state of innervation of

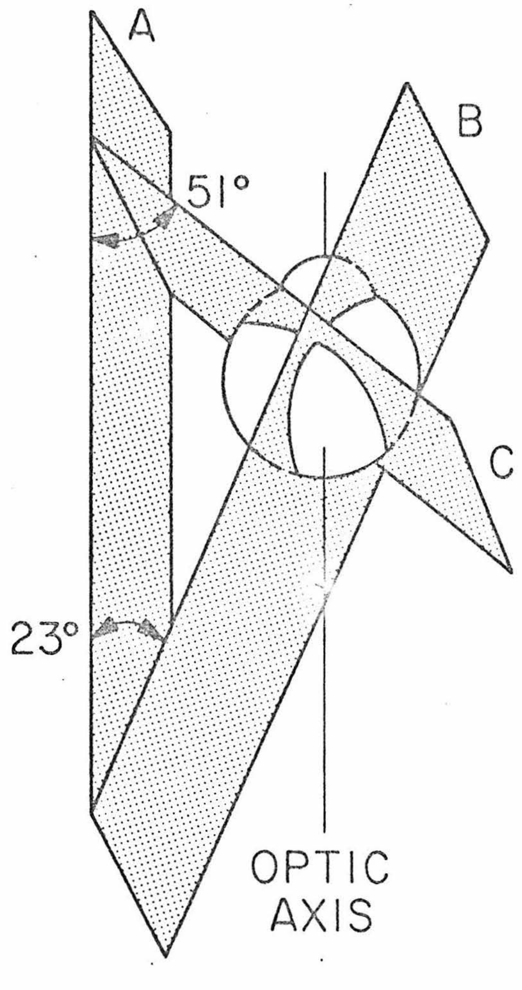


Fig. 2.2. Planes of:(A) Medial Orbital Wall; (B) Vertical recti; and (C) Oblique muscles. (Redrawn from Cogan)

the other pairs (Nakayama, 1975). It is demonstrated that at least two different types of motor systems exist in each extraocular muscle (Kato, 1938). One is a fast motor system or a phasic system which consists of large muscle fibers that are usually located deeper in the muscles. These large fibers are singly innervated by large nerve fibers and have a fast contraction time. The other is a slow motor system or a tonic system which consists of smaller muscle fibers and is located usually in the surface layers of the extraocular muscles.

Both systems are activated during fixations and saccadic eye movements. However, they contribute different proportions to the total activity. One may consider that the slow system is the major component in fixations and the fast system is the major component in saccadic eye movements.

During fixations, all six extraocular muscles have to maintain a specific innervation pattern. The innervation to the small fibers increases nonlinearly as the fixations move to more eccentric locations in the field of action of the muscle fibers (for example, outward movements for the lateral rectus). The innervation to the large fibers also increases along with the innervation of the small fibers, but they become saturated at a level of about half the maximum innervation during saccadic refixation.

It has been shown that the recruitment of the motor unit in each muscle is in an orderly fashion. It is therefore possible to describe the innervation pattern of the six muscles for every fixation position by six members or a 6 x 1 vector; each number represents an innervation state of a set of muscles. Theoretically, three degrees of freedom are needed to describe the rotational states of a sphere fixed in a position. However, it was proposed and demonstrated by Donder, Listing and Helmholtz (Donder's Law and Listing's Law) that there are only two degrees of freedom in the rotational states of the eyeball. At each fixation position, the cyclorotation of the eyeball is fixed. Therefore, the six numbers have only two degrees of freedom. In other words, only two numbers are programmed independently according to the fixation position, and the other four numbers are derived according to constraints. It is not clear yet how the constraints are imposed but the evidence points toward their being imposed in the central neural processing (Nakayama, 1975).

During saccadic refixation, it is not known whether Donder's law or Listing's law is obeyed by the innervation patterns. The nature of the saccadic innervation is quite different from that of fixation. Both large and small fibers are turned on maximally during the first portion of the saccade and then the innervation decays to a new equilibrium value which corresponds to the innervation of the new fixation point, with a time constant of about one-half of the saccadic duration. The innervation of small fibers does not overshoot, but the innervation of large fibers does. The amplitude and the duration of the overshoot pulse depend on the magnitude of the saccade and the final fixation position of the eye (Collin and Scot, 1973). This saccadic innervation pattern is also called the pulse-step pattern. The pulse corresponds to the overshoot, which is necessary to overcome the viscosity in the orbit in order to achieve the high velocity.

The innervation activities of the extraocular muscles are the same as the firing rate of the neural pulses in the corresponding motor neuron. The firing rate of the motorneuron as a function of the eye position can be described by the following equation (Robinson and Keller, 1972):

$$R = K(\Theta - \Theta_T) + r\frac{d\Theta}{dt}$$

where R is the firing rate

Θ is the eye position

Θ_T is the angle at which the neuron is recruited into activity

r/K is close to the time constant of the mechanical visco-elasticity of the globe-muscle system

This is a quantitative description of the final common path of the eye position and the eye movement control. It describes the innervation activity of all types of eye movements and also fixations.

2.2 Premotor Circuitry for the Saccadic Eye Movements

The current knowledge about the neural circuitry which generates the motorneuron discharge pattern of saccadic eye movements is reviewed in this section. The elementary control system theory has been employed in the work of tracing out this circuitry, which provides a clearer insight into many neural signals flowing in the brainstem and cerebellum.

From the neurophysiological studies of the vestibulo-ocular reflex, the existence of a neural circuit which transforms the desired eye velocity signals generated by the vestibular nuclei into the eye position signals has been proposed by Skavenski and Robinson (1973). This circuit is given the name of neural integrator (NI). Much indirect but rather convincing evidence suggests that this neural integrator is also shared by the saccadic system and the smooth pursuit system (reviewed by Robinson, 1975). Although there is not enough anatomical evidence to be able to locate the neural integrator with certainty, the evidence from lesion studies (reviewed by Daroff and Hoyt, 1971, and Cohen, 1971) suggests that it is in the pontine recticular formation. Also, single cell recording from the pons found some "burst units". About one-third of the cells in the pons carry eye-position signals (Keller, 1974). These burst units generate signals proportional to the eye velocity. Since the profile of its firing frequency is a pulse, it is modeled as a pulse generator by Robinson (1973). Eye position signals are derived from velocity signals through the neural integrator. Eye position signals and velocity signals are combined to become the pulse-step innervation for motorneurons. These pulse-step signals are observed in the medial longitudinal faciculus before they arrive at the motorneurons.

2.3 Supranuclear Oculomotor Control

The picture of oculomotor control in the high neural center, such as cerebellum, superior colliculus, frontal eye fields (Area 8), etc. is still not clear. Although there is a large amount of data from electrical stimulation and lesion studies, no well developed theory like those for the premotor circuitry exists for the higher oculomotor center. Many findings seem to present more riddles than they solve. For example, stimulation of the frontal eye fields, the superior colliculi or the cerebellum elicits saccadic eye movements, but lesion or ablation of these areas does not impede saccadic eye movement.

III. EXPERIMENTAL APPARATUS AND DATA PROCESSING

In this chapter the techniques for eye movement measurement, the experimental control and stimulus display systems, and some data analysis schemes which are common to all experiments are described.

3.1 Eye Movement Measurement

A contact lens method is employed throughout this thesis to measure eye movements. It is used because of its capability to record both horizontal and vertical eye movements with good accuracy.

During the experiment, the subject wears an individually fitted contact lens. A stalk with a tiny lamp on its tip and a suction tube are attached to the lens (Fig. 3.1). A mild suction equivalent to 25 cm of water is applied during the experiment to reduce the slippage of the lens. The contact lens moves with the eye and the movement of the lamp on the tip of the stalk is then registered by two photomultipliers, one for horizontal movements and one for vertical movements (Fig. 3.2).

Above the photomultiplier is a guide tube with a knife edge inside the tube. This edge casts a shadow on the receiving surface of the photomultiplier. When the eye moves, this shadow also moves. Therefore, for different eye positions, different amounts of light are projected to the photomultiplier and different voltages are produced. This voltage is proportional to the eye position; the linearity and the resolution of the contact lens system was examined by Beeler (Thesis, 1965).

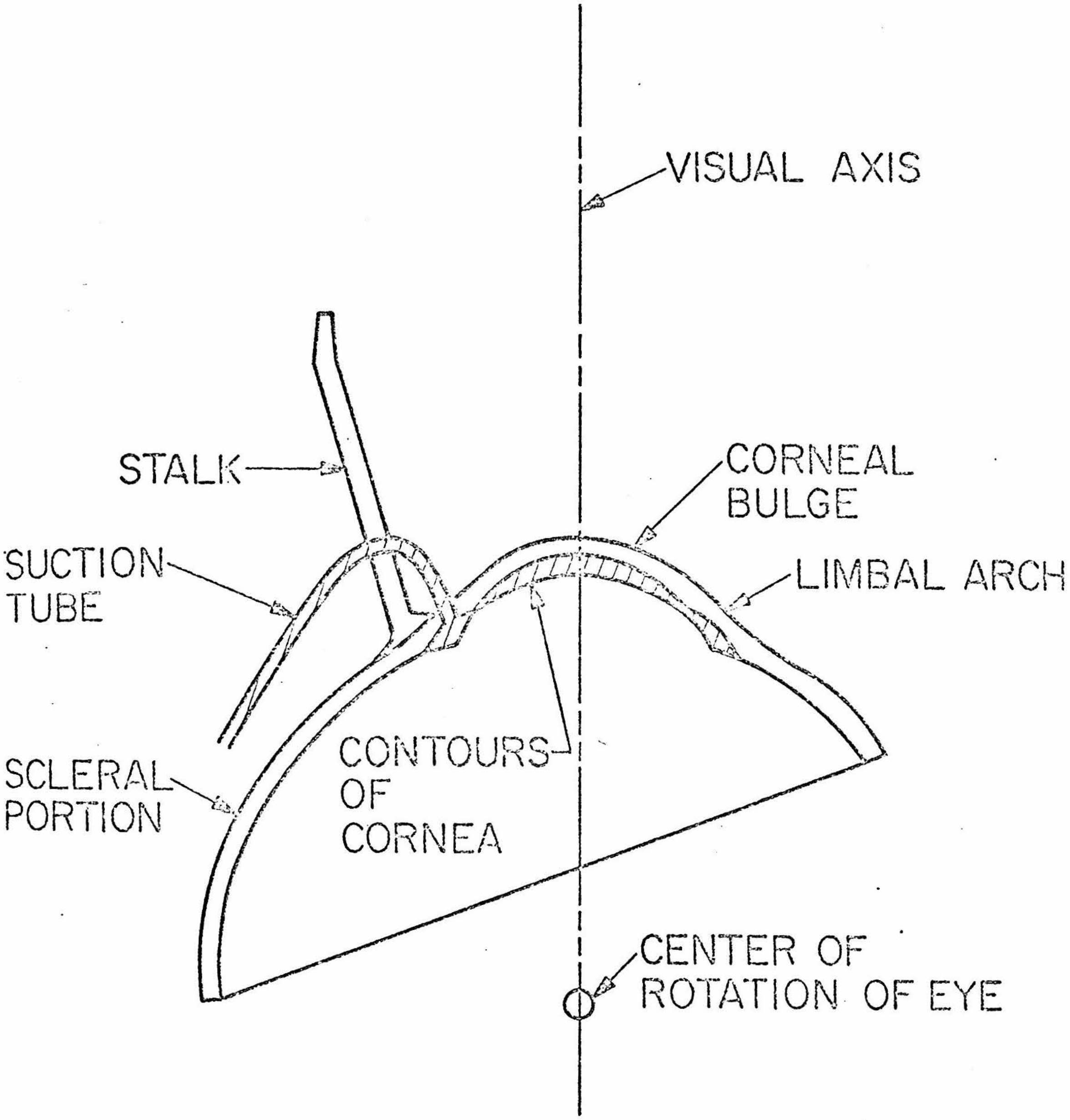


Fig. 3.1. Contact lens worn by the subject for the measurement of eye movements (Cross section).

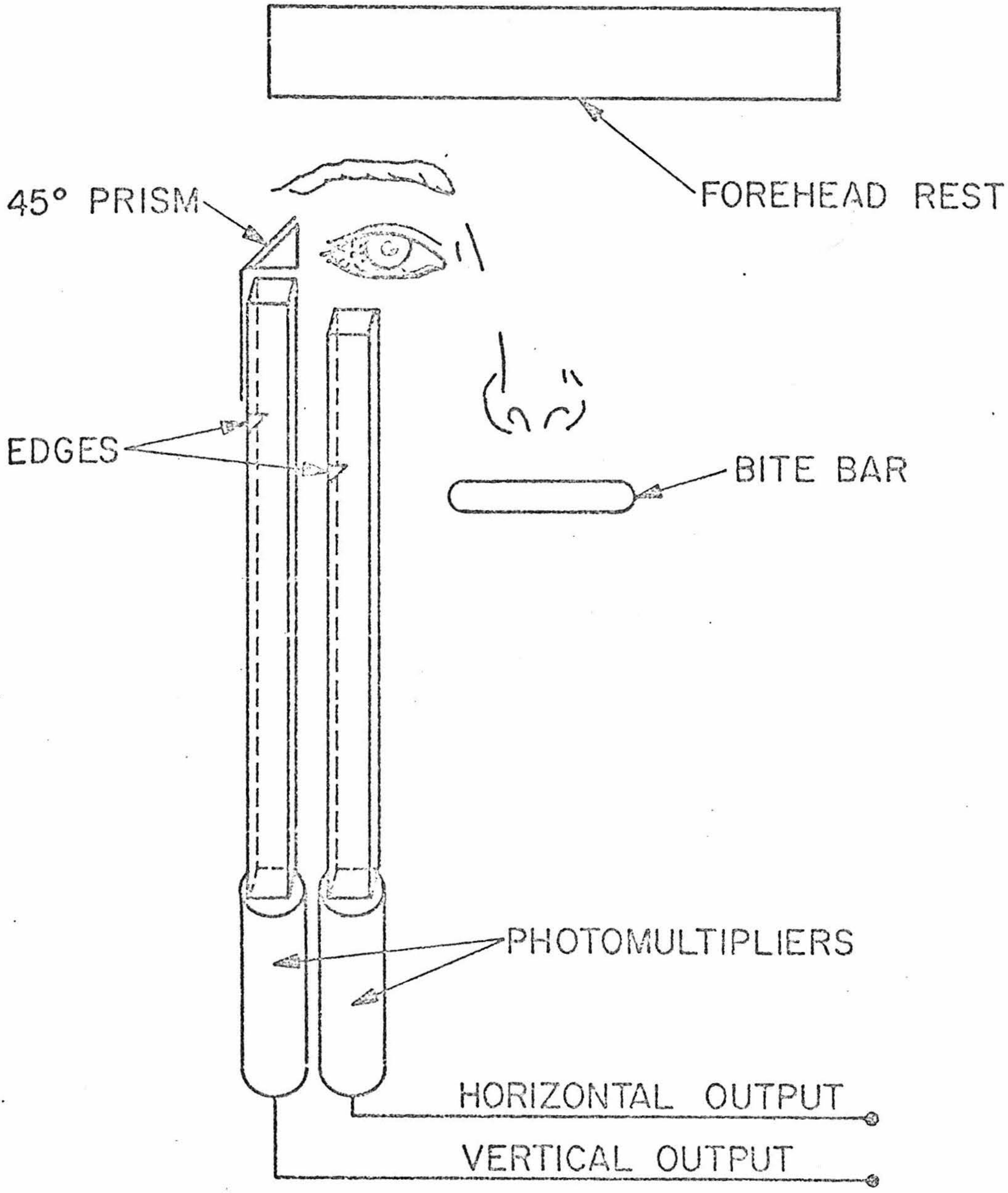


Fig. 3.2. Photomultiplier tube assembly for the measurement of eye movements. The pin-light attached to the contact lens casts the shadow of the edge onto the face of the photomultiplier tube; the output of the PMT's is thus proportional to rotation of the eyeball.

3.2 Experimental Apparatus

The apparatus designed for this study is a flexible real time computer system with the capability of graphic pattern generation and data acquisition. The flexibility is the greatest advantage that a computerized experimental control system can offer; with minimal hardware modification, different types of experiments can be implemented. However, the effort spent on the development of the computer program should be much less than the major hardware modification, otherwise it defeats its own purpose. The requirement for a good real time experimental control computer system can be summarized as follows:

1) It should have acceptable real time response.
2) It should provide flexibility to the experimenter.
3) It should be easy to develop, to modify, and to debug programs.

The system implemented for this study is described in some detail and an evaluation according to the above criteria is also given. The system configuration is shown in Fig. 3.3.

3.2.1 Stimulus Display

A plasma screen is used for displaying the stimulus. It consists of 512 x 512 very tiny neon gas chambers arranged in a grid fashion. There are also 512 horizontal and 512 vertical wire electrodes behind the gas chambers. When two electrodes are selected by a code, the gas in the chamber at the cross point of these two electrodes is ignited and a dot of 30-foot-lambert luminance can be seen. When a dot is ignited, it stays on until an erase code is received. The advantage of this screen

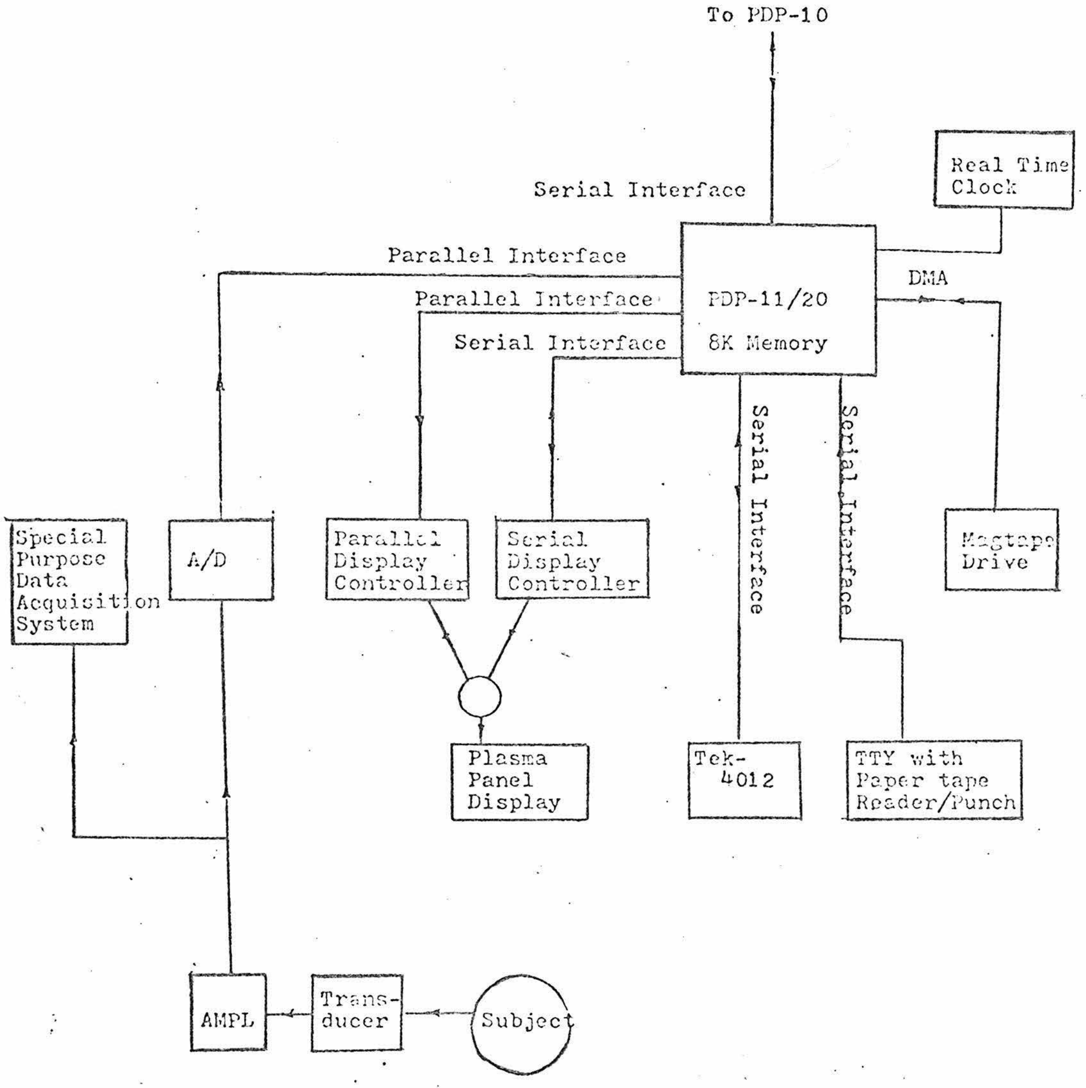


Fig. 3.3. The configuration of the experimental control and data acquisition system.

is that it does not need refreshing as most interactive graphics terminals do. Unlike a storage scope, the dots can still be selectively erased. The definition of the single dot seems to be better than that of the smallest dot obtained on ordinary CRT phosphor.

There are 60 dots in an inch, and the plasma screen is placed 57 inches in front of the subject. The distance between each pair of dots corresponds to one minute of arc.

The serial controller receives ASCll codes from the computer serially, then accordingly generates commands to draw a vector, to write a letter, to write a dot or to selectively erase any area. Instead of a serial controller, a parallel controller can be selected which receives X coordinates and Y coordinates from the computer and ignites the dot corresponding to that position. Each coordinate is received in parallel from the computer, and it does not need decoding. Therefore, it allows the stimulus pattern to be drawn at the highest speed. At this moment the highest speed is limited by the execution time of the computer instructions, which is about 5 μsec.

3.2.2 Data Acquisition

The output voltage from the photomultiplier which corresponds to the eye position is amplified and then digitized. The digitized voltage can be read by the computer program. The output voltage is also sent to a special purpose data acquisition system which can multiplex 128 input signals, then write on a digital magnetic tape for off-line data analysis. This data acquisition can be controlled by the computer program too. In addition, there is also a magnetic tape drive connected to the computer. Data can be read from the tape or written on the tape via a memory buffer in the computer memory.

3.2.3 On-Line Data Display

A Tektronix 4012 storage scope terminal can be used to display eye response on-line by appropriate display programs. The keyboard can also be used to enter experimental parameters on-line.

An ASR33 teletype provides hard copy of the results. It also has a paper tape reader/punch.

3.2.4 Real Time Control

A programmable real time clock is connected to the computer. It can be run at three different clock frequencies and performs standard clock functions.

3.2.5 Computer

The computer is a PDP 11/20 machine with an 8K of core memory. Because of the size of the memory, it is not feasible to support any run-time system of a reasonable high-level language; the program has to be programmed in assembly language. Without any fast secondary storage (i.e., disk) available, to avoid using the cumbersome paper tape system this computer is connected to a central PDP-10 time sharing computer as a remote terminal. The PDP-10 provides file storage, text editing and program compilation facilities. When a program is properly assembled and linked, it is loaded from the disk of the PDP-10 into the memory of PDP-11/20 through a local communications program.

3.2.6 Evaluation

(1) Real-time response: Since it has very little overhead compared with a typical real time operating system, the control system runs quite efficiently and has very good real-time response.

(2) Flexibility: The computer controlled display and two modes of data acquisition provide enough flexibility for implementing typical experiments in eye movement studies.

(3) Ease of use: The nature of assembly program makes a program development and modification more difficult than a high level language. It is generally agreed that it takes an experienced programmer about the same time to program a fixed number of lines of computer programs, no matter what computer language he is using. One line in the high level language may correspond to more than 20 lines in the assembly language. Another intrinsic difficulty is that this system forces the user to program concurrent events in a serial fashion. The experimental control and data acquisition can often be identified as several separate concurrent events. If a system supports multiprogramming, those events can be programmed as separate routines and run concurrently. To program them in a serial fashion tends to complicate program structure and increases the difficulty of program development and modification. A multiprogramming system has not been implemented mainly because of the memory size constraint.

3.3 Data Analysis

Some data analysis can be done on-line such as the detection of a saccade, calculation of its onset, and accumulation of some simple statistics. When a data analysis scheme is too complex to be done in the assembly language or too slow to be done in real time, the data are stored on the magnetic tape using either the special data acquisition system or the magnetic tape drive. Then the data are carried to either the PDP-11/45, IBM370/158 or PDP-10 for processing.

The voltage corresponding to the eye position is sampled at 1000 Hz on-line. The algorithm for the detection of a saccade is as follows: The eye position is examined every msec, a saccade is deemed to occur only if there are five consecutive increases or decreases above a threshold in either the horizontal or vertical components. The onset time is set at the time at which the first increase or decrease occurs. This algorithm has been proved successful by actual trials. Since saccades of two degrees do not last more than 30 msec, the end position of a saccade is taken to be the position of gaze at 50 msec after the onset of the saccade.

IV. TRANSIENT BEHAVIOR OF THE SACCADIC PROGRAMMING SYSTEM--EXPERIMENTS USING DOUBLE-STEP TARGET MOVEMENT

4.1 Introduction

The basic question posed in this thesis is the programming strategy of the saccadic eye movement system. How does the saccadic system generate a saccade of the correct direction and size in response to a target movement? Those who are familiar with target acquisition, ranging, and tracking problems in radar tracking systems may appreciate that this is not a trivial task; the eye movement problem is especially severe since the task must be performed with high speed and accuracy using three pairs of non-orthogonally arranged extraocular muscles.

Various target movement patterns have been employed to study the saccadic eye movement system or oculomotor tracking system in general. They include the single target-step, double target-step, continuous periodical target motion, and continuous Gaussian random target motion. A new type of target motion for the saccadic eye movements, which consists of a long sequence of discrete random-walk target motions, will be described in Chapter V. It will be shown in that chapter that the response behavior of the saccadic programming system has different characteristics when tracking different types of target motion. Thus, the response of the saccadic system to the first two types of target motion, namely single target-step and double target-step, will be called the transient behavior of the system. And the response to the continuous or long sequence of discrete target motions will be called the steady-state behavior of the system. In studying the differences between these two types of behavior, we should be able to learn more about the programming strategy of the saccadic system.

If a system is linear and deterministic, its response to a single impulse input or a step-function input should describe the complete behavior of the system. However, the saccadic programming system is neither linear nor deterministic. In order to probe the behavior of a nonlinear system, it is usually fruitful to study how the system responds to two impulse stimuli in succession, in addition to studying how it responds to a single impulse stimulus; this tells us the second order interactions in the system response. To the saccadic eye movement system, the most powerful stimulus is a sudden target jump in a step function fashion; this will be called a target-step in this thesis. Two target-steps in succession was the stimulus used by Westheimer (1954) in one of the earliest studies of the saccadic eye movement response. A large volume of experiments has followed this work but after more than twenty years very little is known about the central processing of saccadic eye movements. The most comprehensive model so far uses a box indicating 200 msec delay to represent the central processing (Young et al., 1968; Robinson, 1973). No complete theory exists to account for this delay. Therefore, the goal of the experiments shown in this chapter and the next chapter is to put together a theory or a model to show the properties of and the relationships between the stages of information processing taking place during this 200 msec delay.

I will review first the results obtained from previous experiments using two target-steps and the hypotheses resulting from them. Then, two variations of the double target-step experiments will be described. The specific purpose of each experiment is stated before it is described.

4.2 Review of the Previous Double Target-Step Experiments

Various combinations of the two target-steps have been used; most of them used target-steps only on the horizontal axis. The combination of the two horizontal target-steps can be classified into four categories:

(1) Pulse forward: After the first target-step the second target-step jumps further to a new position in the same direction as the first target-step.

(2) Pulse return: The first target-step jumps to either left or right, then the second target-step returns to the original position. The target displacement can be represented by a pulse function.

(3) Pulse partial return: After the first target-step, the second target-step returns only half way to the original target position.

(4) Pulse over-return: After the first target-step, the second target-step overshoots the original target position.

Two studies used a combination which started with a horizontal step followed by a vertical step (Feinstein and Williams, 1972; Lisberger _et al._, 1975).

The time interval between two target-steps is called the interstimulus interval (ISI)

In 1954, Westheimer used the pulse return paradigm and found that the subject's response always consisted of (1) a saccade with normal reaction time (200 msec) which brought the direction of gaze to the position corresponding to the first target displacement, and (2) a return saccade occurring 200 to 250 msec after the gaze had reached the new position. He reported that this was true even for ISI as short as 40 msec. His results indicate that the saccadic system cannot process a new target-step until the initial saccade is complete. This result can be modelled by a sampled-data concept (Young and Stark, 1962). In this model, the input target information is sensed by an impulse sampler at a sampling interval of 200 msec. The sampler is initially triggered by a target movement if there has not been a saccade for more than 200 msec, but when a sample is taken, there is a 200-msec refractory period during which no information can be taken.

Beeler (Thesis, 1965) suggested that the information processing in saccadic eye movements is not as simple as the model proposed by Young and Stark. He found that the subjects did not always respond with two saccades to Westheimer's type of stimulus. There is a threshold value of ISI, above which the saccadic system will respond with two saccades for more than 50 percent of trials. The threshold values of ISI he found to be 100 msec, 150 msec and 50 msec, respectively, for pulse over-return, pulse forward and pulse return target patterns. He also suggested that the sampling period is different for different target movement patterns. The above three target patterns he suggested have sampling periods of 150, 220 and 200 msec, respectively.

In 1966, Wheeles, Boynton and Cohen used the pulse over-return target pattern and found results different from Westheimer's findings.

When ISI was 50 msec they found that 91.5 percent of the subject's responses had only one saccade to the final target position and 8.5 percent of the responses had two saccades. The percentage of two-saccade responses increased as ISI increased. This suggested that the saccadic system could use new target information to cancel the preparation of the initial saccade and to reprogram it. They also found that the latencies between the onset of the second target-step and the beginning of the saccade in the one-saccade response was about 40 msec longer than the normal average saccadic latency. They explained this extra 40 msec as "cancellation time" of the initial saccade.

To account for the percentages of the two types of saccadic response observed by Wheeles et al., the sampled data model was revised by making the time of occurrence of each sample to be stochastically distributed. The distribution can be determined by the percentage of the single-saccade responses at different values of ISI (Young, Forster and Van Houtte, 1968). This revised model is shown in a later chapter as Fig. 6.1a.

Komoda et al. (1973) mixed together all four types of target movement patterns described at the beginning of this section. Their results were similar to those found by Wheeles et al. They also found no significant difference in the average percentages of the two types of saccadic responses between different target motion patterns. Contrary to Wheeles et al. they did not find 40 msec "cancellation time." For the pulse forward target pattern and the pulse partial-return pattern, the latency between the onset of the second target-step and the initiation of the saccade in the single saccade response was shorter than the normal saccadic reaction time. They attributed the shorter reaction time to computation saving because the second target-step was in the same direction as the first one. They suggested that the saccadic system first computed only direction and approximate magnitude, then determined the precise magnitude by refining the initial computation. In addition, they suggested that the saccadic system can process target information continuously instead of by sampling.

Feinstein and Williams (1972) used target-steps consisting of a horizontal step followed by a vertical step, together with two horizontal steps. They found both one-saccade and two-saccade responses to the two horizontal steps, but only two-saccade response to the horizontal-vertical target steps. They suggested different information processing for horizontal and vertical saccades.

Lisberger _et al_. (1975) repeated Feinstein's experiment but found no significant difference in the responses to either horizontal-horizontal steps or horizontal-vertical steps. They also tried to reconcile the different percentages of the two-saccade responses between different subjects and different laboratories by plotting these percentages against $\overline{RT}$-ISI, where $\overline{RT}$ is the average reaction time of the saccade in response to a simple one-step target jump for each subject. Using this normalizing procedure, the disparities between subjects were reduced.

Carlow _et al_. (1975) studied the differences between subjects using pulse over-return target motion. They found considerable differences among 10 subjects, both in the percentages of single-saccade responses and in the latencies. But the general relationships were quite similar from subject to subject. For ISI less than 120 msec, they found the latency of the one-saccade response was shorter than the latency of the second saccade of the two-saccade response. They concluded that the decision making mechanism is programmed to minimize the total latency to the final target position.

Becker and Jügens (1975) also used all four types of horizontal target-steps. They studied the magnitude of the single saccade and the first saccade in the two-saccade responses as a function of the time interval between the initiation of the saccade and the onset of the second target-step. They suggested that for the pulse return and pulse partial-return pattern the saccadic system can update the target position information continuously up to at least 80 msec prior to the initiation of the saccade. But for the pulse over-return and pulse forward pattern, the second target-step had to occur about 170 to 200 msec earlier than the initiation of the first saccade in order to modify the programming of the saccade. They suggested that it is more difficult to lengthen a saccade than to shorten it. They also hypothesized that the direction of a saccade is set earlier than the magnitude.

From this large volume of data, some results which are consistent between the majority of previous work can be extracted. It is generally believed that the saccade can be reprogrammed using the new target information. The saccadic responses are generally classified into two categories: the one-saccade response and the two-saccade response. The percentage of the one-saccade response decreases as ISI increases. This percentage varies between subjects but does not vary significantly between different target movement patterns. As for the hypotheses about the information processing of the saccadic system, two groups (Komoda *et al.*, Becker and Jügens) proposed that the direction and the magnitude of a saccade are computed separately and the direction is set before the magnitude. The rest of the results are in less agreement between investigators. For example, one group (Wheeles *et al.*) reported extra cancellation time in the latency of one-saccade response, while the other group (Komoda *et al.*) failed to find it. A lot of work has to be done in order to reconcile all these differences.

4.3 Experiment I

4.3.1 Purpose of Experiment

The results from the previous double target-step experiments give us a very confusing picture about how the saccadic system programs a saccade. The recorded differences in the percentage of responses and latencies may depend heavily on the different experimental conditions. These differences are difficult, if not impossible, to sort out. One may think another double target-step experiment will not clarify the situation. However, I believe that an experiment in this paradigm but with different emphasis can be a good starting point. It gives us some data obtained in our own experimental conditions to test various hypotheses proposed by previous experimenters.

There are some interesting hypotheses about the processing of the direction and the magnitude of a saccade (see Sec. 4.2, Komoda *et* *al.*, 1973; Becker and Jügens, 1975). All these experiments used horizontal target-steps only. Hence the same set of extraocular muscles are always used. If the saccadic programming system learns this fact through repetition, the direction processing only needs to determine which of these two muscles is agonist or antagonist. This learning may or may not affect the directional processing. In the following experiments, two-dimensional target-steps were used and the direction of each target-step was randomized. This places the emphasis on the properties of the directional processing mechanism. Another advantage of using two-dimensional target-steps is that the data can be less noisy. For a refixation of large magnitude, a great portion of saccadic responses consists of two saccades. They are preprogrammed or prepackaged as hypothesized by Becker and Fuchs (1969). In the one-dimensional situation, if a so-called "single-saccade response" consists of this package, it will be misinterpreted as a "two-saccade response." This may be a significant error in some cases. For example, in the study by Becker and Jügens, they used 15° and 30° target-step sizes in which a significant portion of responses would contain correction saccades (Weber and Daroff, 1972).

4.3.2 Methods

The stimuli were displayed on the plasma screen. At a viewing distance of 57 inches a single dot subtends 1 min arc of visual angle. The stimulus was an annulus subtending 21 min arc and width was 2 min arc. It could be displayed in 500 μsec and erased in a few μsec.

The target was viewed monocularly. At the beginning of each trial, the subject was asked to fixate on a target presented at the center of the screen, and his eye positions were monitored by the computer. The eye movements were measured using a contact lens method. When the computer determined that the observer was fixating the target, it was programmed to move the target two degrees to one of the eight positions shown in Fig. 4.1a. The target might be moved again after various time intervals. Three paradigms for target presentations were used.

1. Single-step presentation--the target remained stationary after the first jump (Fig. 4.1b). This served as the control of the experiment.
2. Adjacent presentation--the target jumped again to one of the two adjacent vertices of the octagon and stayed on until the next trial (Fig. 4.1c).
3. Opposite presentation--the target jumped again to the vertex opposite to the position of the first target-step and stayed on until the next trial (Fig. 4.1d).

For stimuli 2 and 3 the time intervals between the first and the second target jumps were 50, 100 and 150 msec. All target positions, stimulus modes, and time intervals were presented randomly. Subjects were instructed to follow the target-steps as quickly as possible. Two subjects were used in this study.

4.3.3 Results and Discussion

Several commonly used terms in the following discussion are defined here (Fig. 4.1h):

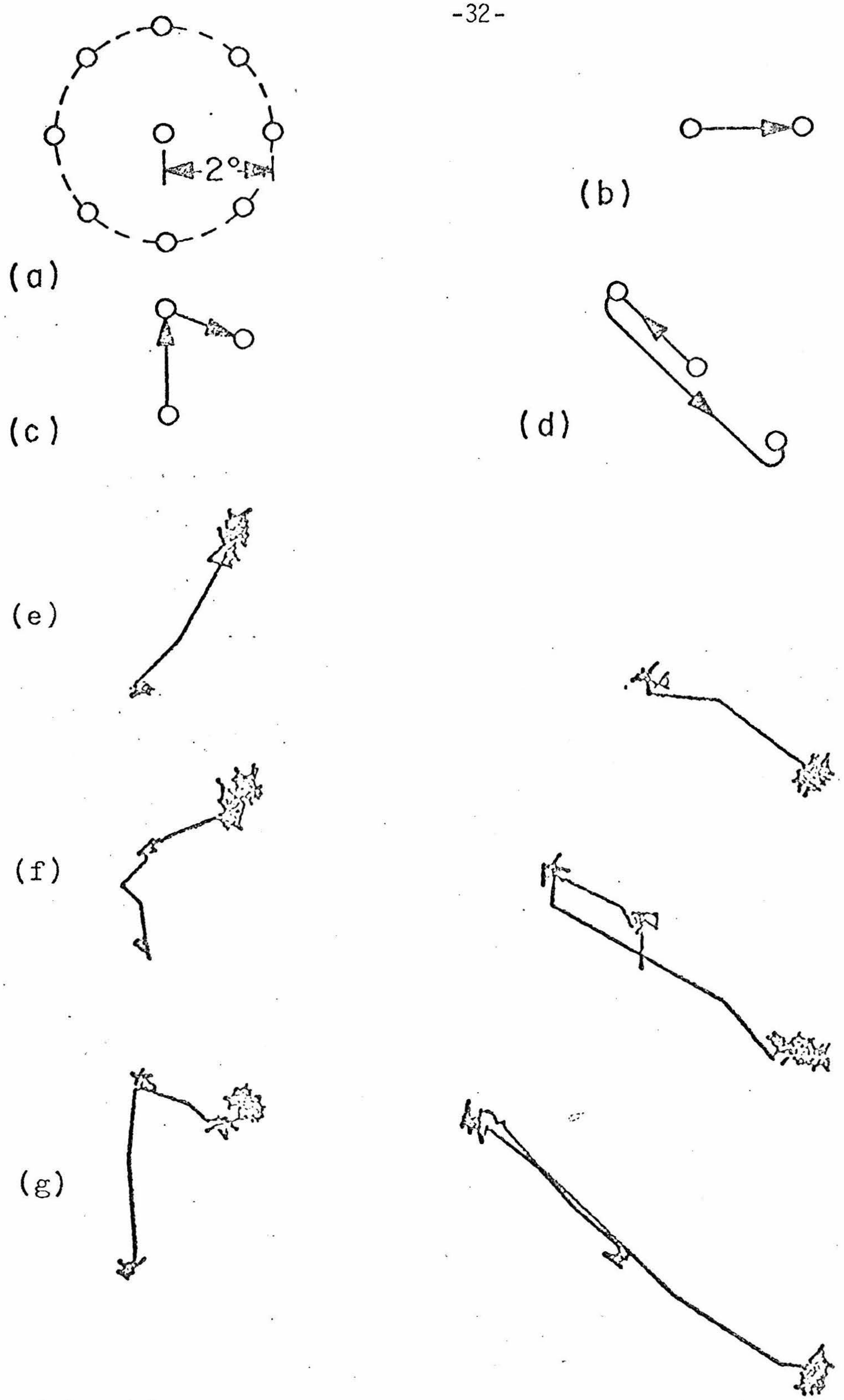


Fig. 4.1. (a) The center fixation location and eight locations where the target can jump to. (b) Single-step presentation. (c) Adjacent presentation. (d) Opposite presentation. (e) Reprogrammed saccade response. (f) Intermediate two-saccade response. (g) Full two-saccade response.

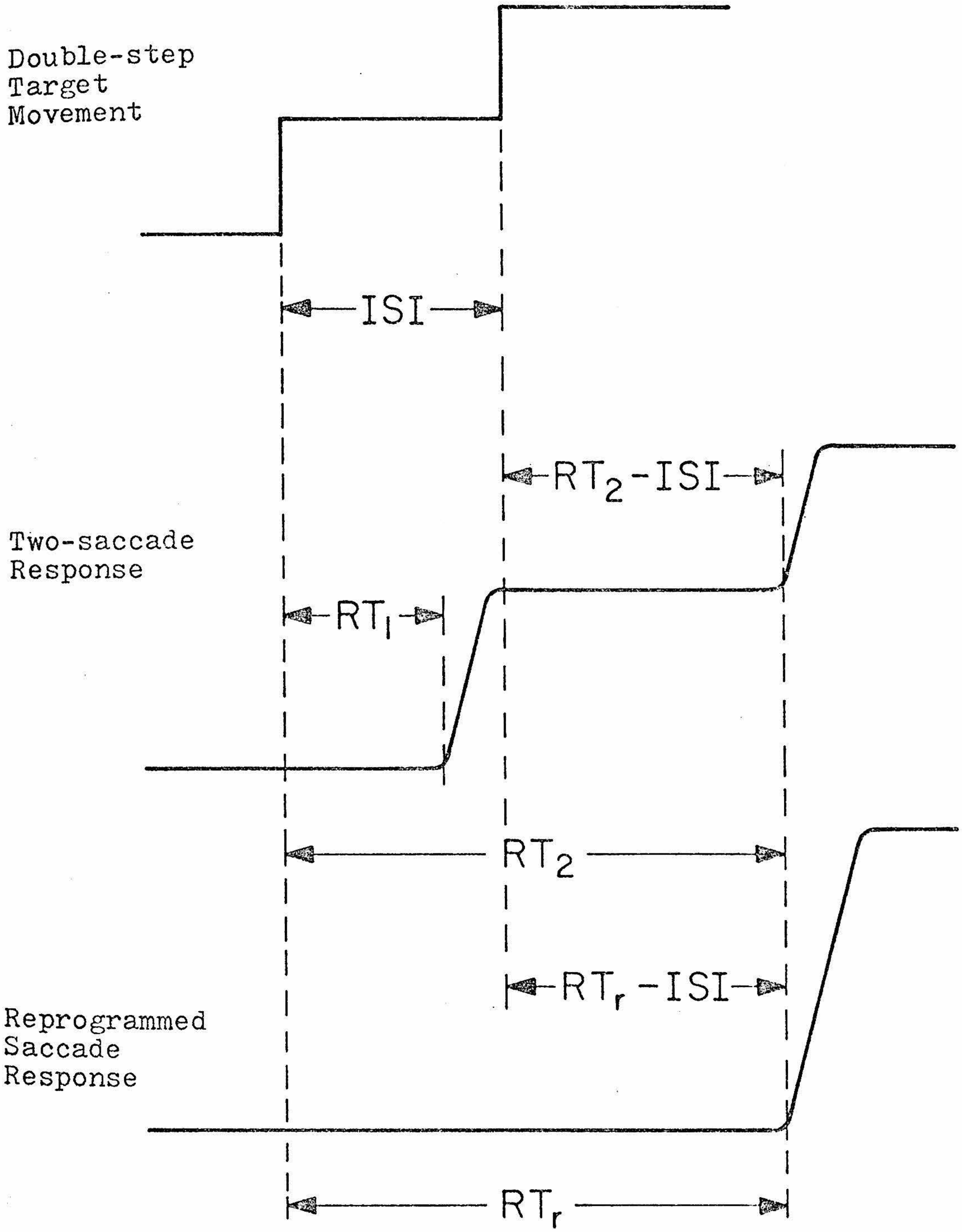


Fig. 4.1h. Definitions of RT_r, RT_1 and RT_2

ISI (interstimulus interval) is the time interval between two target-steps

$\overline{RT}$ is the average reaction time of saccadic eye movements in response to a single-step target jump.

$\overline{RT}_r$ is the average reaction time of a reprogrammed saccade (see below) measured from the beginning of the first target-step (Fig. 4.1e).

$\overline{RT}_1$ and $\overline{RT}_2$ are average reaction times of the first and the second saccades in two-saccade responses (see below) measured from the beginning of the first target-step (Fig. 4.1f,g).

Latencies measured from the beginning of the second target jump are $\overline{RT}_r$-ISI, $\overline{RT}_2$-ISI.

4.3.3.1 Classification of saccadic responses

The responses of saccadic eye movements to this two-step stimulus have been classified as one-saccade and two-saccade responses after Wheeles *et al.* In one-saccade responses, the saccade moved the subjects' fixation from the original gaze position to the final target position. In two-saccade responses, the first saccade brought subjects' gaze to the first target position then the second saccade moved fixation to the final target position.

However, in two-dimensional eye movements the above dichotomy was not so clear cut. There were cases in which the subjects responded with two saccades but both in the direction of the final target-step. The second saccade in this case could be a correction saccade. If only horizontal eye movements were studied and both target-steps were in the same direction, such a response would be mistakenly classified as a "two-saccade response" whereas it should be classified as a "one-saccade response" with a correction saccade. This error might become serious for those studies involving large saccades such as 15°-30° in which a large percentage of correction saccades exists. We therefore used the term "reprogrammed saccade response" to replace the "one-saccade response" for those responses in which the first target-step was ignored.

In the cases when the saccadic system responded to both target-steps, the magnitude of the first saccade was sometimes much smaller than the magnitude of the first target-step. Many of them had magnitudes of only half of the target distance. This short-fall could be due to reprogramming efforts of the saccadic programming system in response to new target information; for example, the first saccade could not be totally reprogrammed, but partial reprogramming was still possible. It could also be argued that the reduced magnitude was not due to reprogramming but was originally programmed that way, and normally would be followed by a correction saccade if there were no second target-step. If this argument holds, one would expect about the same percentage of short saccades in the control experiments (responses to single target-step), two-saccade responses and reprogrammed saccade responses. Figure 4.2 shows the distribution of the ratio of the magnitude of the first or the only saccade to the target-step magnitude for one subject. Table 4.1 shows the percentages of the first saccade less than 3/4 target-step. There is a significant increase in short

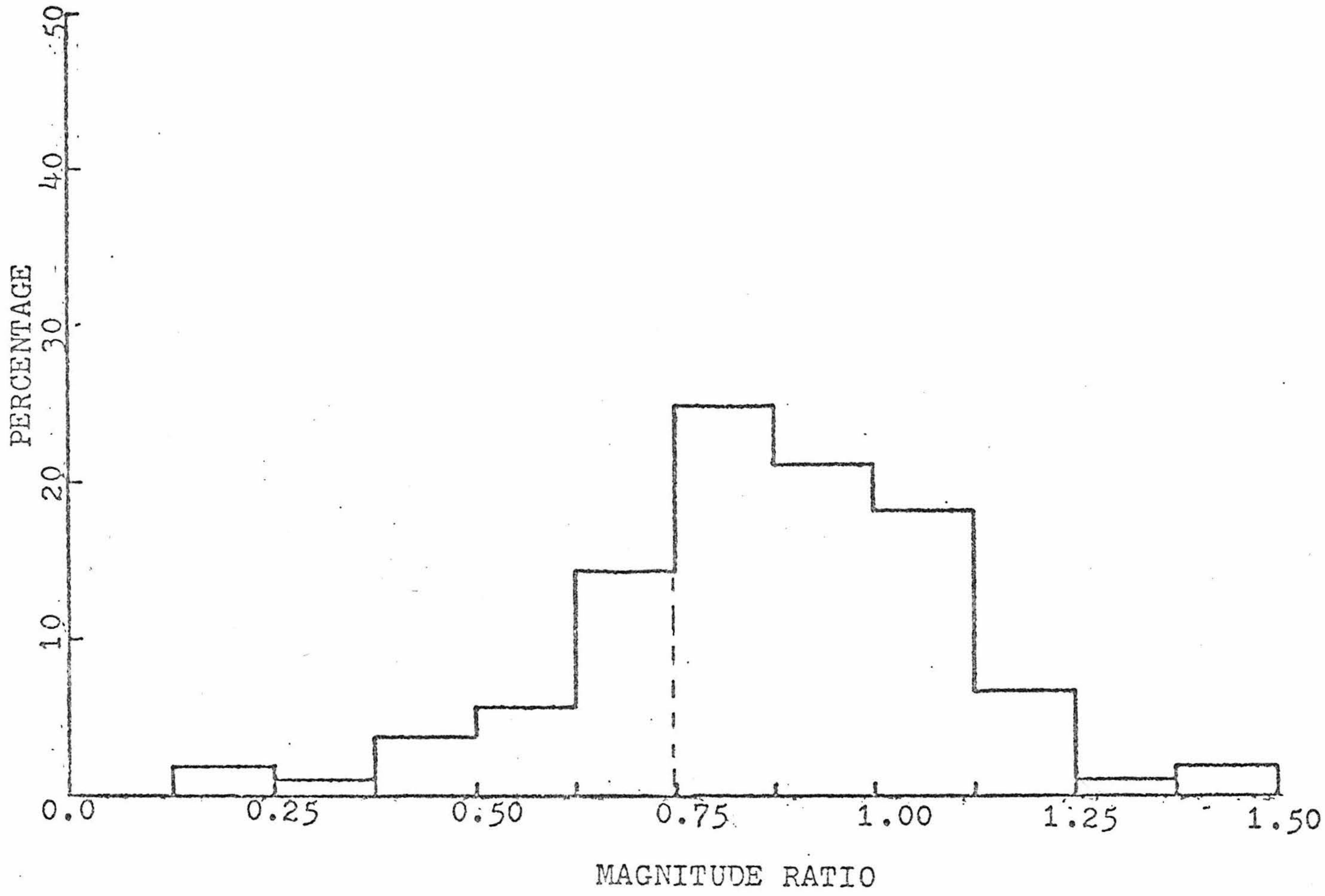


Fig. 4.2a. Distribution of the magnitude ratio. Single-step response. Subject MB.

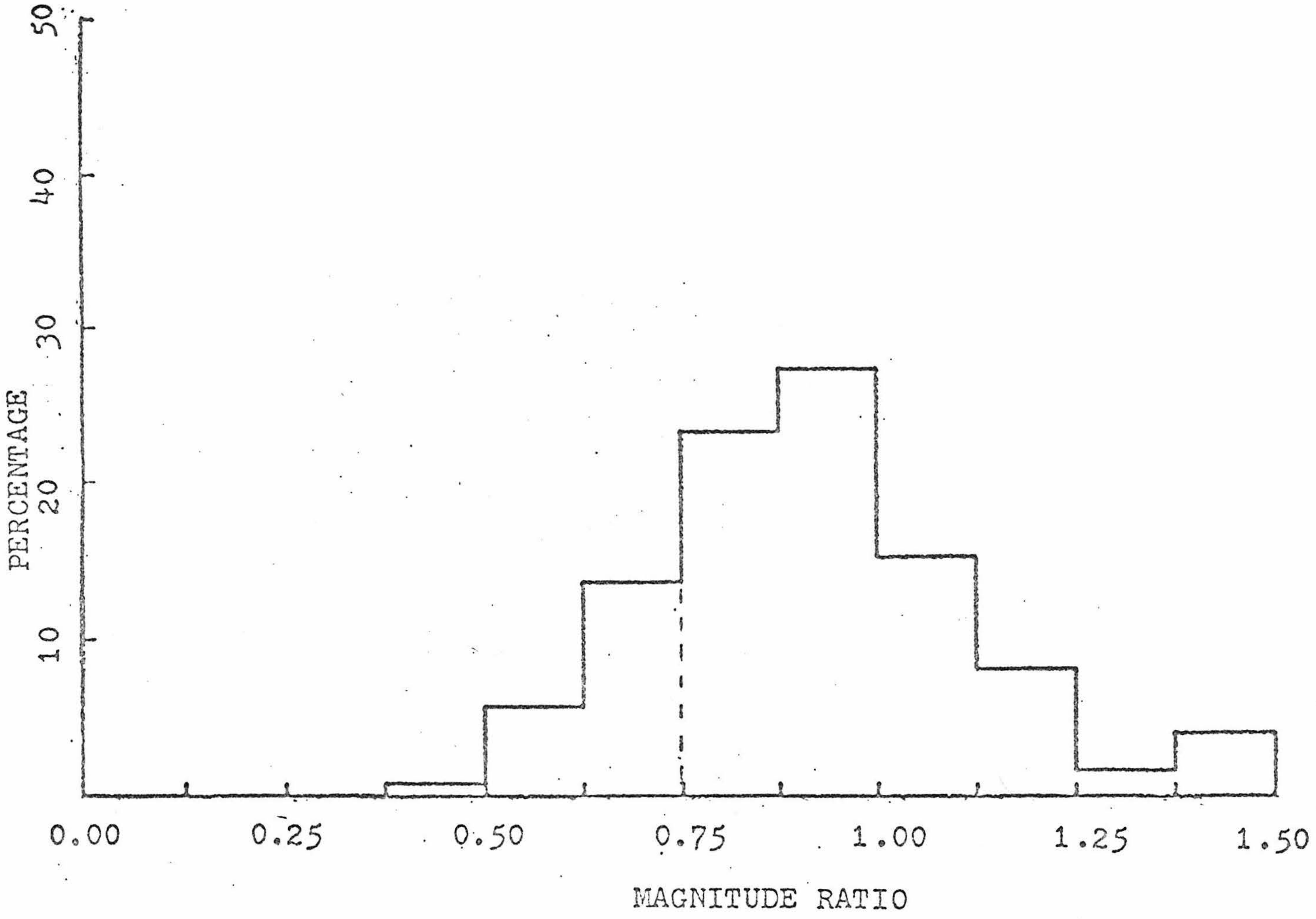


Fig. 4.2b. Distribution of the magnitude ratio. Reprogrammed saccade. Subject MB.

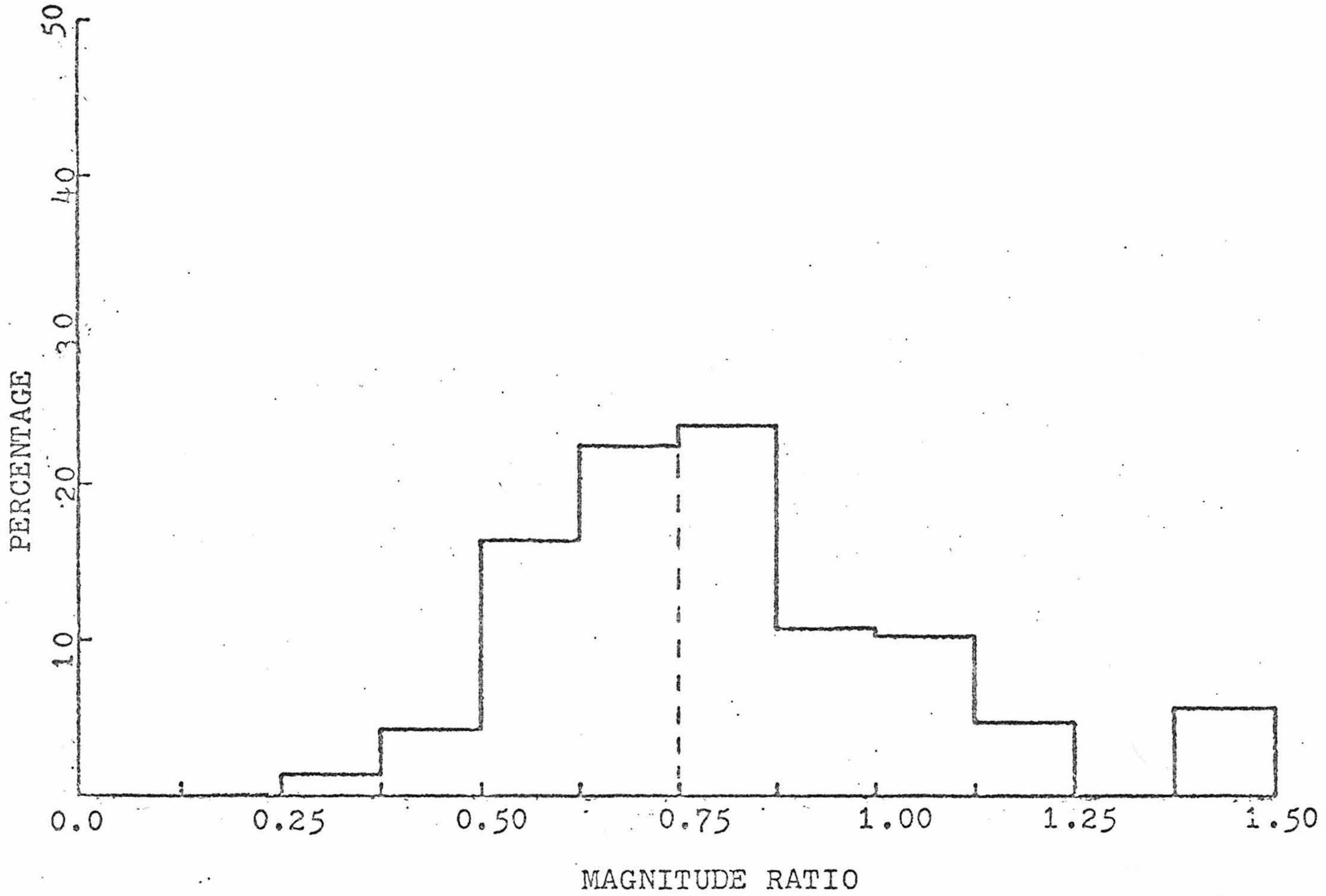


Fig. 4.2c. Distribution of the magnitude ratio. The first saccade in two-saccade response. Subject MB.

first saccades in the two-saccade response, hence these can probably be explained as partially reprogrammed saccades.

TABLE 4.1

Percentage of First Saccade less than 3/4 Target-Step

Single Target-Step	26.7
Reprogrammed Saccade	20.0
Two-Saccade Response	44.5

Figure 4.3 shows the frequency distribution of the differences between the direction angles of the first or the only saccade and its calibrated direction angle. All three plots show similar distribution. Thus it seems appropriate to classify the saccadic responses to two-step target movements into three classes instead of two:

(1) Reprogrammed saccade response--The initial saccade is completely reprogrammed and the first target-step is ignored. The saccadic eye movements are directed toward the final target-step only (Fig. 4.1e).

(2) Intermediate saccade response--The subject responds to both target-steps, but the magnitude of his initial saccade is shorter than 3/4 of the first target distance. The second saccade brings his gaze to the final target position. 3/4 is chosen arbitrarily (Fig. 4.1f).

(3) Full two-saccade response--Same as intermediate saccade response except that the magnitude of the first saccade is over 3/4 of the initial target distance (Fig. 4.1g).

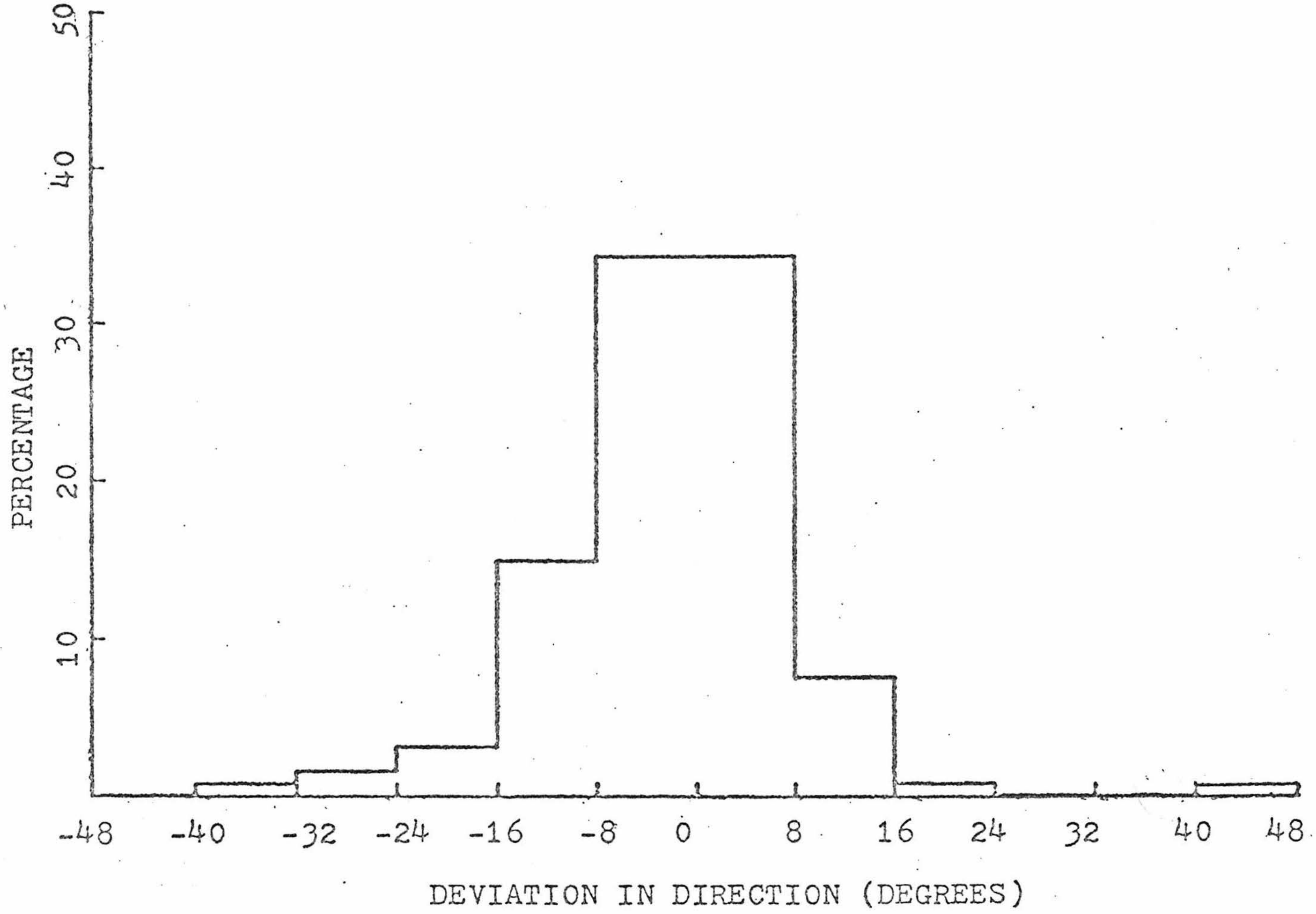


Fig. 4.3a. Distribution of the deviation in the direction of a saccade. Single-step response. Subject MB.

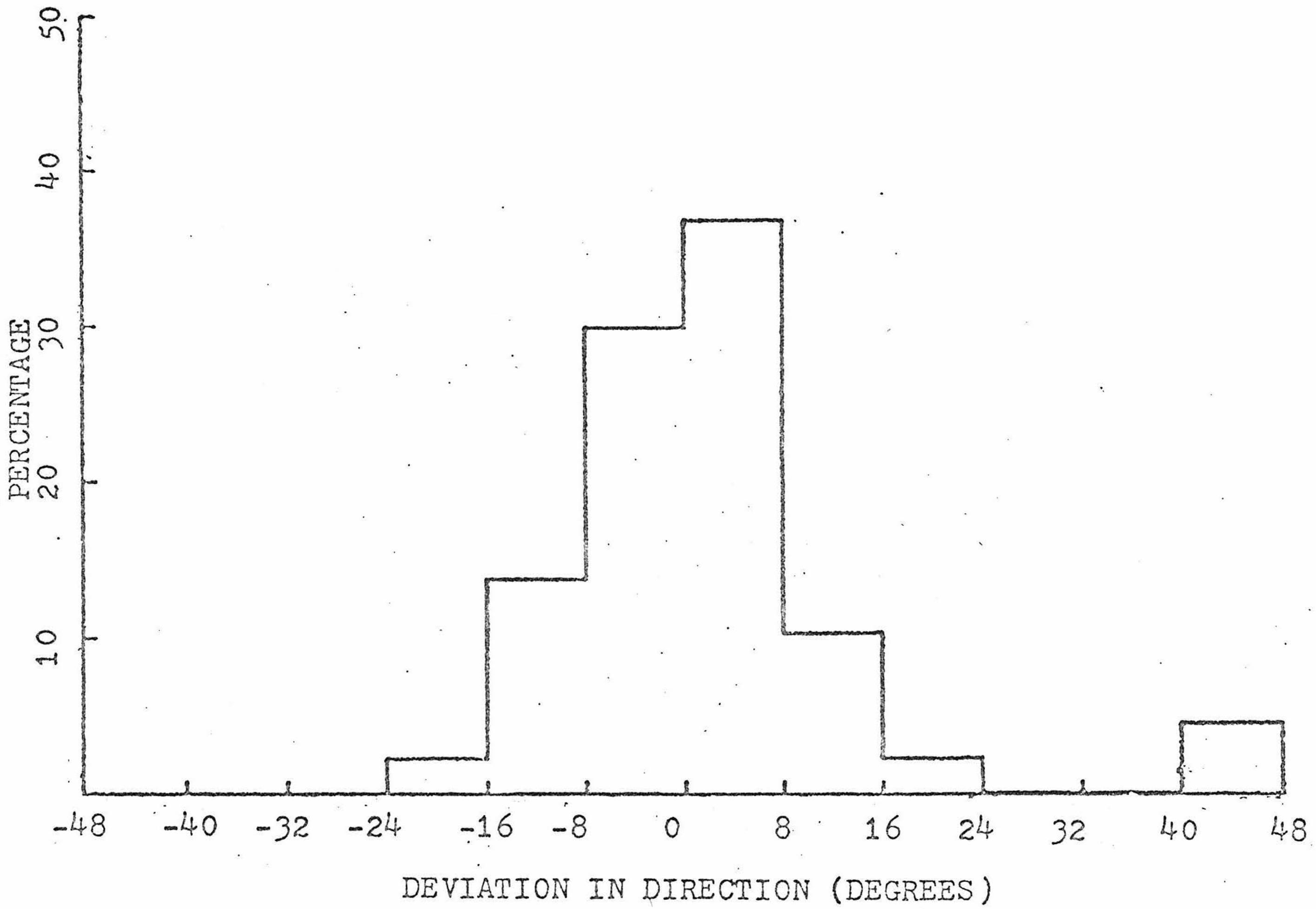


Fig. 4.3b. Distribution of the deviation in the direction of a saccade. Reprogrammed saccade. Subject MB.

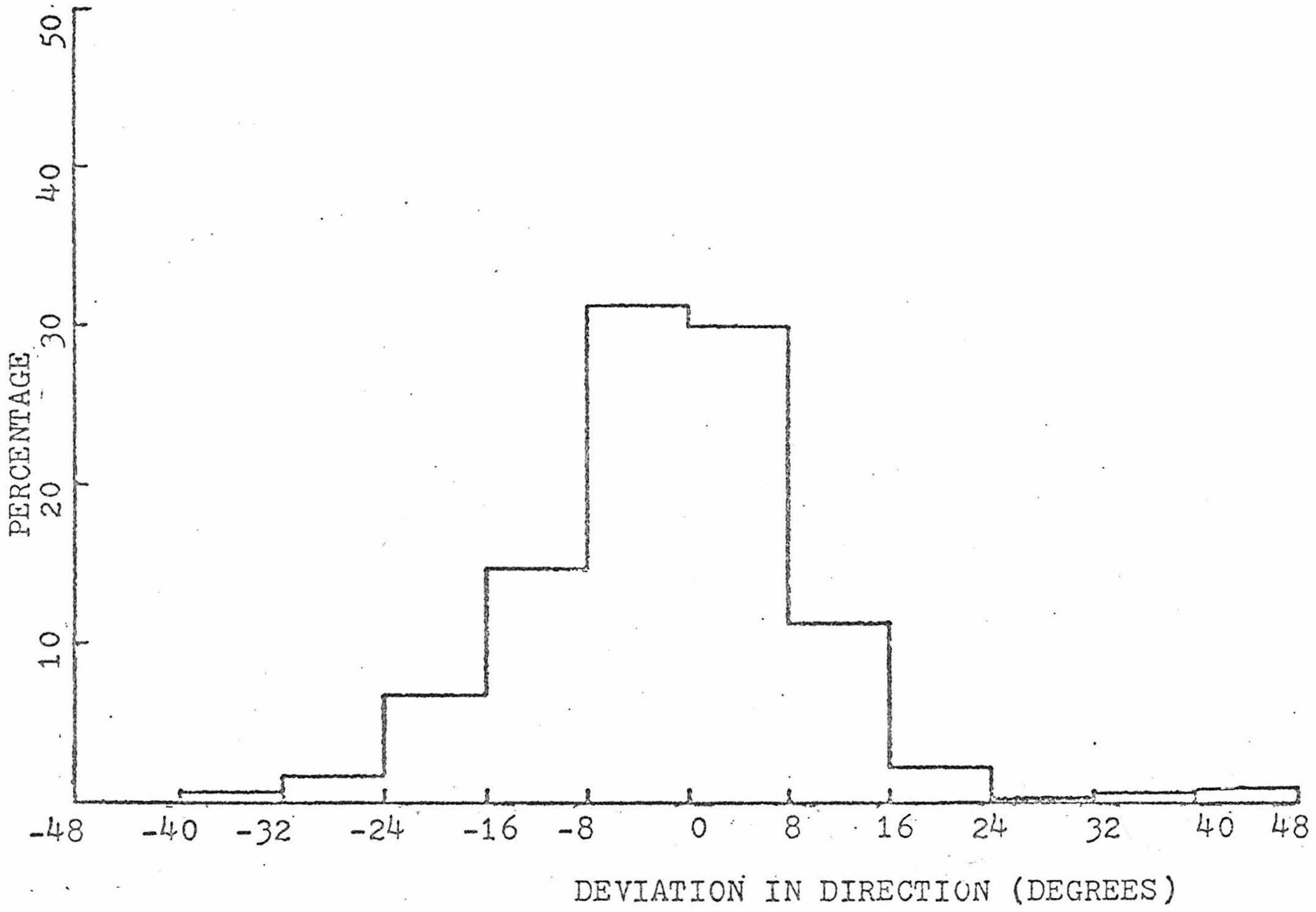


Fig. 4.3c. Distribution of the deviation in the direction of a saccade. The first saccade in two-saccade response. Subject MB.

4.3.3.2 Information processing in the programming of saccades

The reprogrammed saccade response and the intermediate saccade response represent two levels of reprogrammability of saccadic programming system. It appears that there is a state in the programming process after which the direction of the saccade cannot be changed but the magnitude can still be shortened in response to new target information. This suggests that direction computations and magnitude computations are separate processes. This has been suggested by Komoda et al. (1973). The intermediate saccade response further suggests that at least sometimes direction computation is finished earlier than magnitude computation.

The fact that only a very small percentage of shortened saccades have magnitudes less than half the normal tends to support the hypothesis that although the magnitude computation process requires the results of the direction computation, it actually starts before the end of the direction computation. If magnitude computation is serial with and follows direction computation, the chance of a saccade being partially reprogrammed at its early state of magnitude computation is greater and one would expect more saccades with less than half normal magnitude.

Now a general picture of information processing in the saccadic programming system can be drawn as follows. When a target is detected, the saccadic control system starts to compute the direction and the magnitude of the eye rotation. The direction computation hypothetically corresponds to the process of determining which sets of extraocular muscles should be activated and how to balance the side effects of each pair of extraocular muscles involved. The magnitude computation determines the innervation of each extraocular muscle pair, which in turn determines the magnitude and the time course of the saccade. When the eye velocity pulse is generated, neural circuitry converts it into the innervation of the extraocular muscles. This circuitry is under intensive study by the neurophysiologists as reviewed in Chapter II. I will call it execution process. The processes involving direction computation and magnitude computation have not been systematically studied yet.

4.3.3.3 Probabilities of three types of responses

The probabilities of three types of saccadic responses for different time intervals between target-steps are given in Table 4.2. The probability of a reprogrammed saccade for two subjects is shown in Fig. 4.4a as a function of ISI. The probability decreases monotonically as ISI increases.

TABLE 4.2

Probabilities of Three Types of Saccadic Responses

	Subject MB			Subject RW		
ISI (msec)	50	100	150	50	100	150
Reprogrammed saccade	0.83	0.45	0.128	0.81	0.42	0.05
Intermediate two-saccade	0.085	0.25	0.38	0.10	0.15	0.24
Full two-saccade	0.085	0.30	0.492	0.09	0.43	0.71
$\overline{RT}$	203.7 msec			196 msec		

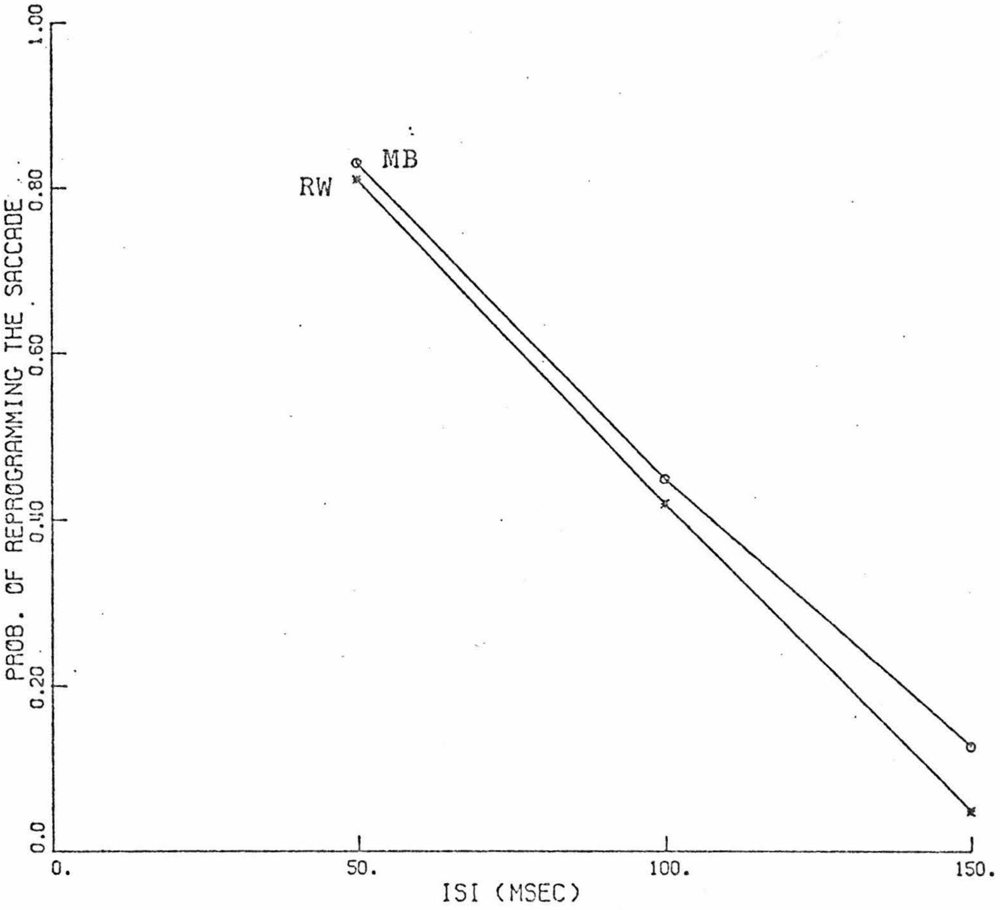


Fig. 4.4a. The probability of reprogramming a saccade vs ISI. Subjects RW, MB.

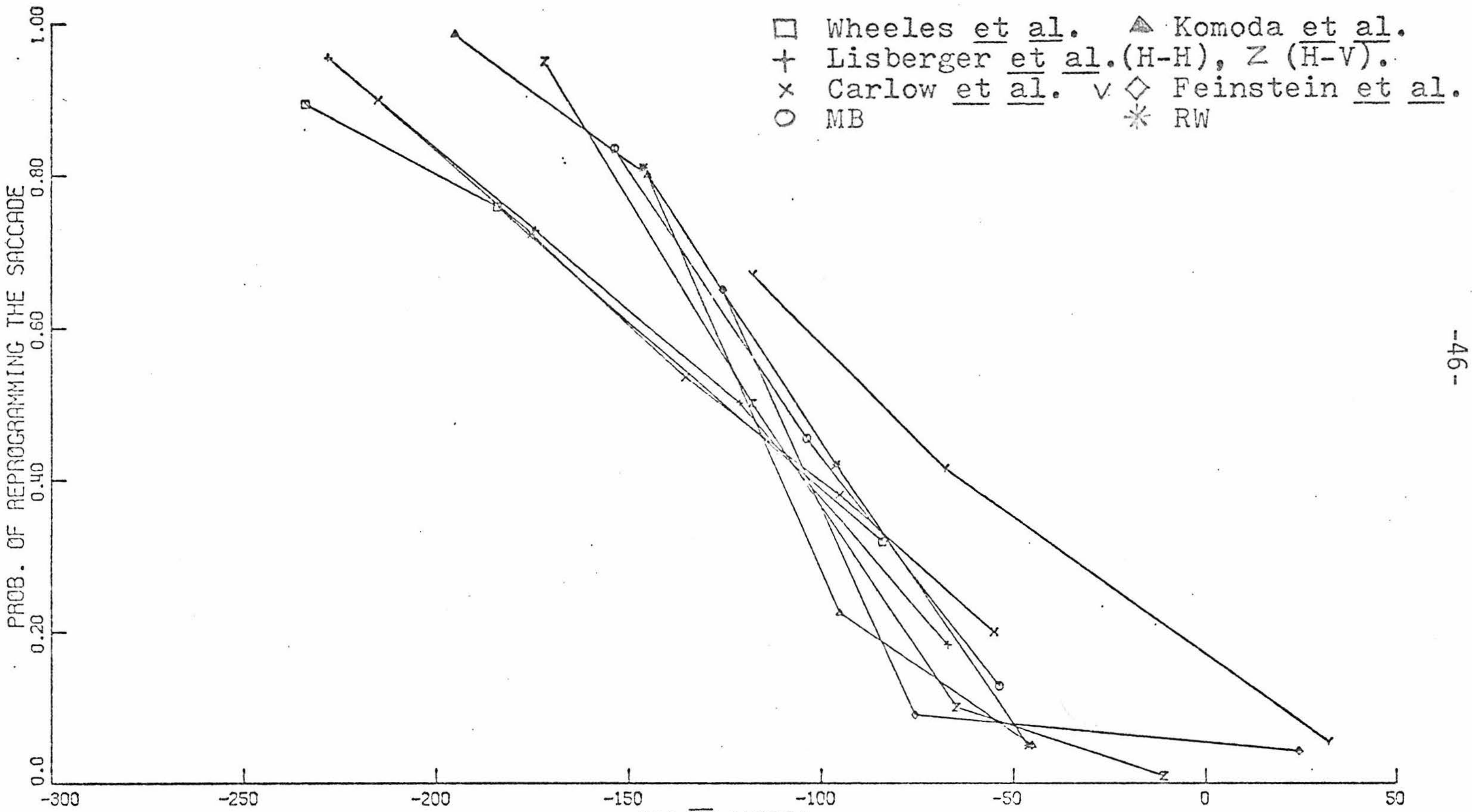


Fig. 4.4b. The probability of reprogramming a saccade vs ISI-$\overline{RT}$, for different studies. (Redrawn from Lisberger *et al.* 1975)

The data from previous publications show a similar relationship, but the actual probabilities vary greatly; for example, at ISI of 100 msec the probability of a reprogrammed saccade varies from 0.80 (Komoda *et al.*) to 0.08 (Feinstein and Williams). The difference between these probabilities might be caused by different reaction times or information processing times for saccadic eye movements among different observers. Lisberger *et al.* (1975) showed that many of the disparities between the results presented by various research groups were reduced if the probabilities were plotted as a function of $\overline{RT}$-ISI.

In Fig. 4.4b we plot the probabilities of reprogrammed saccade responses from various groups as a function of ISI-$\overline{RT}$. The negative sign of ISI-$\overline{RT}$ indicates that the second target-step occurs prior to the actual eye movements. From Fig. 4.4b it is evident that the earlier new target information is presented relative to the projected beginning of the initial saccade, the higher is the probability of the initial saccade being reprogrammed.

If this scheme for normalization resulted in complete reconciliation of the differences for various subjects and laboratories, this would indicate that the presentation time of the new target-step before the initial saccade is the most important factor affecting the reprogrammability of a saccade. For different subjects with different reaction times, this result will indicate that there is a fixed probability that the initial saccade may be reprogrammed as long as the second target-step is presented at a fixed time before the initiation of the first saccade.

If the above statement is true, what information does it give us about the origin of variations in the reaction time of saccadic eye movements? It is reasonable to assume that the reprogrammability depends on the time relationship between the detection of the second target-step and some processes in the programming of the first saccade. These will be referred to as critical processes for the convenience of discussion.

These critical processes must occupy the time interval close to the end of the saccadic reaction time. Any variation in the processing times of these critical processes without suitable change in the detection time of the second target-step will cause the above normalization scheme to fail. Since the relative time interval between the presentation of the second target-step and the initiation of the first saccade is the critical factor in this scheme, the increase of the processing time in the critical processes has to be matched by the decrease of the detection time in order for the detection of the second target-step to fall at the correct point of the critical processes.

Therefore, this normalization scheme is implicitly based on the assumption that the variations in the processing times of the critical processes and the detection processes will compensate each other, and the variations in the rest of the processing times make up for the remainder of the variations in a subject's saccadic reaction time.

One may think that it is more reasonable to assume that the variations in saccadic reaction times are distributed among all programming processes in roughly the same proportion. In this case, a better factor to normalize the effect of different individual reaction times should be ISI/$\overline{RT}$. The probabilities of reprogramming a saccade for our two subjects and from different studies are plotted against ISI/$\overline{RT}$ in Fig. 4.4c,d.

Both normalization factors reduce the disparities among different observers but neither accomplishes the task completely. This suggests that neither the compensatory assumption nor the equal distribution assumption of the variations in the saccadic reaction time covers the whole story. I chose normalization factor ISI/$\overline{RT}$ because it seems more logical.

4.3.3.4 Reaction times of reprogrammed saccades

Wheeles *et al.* found that the average reaction time of reprogrammed saccades measured from the second target-step ($\overline{RT}$-ISI) was about 40 msec longer than the normal reaction time of saccades. They explained this extra 40 msec as the time required to cancel the programming of previous saccades. However, Komoda *et al.* found no "extra cancellation time", and if both horizontal target-steps were in the same direction, it even took less time than the normal latency to reprogram a saccade.

In our opposite presentation, the two target-steps were in completely opposite directions. To reprogram a saccade in this case, agonist and antagonist oculomotor muscle pairs had to switch their roles. In adjacent presentation the two target-steps were at a 45° angle. To reprogram a saccade, the antagonistic muscle remains the antagonist, but the new saccadic eye movements may require additional

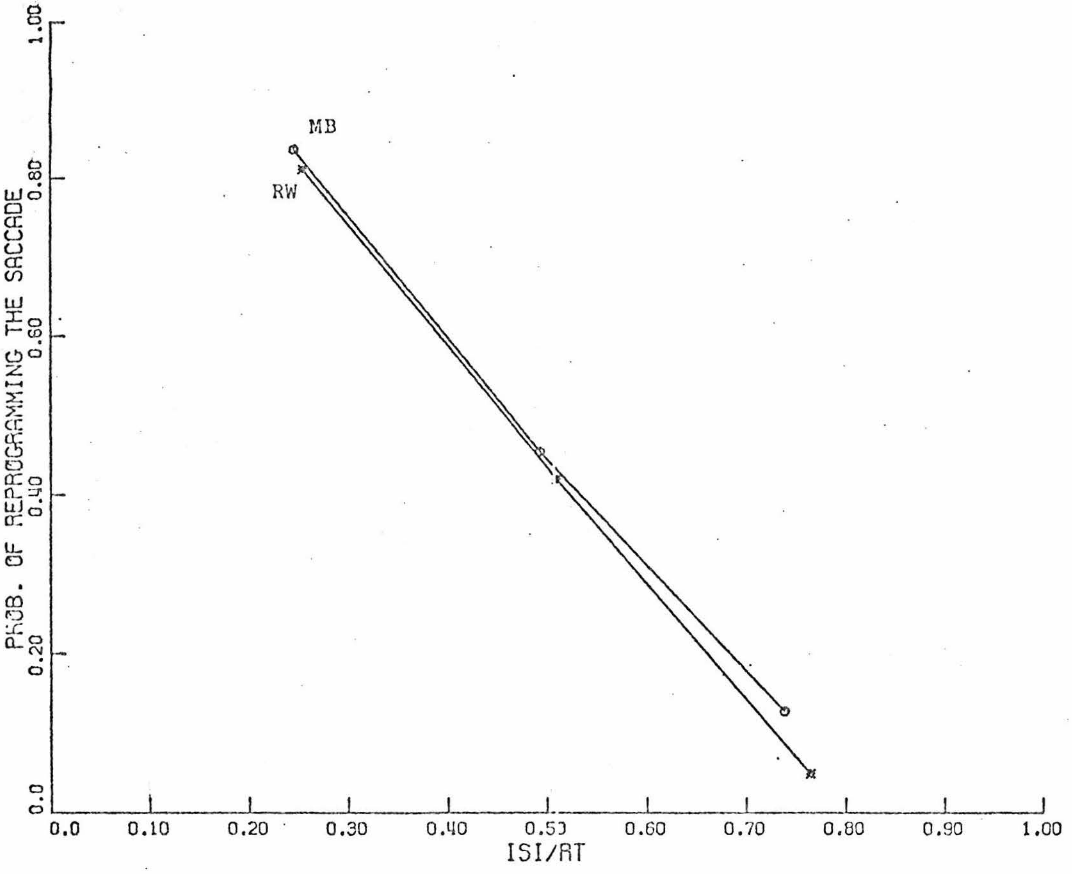


Fig. 4.4c. The probability of reprogramming a saccade vs ISI/$\overline{RT}$.
Subjects RW, MB.

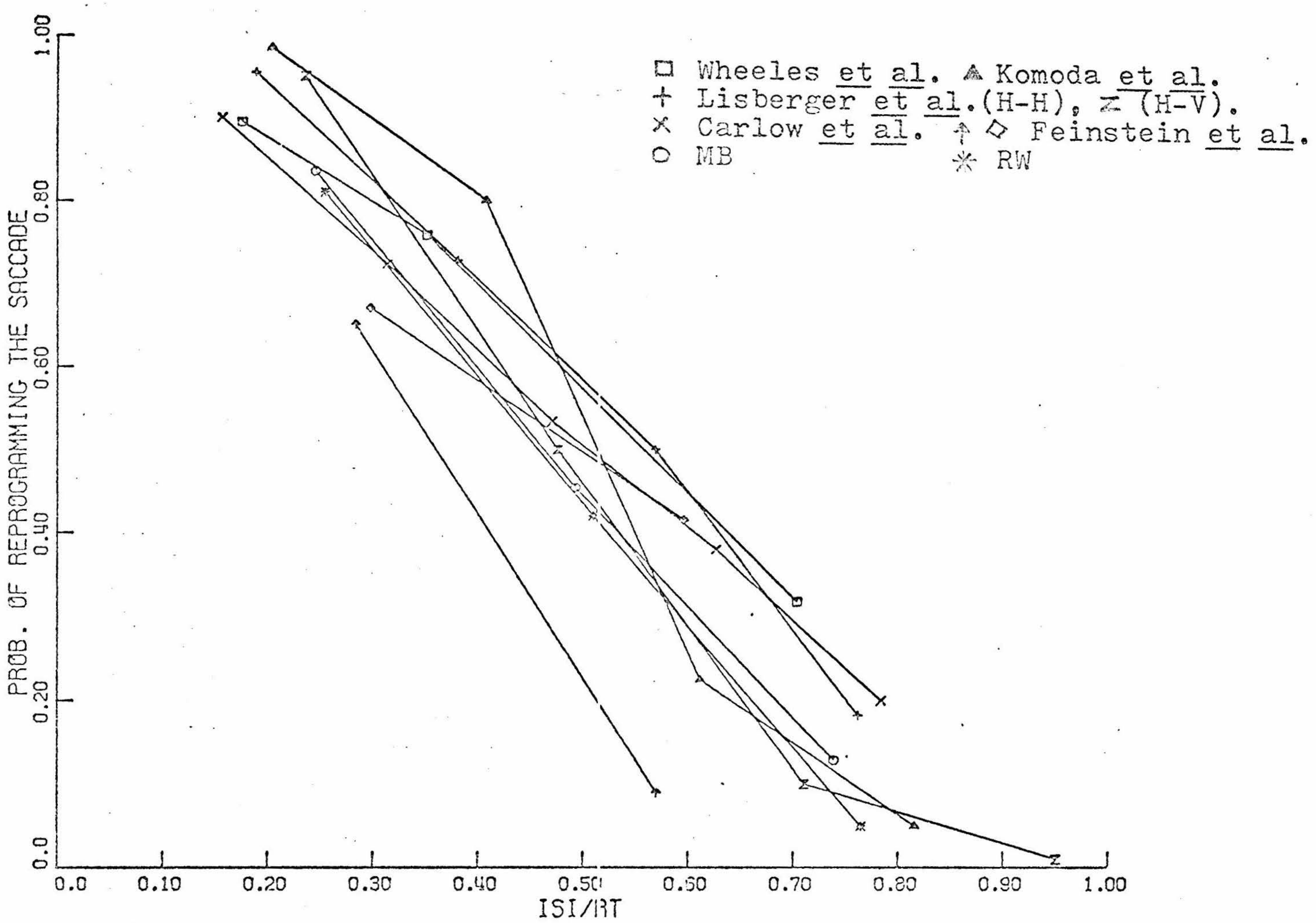


Fig. 4.4d. The probability of reprogramming a saccade vs ISI/$\overline{RT}$ for different studies.

sets of oculomotor muscles to participate.

The average reaction times of reprogrammed saccade for opposite and adjacent presentations are shown in Fig. 4.5a,b. Figure 4.5a shows $\overline{RT}_r$ as a function of ISI, and Fig. 4.5b shows ($\overline{RT}_r$-ISI) as a function of ISI. For the adjacent presentation, the average reprogramming times were about the same as normal saccadic reaction times for both subjects. For opposite presentations extra time was observed for both subjects. However, it was about 40 msec more for one subject and 80 msec more for the other.

The fact that more than the normal programming time of a saccade is needed to reprogram a saccade in the opposite direction may have important implications in our understanding of the mechanisms of saccadic programming. One possible explanation for this extra time is that it is required to switch the role of agonist and antagonist in the central program. In other words, in order to program a new saccade in the opposite direction, the previous programming for the antagonist must be erased. This explanation implies that in these early stages of saccadic programming, the control programs for both agonistic and antagonistic oculomotor neurons already exist. Many people think that the inhibitive signals to the antagonistic motorneurons are driven from the signals sent to agonistic motorneurons through "sign conversion" processes of interneurons. They believe that central processes do not program both agonistic and antagonistic motorneurons individually. If this is true, there is no need to cancel the previous programming of the antagonist. In this event the

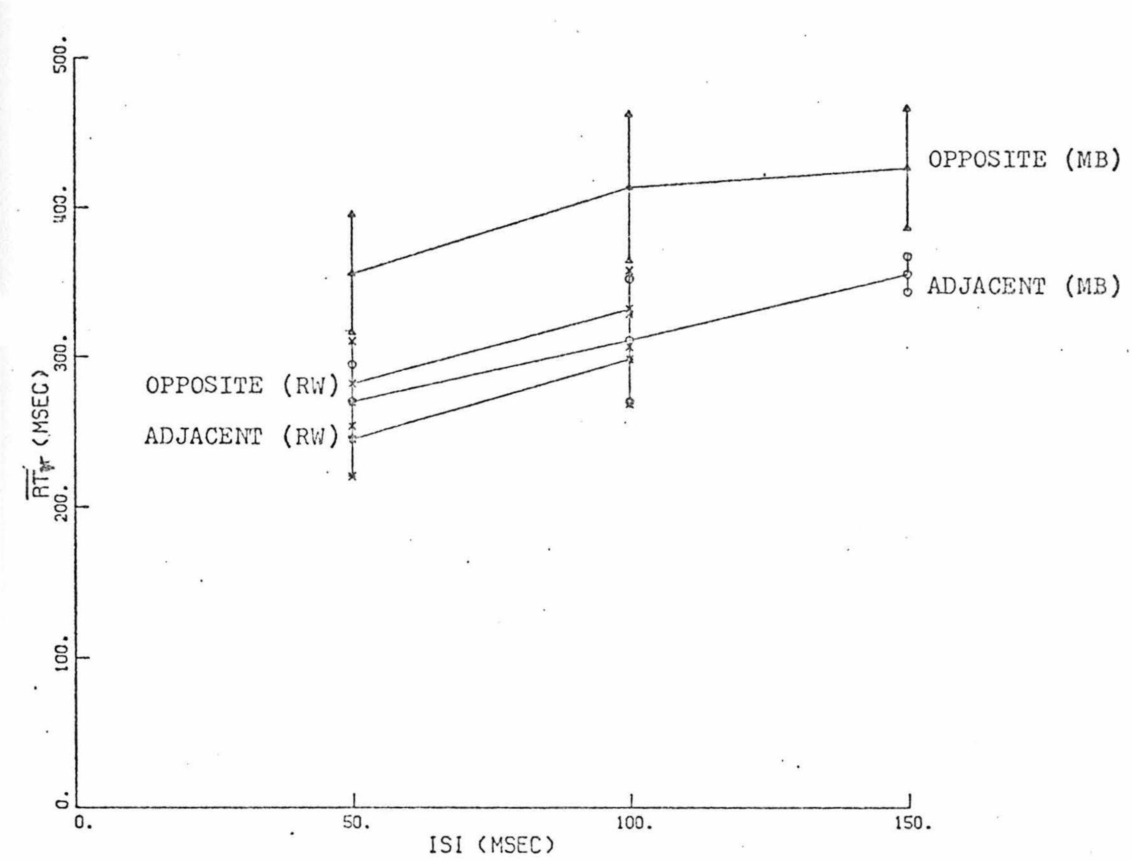


Fig. 4.5a. Average reaction times of the reprogrammed saccade as a function of ISI. Both Subjects. Both opposite and adjacent presentations.

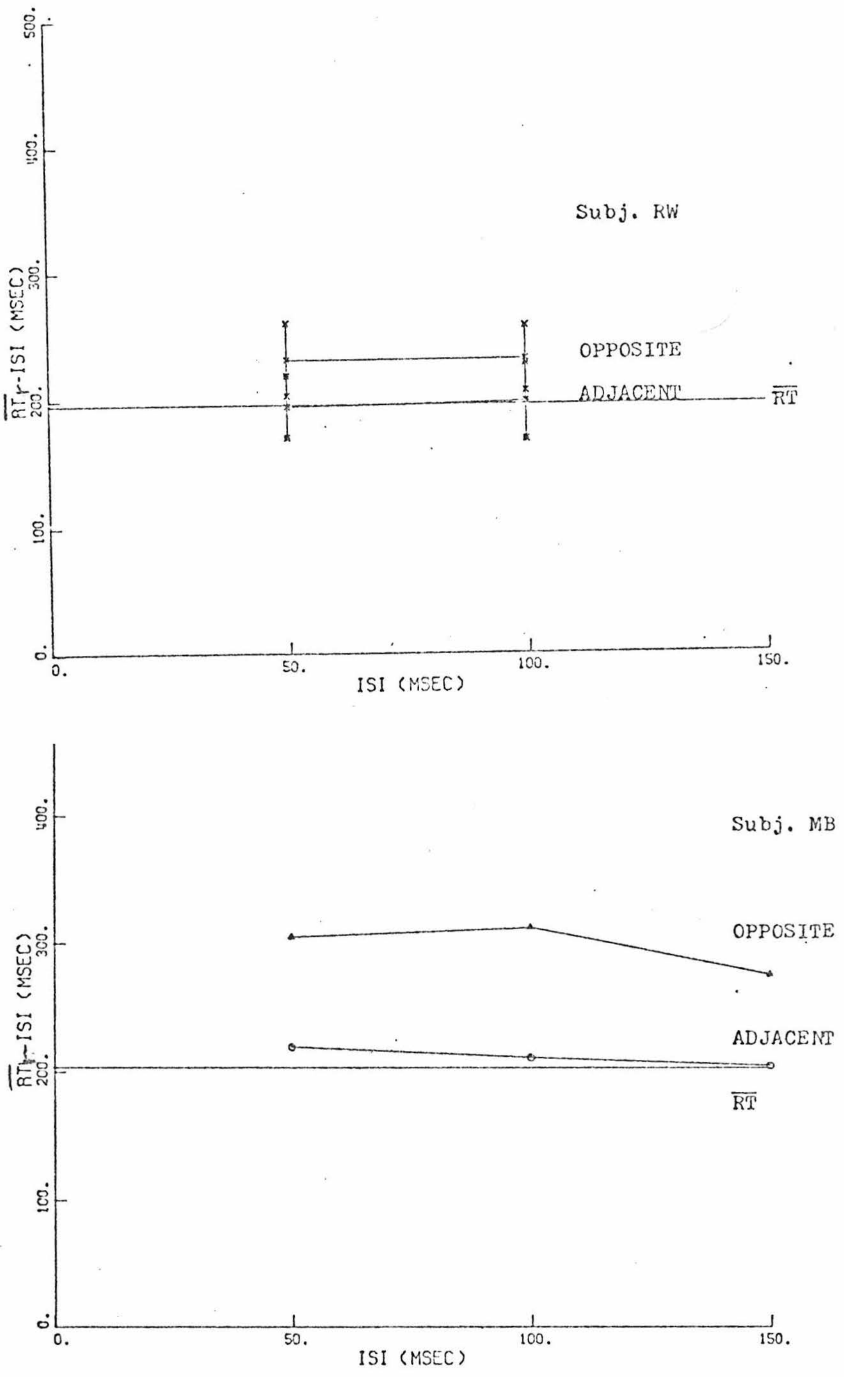


Fig. 4.5b. Average reaction times of the reprogrammed saccade measured from the onset of the second target step. Both opposite and adjacent presentations. Top is for Subject RW and bottom is for Subject MB.

extra time could be explained as the cancellation time for the previous program for the agonistic motorneurons.

There are two plausible theories to explain the extra programming time for opposite presentations. For simplicity, let us call them the "antagonist cancellation theory" and the "agonist cancellation theory." To differentiate between these two theories, the following modified two-target-step experiment was performed. Only the two horizontal and the two vertical vertices of the octagon are used (Fig. 4.6a). Let the first target-step appear at any one of the four vertices and the second target jump to one of two vertices on the perpendicular axis (Fig. 4.6b). This target pattern will be referred to as orthogonal presentation. If the saccade is reprogrammed, a completely different pair of agonistic and antagonistic motorneurons will be involved. If the agonist motorneurons which are required for a saccade to the first target position are not needed for the reprogrammed saccadic eye movement, the agonist theory would require the previous program to these motorneurons to be cancelled, and extra cancellation time should be observed. Conversely, for the new reprogrammed saccadic eye movement, there are no antagonistic motorneutrons which have been previously programmed, therefore no cancellation is needed. In summary, if an increased reaction time is observed for the reprogrammed saccade, this would argue against the antagonist cancellation theory, while an unchanged reaction time would argue against the agonist cancellation theory.

In this experiment the orthogonal presentation was randomly intermixed with the opposite presentation and the single-step presen-

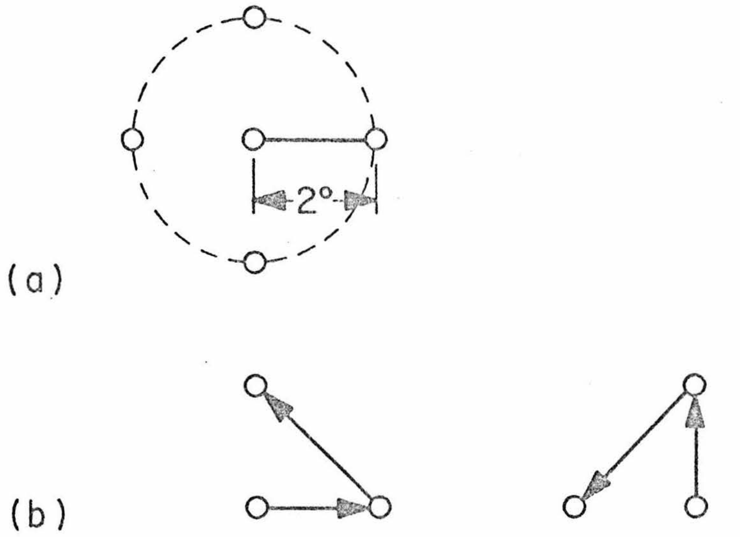


Fig. 4.6. (a) Four locations that the target can jump to.
(b) Two examples of target-jump sequence.

tation of the previous experiment is used as the control. The results showed a comparable percentage of reprogrammed saccade response as the previous experiment. The average reaction times of the reprogrammed saccades ($\overline{RT}_r$) for both types of target presentation are shown in Fig. 4.7 for subject RW. The first point that can be made from these data is that the reaction time for orthogonal presentation is increased, thus the antagonist cancellation theory is not upheld. Secondly, the change in the reaction time for the opposite presentation is the same as that for the orthogonal presentation, hence we might assume that the same mechanism is operative in both cases. The extra time seems to be used to erase the previous direction program even though that particular muscle will not be activated in the new reprogrammed saccade. This may hint at the existence of a memory buffer which will hold the results of the directional computation. If the direction of the reprogrammed saccade is not a direction similar to the previous one, the unfinished computation results in the memory may have to be erased before the new results can be put in. Further properties of this memory are discussed in Chapter V.

4.3.3.5 Reaction times of two-saccade responses--A discussion of sample data control system models of saccadic eye movements

Young and Stark (1962) proposed a sampled-data control system model for saccadic eye movements. They originally used a periodical impulse sampler to sample input information every 200 msec. This sampling concept was derived from the discrete nature of saccadic eye movements. For example, when tracking a fast ramp target motion or

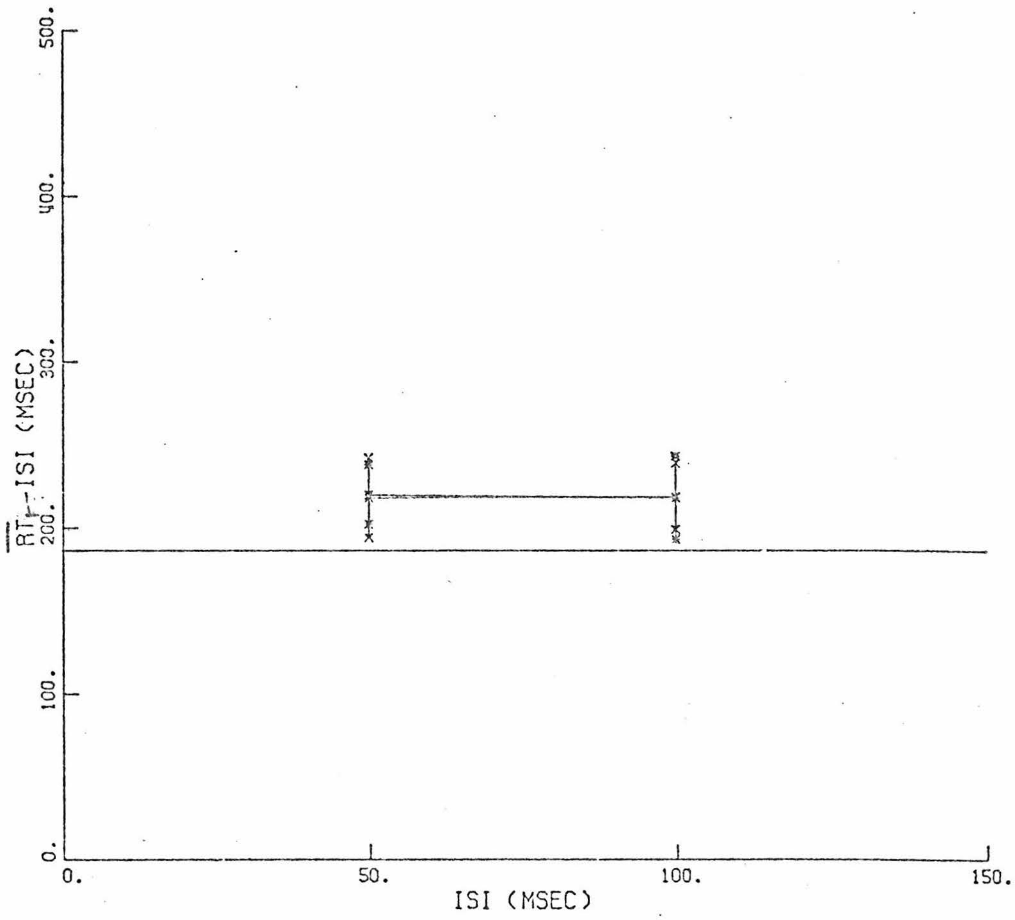


Fig. 4.7. The average reaction times of the reprogrammed saccade measured from the onset of the second target step. For both opposite and orthogonal presentations. Subject RW.

following a single target displacement in stabilized vision (Fender and Nye, 1961) the position errors were corrected by a sequence of saccadic eye movements in the same direction but spaced 200 msec apart. This model has proven to be successful in human engineering applications and some clinical applications. This model was consistent with the results of Westheimer's pulse-step experiments but had to be modified to explain the results obtained by Wheeles et al.

One modification proposed by Young, Forster and Van Houtte (1968) was to let the occurrence of the sample be statistically distributed with an average sample interval of 200-240 msec. Becker and Fuchs (1969) and Robinson (1968) proposed a different modification which assumes that each sample pulse has finite duration. The duration is a stochastic variable and the information arriving within this duration will be processed continuously.

Although both modifications can explain the probability of reprogramming saccades, the sampling interval of 200 msec conflicts with some experimental observations. This sampling interval predicts that on the average no two saccadic eye movements can occur within 200 msec of each other. This is because new information cannot be processed until the next sample occurs and the average sampling interval, or the average refractory period is about the reaction time of saccadic eye movements. This predicts that the average reaction times of the second saccade in two-saccade responses will be constant for those ISI's less than 200 msec and $\overline{RT}_2$-$\overline{RT}_1$'s are about 200 msec.

On the other hand, several people have argued for continuous processing in the saccadic programming system (Komoda et al., 1973; Becker and Jügens, 1975). The continuous processing model would predict that $\overline{RT}_2$-ISI should be constant for all ISI or $\overline{RT}_2$ is a linear function of ISI with slope 1.

Figures 4.8a,b,c,d show the average reaction times of the first and the second saccades in two-saccade responses. Both opposite and adjacent presentations are plotted. There is no significant difference between these two cases. This is expected, since in both cases the direction of the second saccade is on the opposite side of the first saccade (180° and 112.5°, respectively).

The shape of $\overline{RT}_2$ and $\overline{RT}_2$-ISI as a function of ISI does not fit completely with either model. The parameter $\overline{RT}_2$-ISI is roughly constant for ISI of 100 and 150 msec, but $\overline{RT}_2$-ISI increases by about 50 msec when ISI is reduced to 50 msec. In other words, when ISI is greater than 100 msec, the data are consistent with the prediction of a continuous processing model, but not for ISI's less than 100 msec.

These results suggest that two saccadic eye movements can be programmed in parallel to each other temporarily as long as the two target-steps are at least 100 msec apart. In other words, in the two-step target presentations, when the appearance of the second target-step comes at such a stage that the programming of a saccadic eye movement to the first target-step cannot be cancelled, the programming processes for a new saccadic eye movement to the second target position will start immediately, even though the system is still

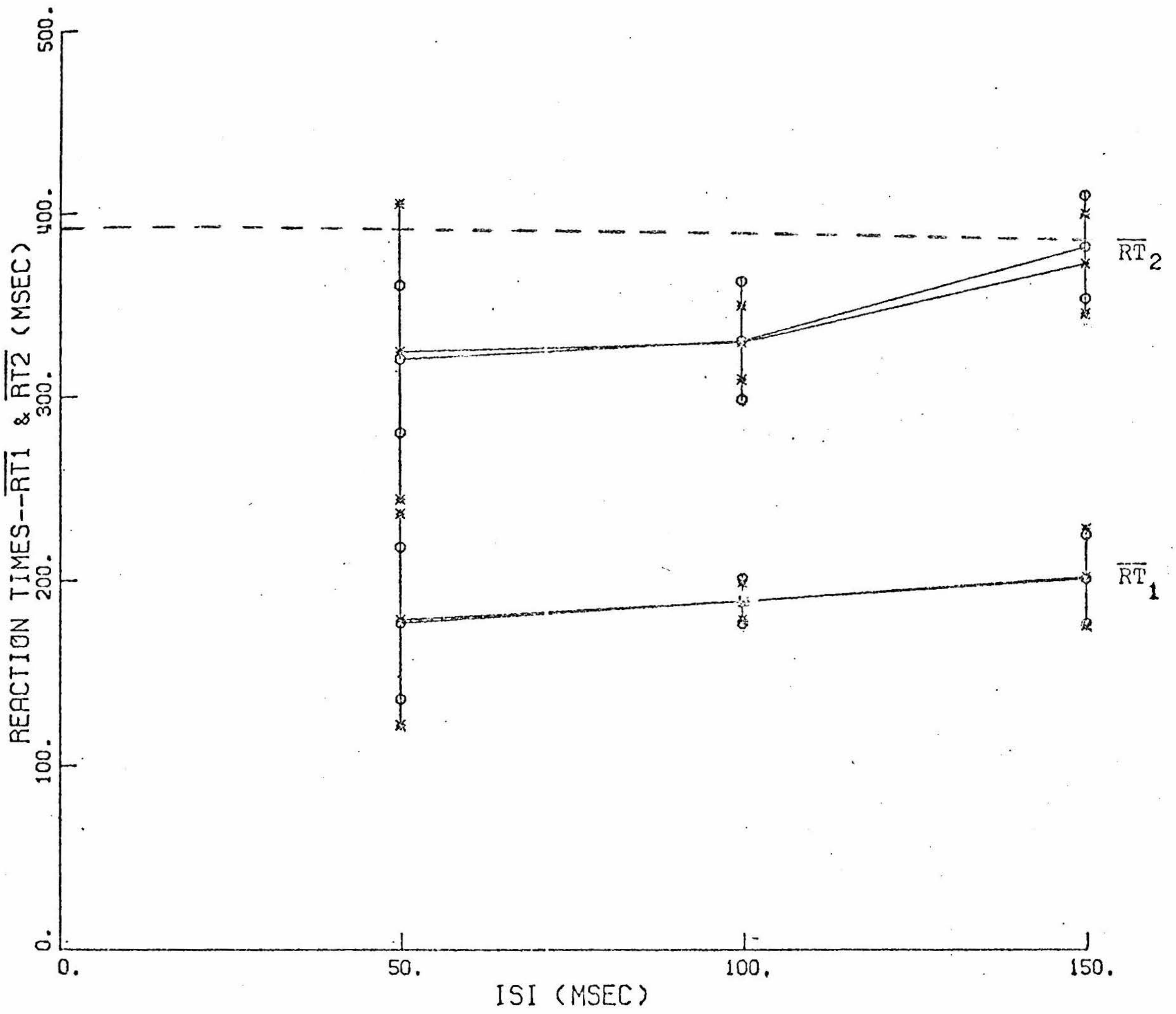


Fig. 4.8a. Dashed line shows the predicted RT_2 from a sampled-data model. Subject RW.
0 - adjacent presentation, * - opposite presentation.

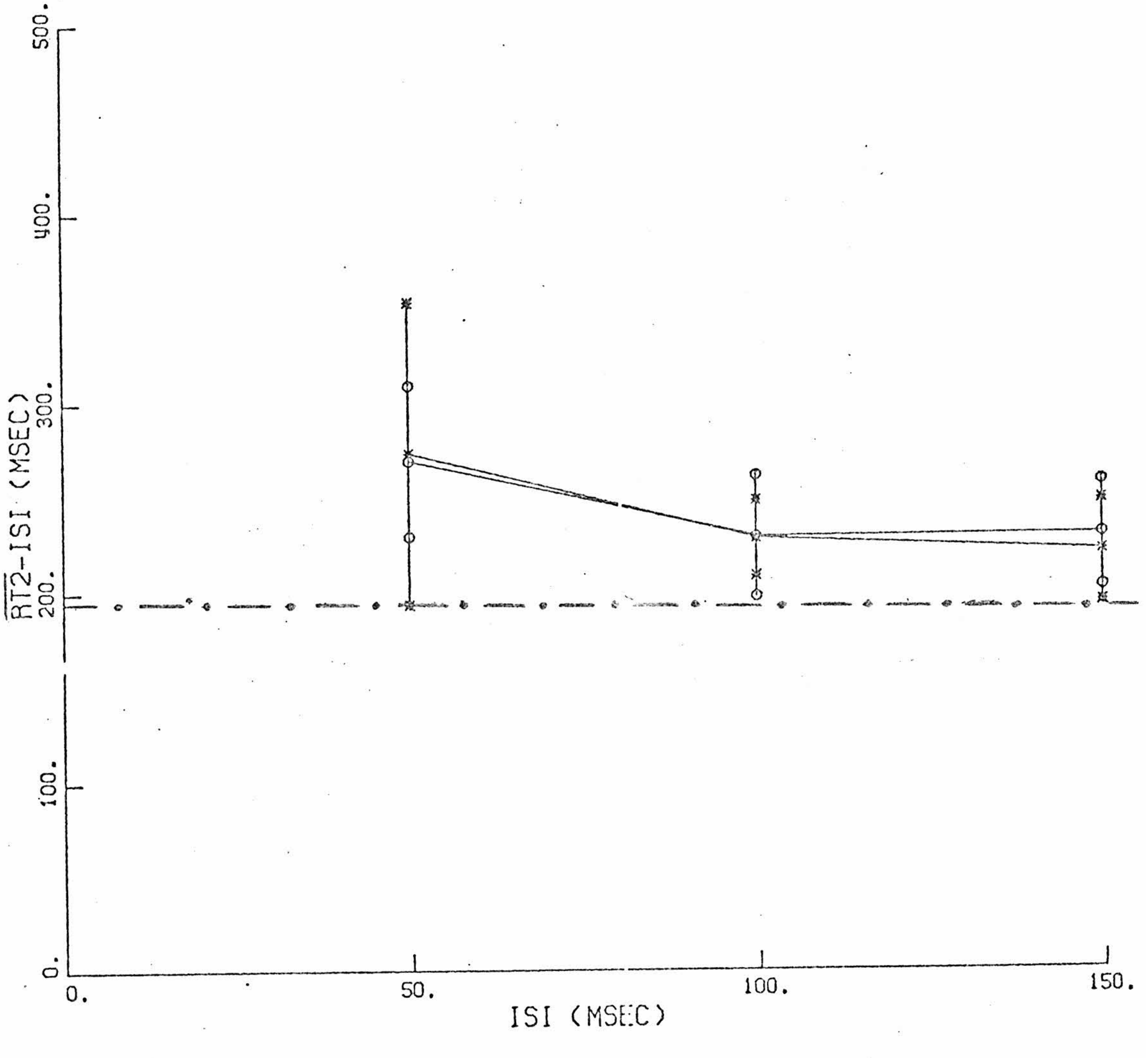


Fig. 4.8b. Dash-dot line shows the predicted $\overline{RT_2}$-ISI from a continuous processing model. Subject RW.
0 - adjacent presentation, * - opposite presentation.

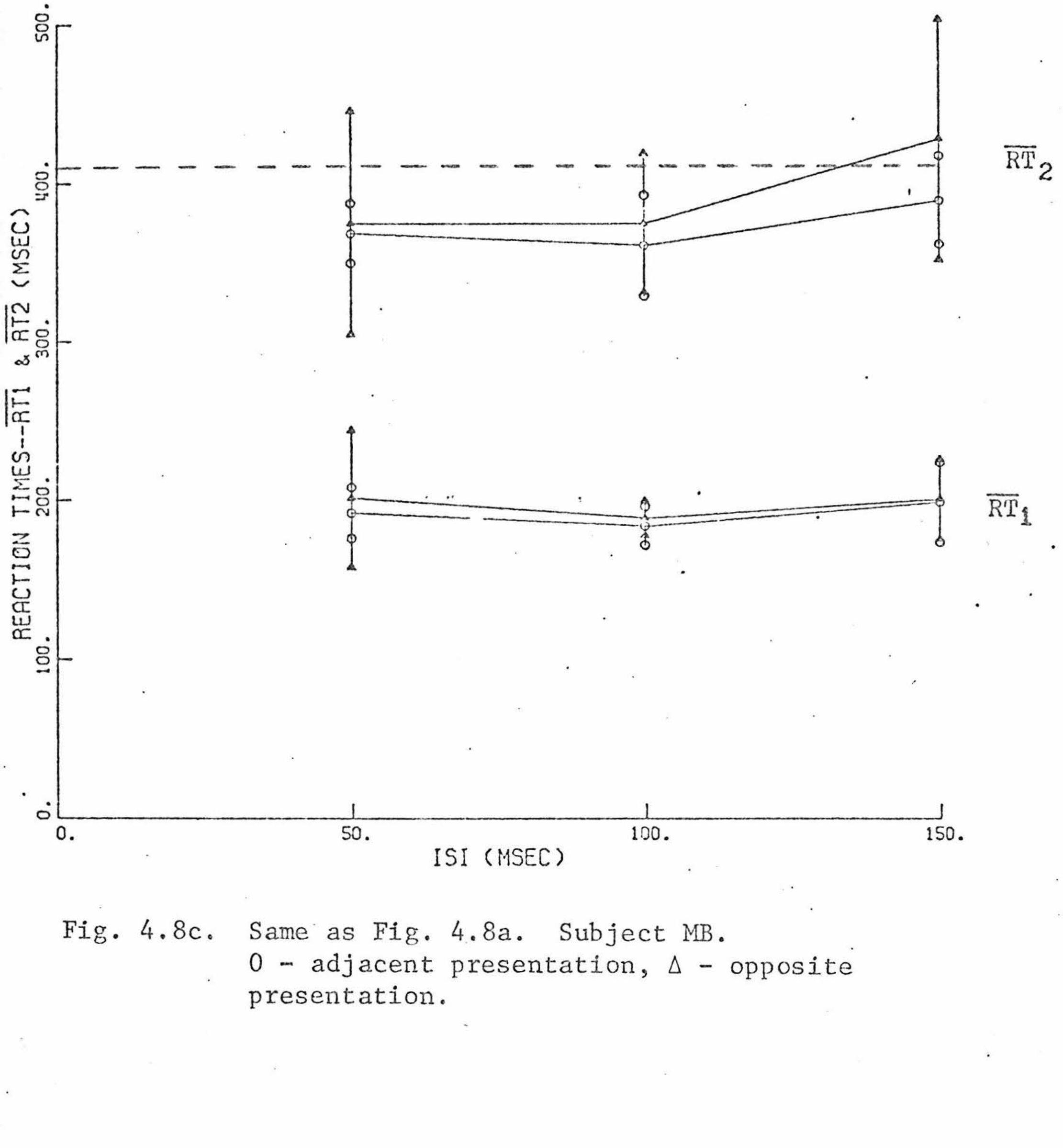


Fig. 4.8c. Same as Fig. 4.8a. Subject MB.
0 - adjacent presentation, Δ - opposite presentation.

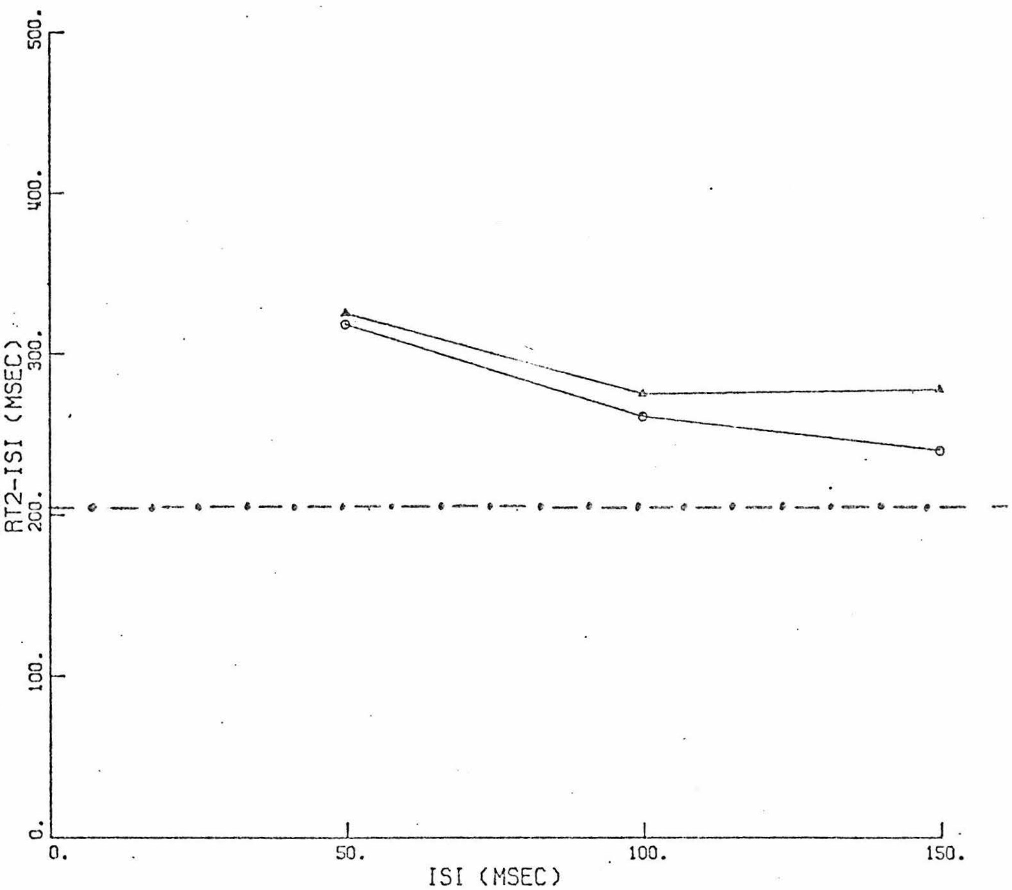


Fig. 4.8d. Same as Fig. 4.8b. Subject MB.
0 - adjacent presentation,
Δ - opposite presentation.

processing the first saccade. If the new target information appears within 100 msec of the old target information, a refractory period in the programming is evident. The estimated length of this refractory period is about 100 msec.

What is the nature of this refractory period? In order to program two saccades at the same time, the programming processes must know where the first saccade will end up before the eye is actually moved. This can be achieved through an internal feedback from the programming of the first saccade. When the programming of the second saccade reaches the stage of computing its direction and magnitude, it has to use this feedback information. If this feedback is not there, the programming of the second saccade will have to wait. So the observed 100 msec refractory period may well be the processing time of direction and magnitude computation processes for the first saccade.

This may suggest a sampling interval of 100 msec; however, a sampled-data model with this sampling interval is unable to explain some other phenomena. Therefore, instead of a sampled-data model, an information processing model is proposed in Chapter VI to represent the programming processes of saccadic eye movements.

4.4 Experiment II

4.4.1 Purpose of Experiment

In Experiment I, it is shown that the probability of reprogramming a saccade depends on when the new target-step is presented in relation to the reaction time of a saccade. To be precise, the probability should depend on when the new target-step is detected in relation to the reaction time of a saccade. These two statements are certainly different because different observers have different detection times for the same target and even the same observer may exhibit spontaneous fluctuations in detection times. It is interesting to investigate how the variations in detection time may affect the probability of reprogramming a saccade. Since it is difficult, if not impossible, to control the subjective variation of an observer's detection time, one can change the distribution of his detection time by manipulating the detectability of the target; for example, change the brightness of the target.

If we change the detectability of the second target-step, the way in which the probability of reprogramming a saccade is affected can give us some clues about how the information processes in saccadic programming are connected.

A logical arrangement is that the detection process, computation process and execution process are connected sequentially in that sequence. From the discussion of the results of Experiment I, the function of $\overline{RT}_2$ vs ISI (Fig. 4.8a,b) suggests that when the computation process is processing a saccade, the detection process can process new incoming information. Whether the initial saccade is cancelled or not depends on the timing relation between the detection of the second target-step and the computation process of the initial saccade. In this arrangement, any change in the detection time is equivalent to a change in the presentation time of the second target-step with the same detection time. Therefore, the change in the detection time should cause the probability curve of reprogramming a saccade in Fig. 4.4a to shift linearly along the horizontal axis. It also causes the average reaction time of the saccade in response to the second target-step to increase or decrease (that is, $\overline{RT}_r$ or $\overline{RT}_2$) by the same amount as the time interval shifted on the ISI axis in Fig. 4.4a.

Although the above connection is the most logical one, there is always the possibility that some other connection is true. For example, the computation processes may directly work on the raw input data instead of getting data from the detection process. In this connection, the detectability of the target will affect the processing time of the computation process. The linear shift of the probability curve along the ISI axis may still occur, but the amount of change in $\overline{RT}_r$ and $\overline{RT}_2$ will not be the same as the amount shifted on the ISI axis.

This experiment is designed to change the detectability of the second target-step from Experiment I and study what effect it has on the probability of reprogramming a saccade and on the reaction times.

4.4.2 Methods

The same paradigm for target presentation as in Experiment I was used. The target for fixation and the first target-step was the same annulus as was used in Experiment I, but the target for the second step was different.

Two different targets were employed. In the first one I tried to increase its detectability by filling the inside of the annulus so that the (area x luminance) ratio of this target over the previous annulus target was about 3.2/1.

In the second case the detectability was decreased by using only four dots arranged in 2 x 2 matrix to replace the previous annulus; the (area x luminance) ratio was 1/29.

The instructions to the subject were the same.

4.4.3 Results and Discussion

The results of the experiment using the center-filled target for the second target-step were very close to those obtained from the previous experiment. The increased brightness did not affect the latencies and the ability to reprogram saccades. The explanation is that the annulus used in the previous experiment already saturated target detectability; therefore, increasing its brightness did not increase its detectability.

The experiment using only four dots as a target for the second target-step showed some different results. Figure 4.9 shows the probability of reprogramming saccades, together with the same curve from Experiment I for one subject. Figures 4.10 and 4.11 show that the average reaction times for reprogrammed saccades and the second saccades of two-saccade responses are about 40-50 msec longer for this less detectable target than for the previous experiment. Also, the probability curve for reprogramming saccades was shifted to the left by about 50 msec along the ISI axis. These results are consistent with the sequential connections of information processes in the saccadic programming system, as discussed in the Purpose of Experiment.

The argument presented above does not exhaustively prove that the proposed system arrangement is actually the true one; however, since

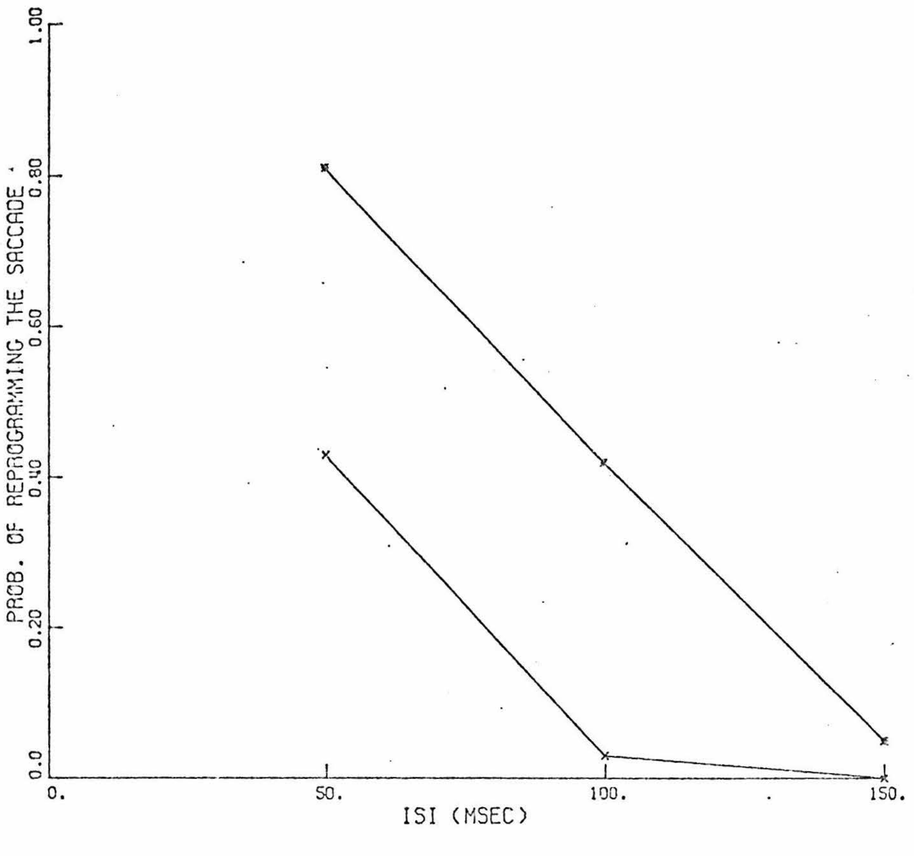


Fig. 4.9a. Comparison of the probability of reprogramming a saccade. * - from experiment I, x - for less detectable second target-step. Subject RW.

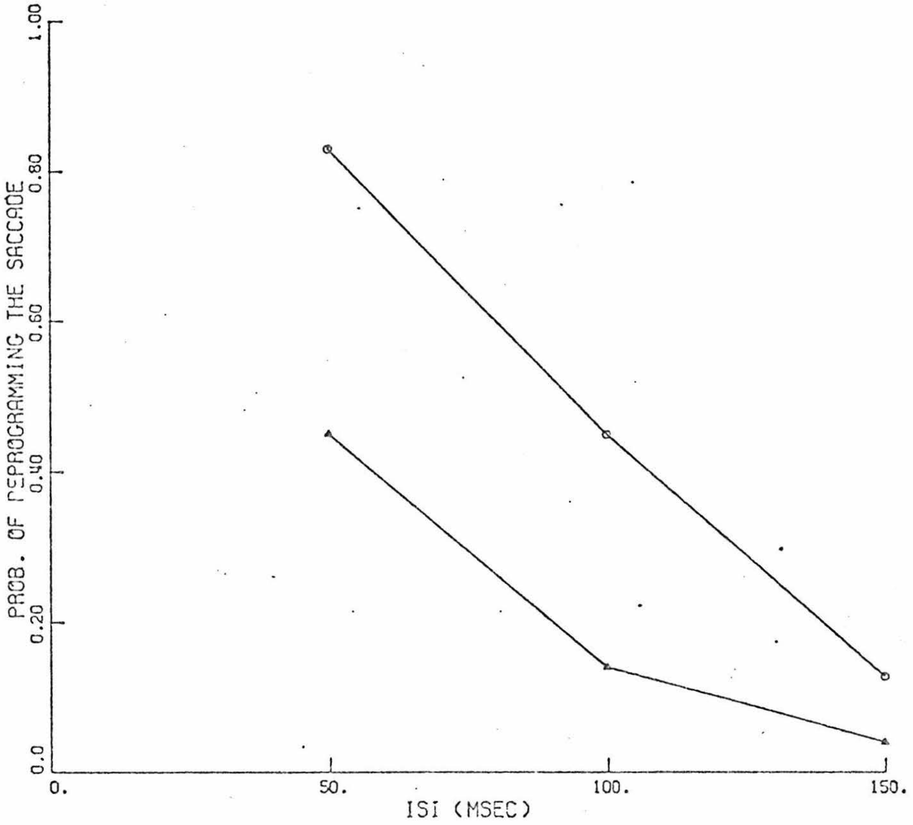


Fig. 4.9b. Comparison of the probability of reprogramming a saccade. 0 - from experiment I, Δ - for less detectable second target-step. Subject MB.

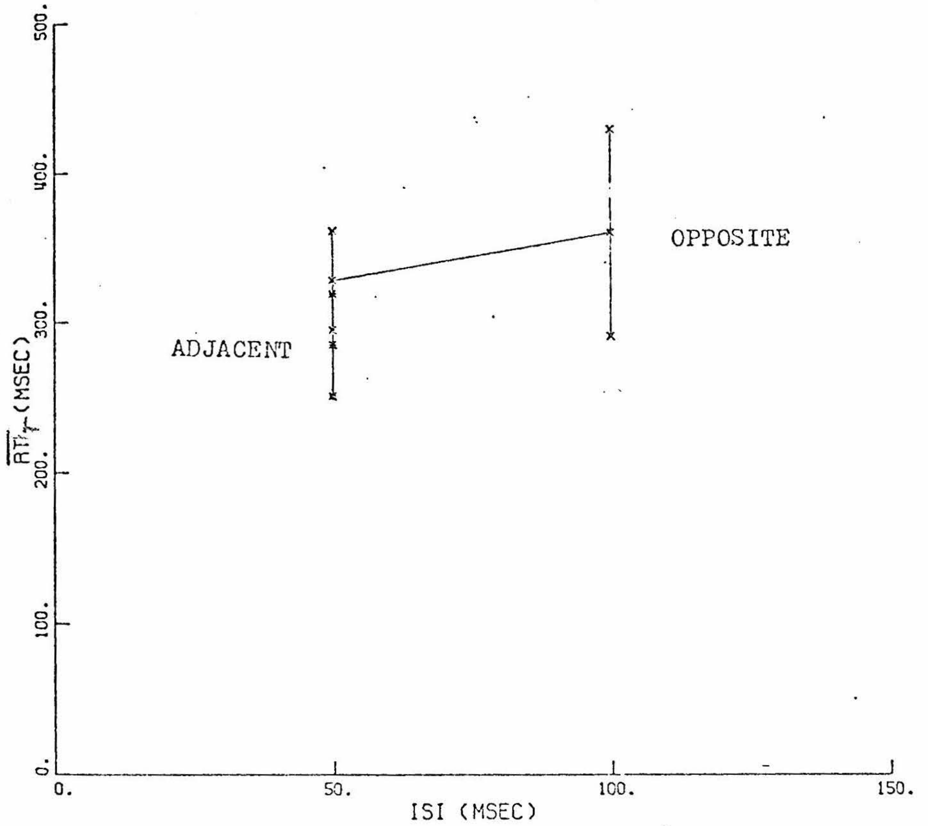


Fig. 4.10a. The average reaction time of the reprogrammed saccade for a less detectable second target-step. Both adjacent and opposite presentations. Subject RW.

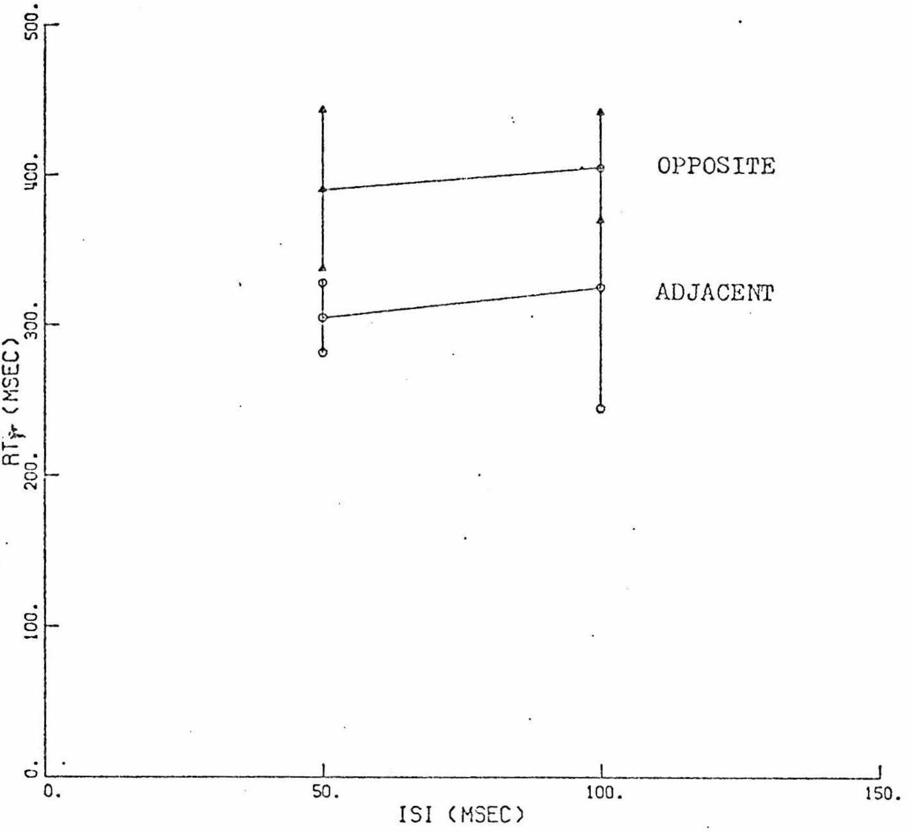


Fig. 4.10b. Same as Fig. 4.10a. Subject MB.

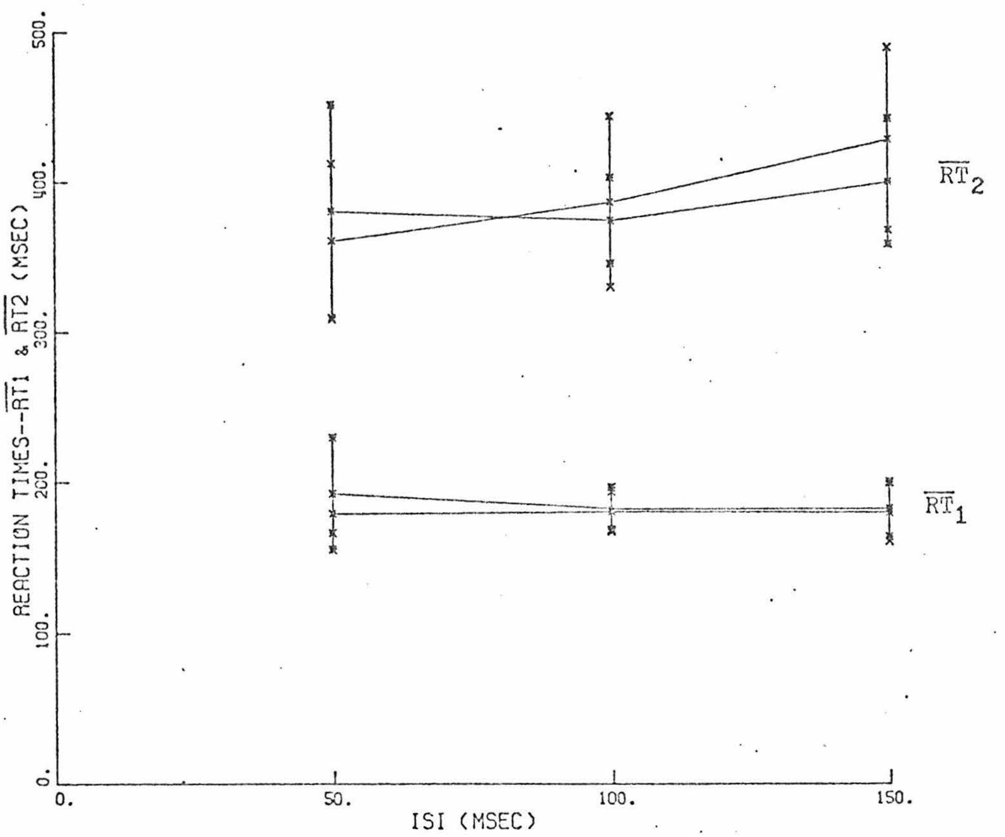


Fig. 4.11a. $\overline{RT_1}$ and $\overline{RT_2}$ for a less detectable second target-step. * - adjacent presentation, x - opposite presentation. Subject RW.

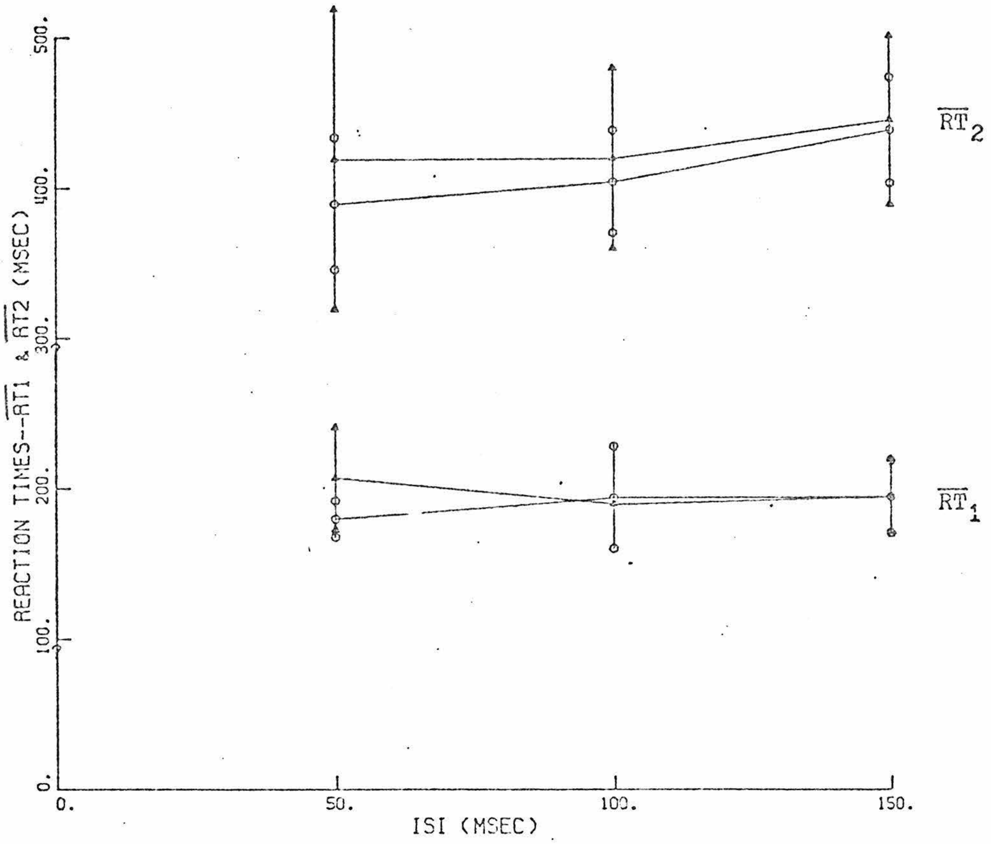


Fig. 4.11b. $\overline{RT_1}$ and $\overline{RT_2}$ for a less detectable second target-step. 0 - adjacent presentation, Δ - opposite presentation. Subject MB.

sequential connection is the most logical, the compatability with the experimental results makes it most plausible.

4.5 Conclusion

From the results of the experiments described in this chapter, some hypotheses proposed by previous experiments are tested and some new interpretations and new hypotheses are given. A general structure for information processing in the saccadic programming system can be put together. The results and hypotheses are summarized below.

The saccadic responses can be classified into three types of responses, instead of the traditional two, according to the different levels of reprogramming. These are the reprogrammed single-saccade response, the intermediate two-saccade response, and the full two-saccade response. The probability of each type of response can be expressed as a function of the time of presentation of the second target-step. In fact, it should depend on the detection time of the second target-step. Although the detection time is difficult to measure, this argument can be shown indirectly by changing the detectability of the second target-step. The results presented above are compatible with the hypothesis that the detection process and the computation process are connected sequentially and the latter gets input only from the result of the detection process. Whether a saccade is reprogrammed or not depends on the time relation between the detection of the second target-step and the processing state of the computation process of the initial saccade.

The intermediate two-saccade response represents a level of reprogramming in which the direction of the saccade cannot be reprogrammed but the magnitude can still be shortened. This implies that the direction computation finishes before the magnitude computation. A similar hypothesis was proposed by Komoda _et_ _al_. (1973) and Becker and Jügens (1975), but from different observations. The direction computation puts the results into a memory buffer, which may be accessed by the magnitude computation process. If the initial saccade is cancelled and the new saccade is in a similar direction, then the partial results of the direction programming of the cancelled saccade can still be used, probably with small modification, since the same combination of muscles is used as agonist or antagonist and only the contribution by each of them needs to be changed. If the new saccade goes in a completely different direction, different pairs of muscles will be involved, and the partial results from the previous programming have to be erased. I have found that the erasing of the total buffer takes about 40 msec for one subject and 80 msec for another. The storage of information in this buffer can also explain the shorter latency when the new saccade is in exactly the same direction as the cancelled one, as observed by Komoda _et_ _al_.

A processing scheme with about 100 msec refractory period was demonstrated by my results. Similar results exist in many previous studies. The scheme is as follows. When the computation process is processing a saccade, the detection processes can simultaneously process the incoming information. If the detection of the second target-step comes sufficiently late that the previous saccade cannot be cancelled, two saccades will be observed. But the programming of the second saccade cannot enter the computation process until the previous computation is done, since the computation of the direction and the magnitude of the new saccade depend on the results of the previous computation. This accounts for the 100 msec refractory period when a saccade is programmed. Therefore, it is neither sampling nor continuous processing. A pipeline structured parallel processing will be proposed in Chapter VI to explain the results.

V. STEADY STATE BEHAVIOR OF THE SACCADIC PROGRAMMING SYSTEM--EXPERIMENTS USING RANDOM WALK TARGET MOVEMENT

5.1 Introduction

Since Fender and Nye (1961) used engineering analysis techniques to analyze the oculomotor tracking response to the various sinusoidal target movements, there have been many studies of the tracking behavior of the oculomotor system. Two main properties of the oculomotor tracking system are established: (1) The tracking system acts like a low pass filter. The gain of the system drops rapidly when the frequency of the sinusoidal target motions or the bandwidth of the gaussian random target motion exceeds 1∿2 Hz (Fig. 5.1a). (2) The phase lag depends greatly on the types of target motion. The lag is greater for a target motion consisting of gaussian noise or the sum of the nonharmonically related sinusoids than for the predictable motion such as single sinusoids (Fig. 5.1b). The phase lag of the system when tracking a predictable target motion is much less than what would be expected from a minimum-phase relation. A predictor model (Dallos and Jones, 1963) and a time delay model (St. Cyr and Fender, 1969) are proposed to explain the phase characteristics.

In those studies of the oculomotor tracking system, both the saccadic system and the smooth pursuit system are stimulated. The eye movement response is the combined pattern of both types of eye movements. The experiments in Chapter IV showed that the saccadic system alone is able to follow two target jumps with more than ninety percent

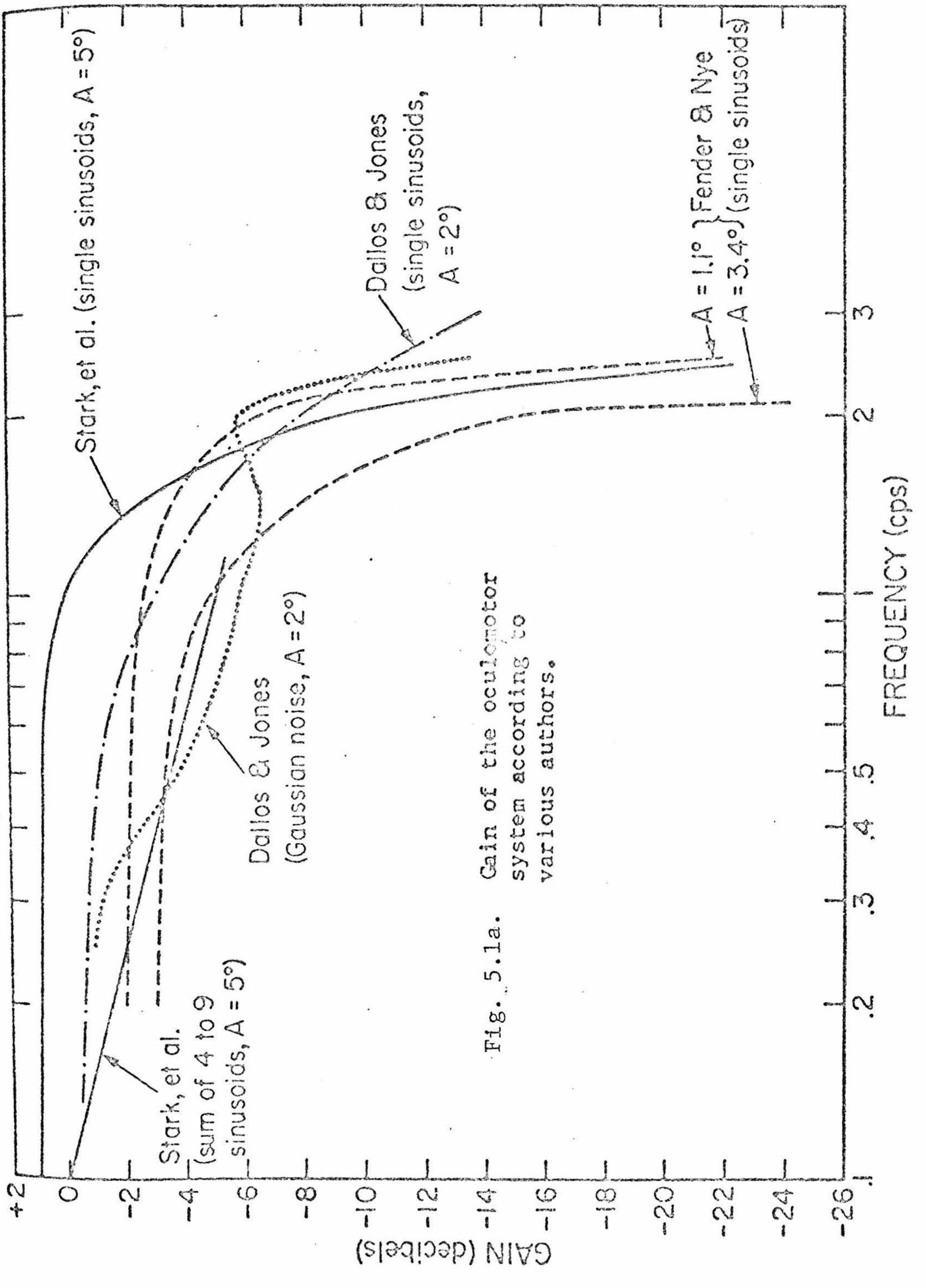


Fig. 5.1a. Gain of the oculomotor system according to various authors.

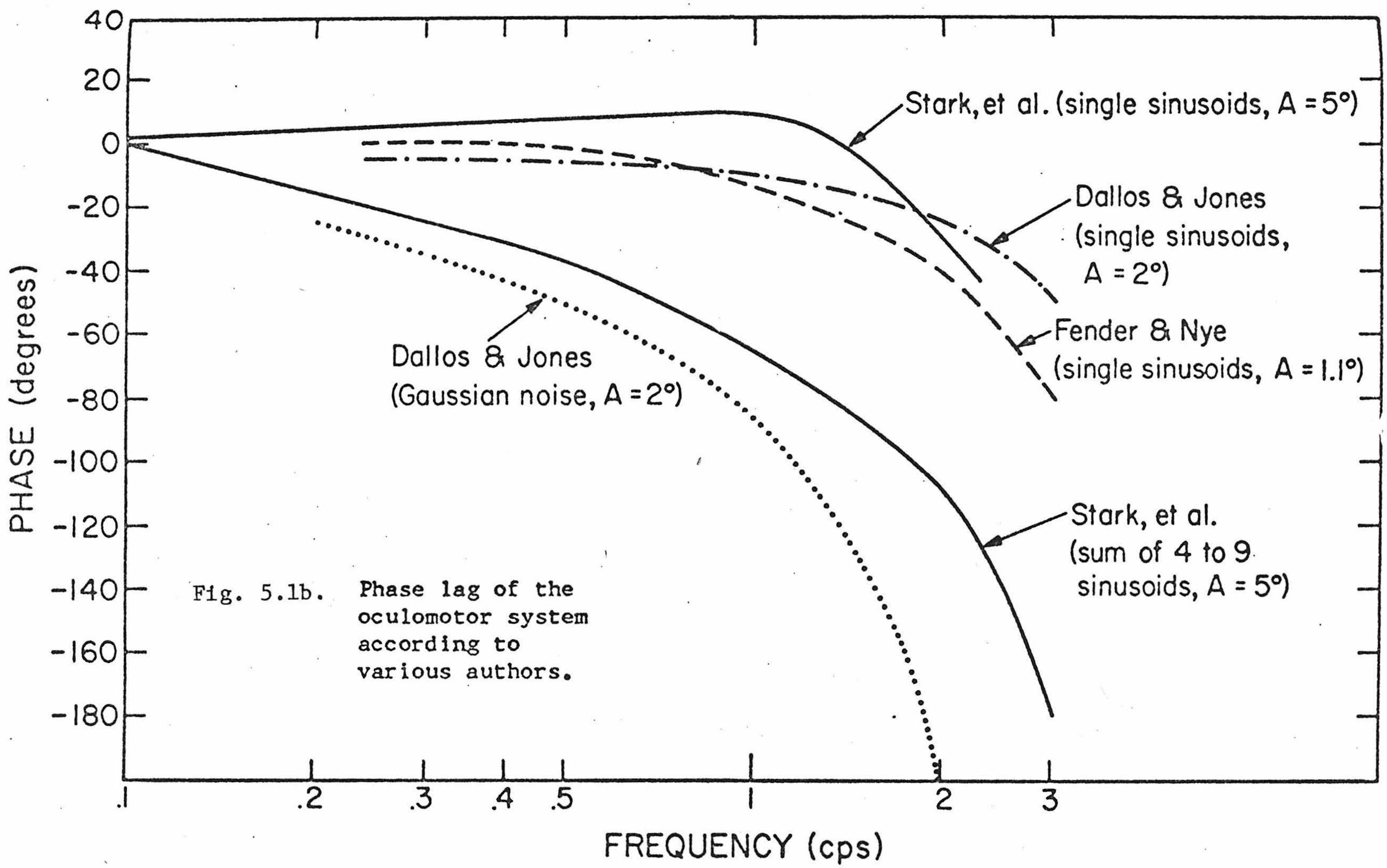


Fig. 5.1b. Phase lag of the oculomotor system according to various authors.

probability when there is as little as 150 msec between the two jumps. This roughly compares to a 3.3 Hz response by the analogy that the time interval between the two target-steps is equivalent to the time interval from peak to trough in a sinusoid. This analogy may be interpreted as indicating that the saccadic system can track a 3.3 Hz signal for ninety percent of time. It tends to show that the gain of the saccadic system in tracking a double-step target movement is higher than those values in Fig. 5.1a, although they are not directly compatible.

From this observation, one may wonder whether the saccadic system can do as well when tracking a long sequence of random target movements as it does in following transient double-step target movements. It is plausible that the tracking performance of the saccadic system degrades when following a long sequence of random target movements. Otherwise, the brain should be smart enough to use the saccadic system alone instead of the combination of the saccadic system and the pursuit system to track random target movements, because the saccadic system alone will give better overall performance.

When a human subject uses his saccadic eye movements to follow a long sequence of quick target jumps, the steady state behavior, in terms of engineering analysis, of the saccadic system can be studied.

In the literature, only one study of the steady state behavior of the saccadic eye movements was found. In that study the target spot was moved in a square wave fashion, that is, jumping back and forth between two locations (Young, 1962). The results showed that the human subject can quickly predict the time of the target jump. As the frequency of the target jump increased up to 1.3-1.7 Hz, the prediction became less significant and occasionally entire steps might be missed. When the target frequency increased to 2 Hz, the eye movements became continuous movements rather than clear saccades.

This experiment does not answer satisfactorily the above question, because of the periodicity in the stimulus. When the frequency increases, the subject knows that the target will always come back to one of the two locations. Instead of following the target movements, he can simply fixate at one location and still have the feeling that he is following the target. This strategy certainly degrades the tracking performance of the saccadic system.

Therefore, in this chapter two experiments will be described which study the steady state tracking behavior of the saccadic system using target movements consisting of a sequence of target-steps which generate a random walk. This type of target movement should elicit saccadic eye movements alone.

The specific questions which the two experiments are designed to answer are the following. Can the saccadic eye movements system follow a long sequence of random target jumps as well as it does in following double-step target movements? If yes, why does the oculomotor system not use the saccadic system alone to track random target motion? If not, why is the steady state tracking behavior of the saccadic system inferior to its transient tracking behavior? This is also tied with the main question of this thesis--what is the programming strategy of the saccadic eye movements system?

5.2 Review of the Previous Oculomotor Tracking Experiments

Fender and Nye (1961) studied the response of the oculomotor system to a target moving sinusoidally with different retinal image feedback induced by optical methods. They concluded that the system behaved like a low-pass filter with the cut-off frequency at about 2.3 - 3 Hz and the phase was less than what would be predicted from a minimum-phase network.

Young (1962) used target motions consisting of several non-harmonically related sinusoids which are subjectively unpredictable. Dallos and Jones (1963) used target movements which were bandlimited gaussian noise. They found that the gain of the oculomotor system was lower and the phase lag was larger. This nonlinear phenomenon was modelled by Dallos and Jones as the existence of a predictor which enabled the subjects to anticipate the target motion if it was predictable. Therefore, the system characteristics depend on the predictability of the target motion.

St. Cyr and Fender (1969) found another nonlinear abnormality of the system. Although the gain of the oculomotor system decreased as the frequency of the target motion increased, when the target motion consisted of a narrow band of sinusoids, the oculomotor system responded preferentially to the highest frequency component. In other words, the gain in this narrow frequency band actually increased with frequency.

Yasui (1975) studied the tracking of the apparent movements of an after-image when the subject was rotated on a rotational chair.

In his data analysis, he isolated the smooth pursuit eye movements by subtracting out the saccadic components. This was one of a few experiments which tried to study the tracking behavior of the pursuit eye movements system alone. Williams (1978) used a stimulus which consists of a row of closely spaced dots to study the smooth pursuit system. In this stimulus the position of individual dots is impossible to distinguish and therefore is irrelevant. He showed that this type of stimulus is suitable for studying smooth pursuit eye movements because there is no position information.

The only study of the steady state behavior of the saccadic system alone was mentioned in the last section, and the reason was given why it did not answer the questions posed.

5.3 Stimulus and Data Analysis

The most powerful stimulus for a saccadic eye movement is the sudden target-jump. Mathematically a target-jump in space can be represented by a step function in the position domain, or equivalently, by an impulse function in the velocity domain. Therefore, a sequence of target-jumps in one-dimensional space can be represented by a sequence of impulses with different weights, which correspond to the sizes of the target-jumps, at the onset time of each target-step.

To generate a random target sequence, the most common choice is the discrete gaussian sequence which can be obtained by digitizing continuous gaussian noise with a suitable sampling frequency or by a pseudorandom number generator with a gaussian amplitude envelope. This sequence of random numbers represents the target position with a fixed time interval between two numbers in the sequence. However, this type of random target-jumps is not suitable for this experiment. It has similar disadvantages to that described in the introduction of this chapter for square wave target movements. Because the stationary gaussian time sequence has a mean amplitude and a stationary variance, as the bandwidth of the time sequence increases, the subject will find that the optimal strategy to follow the gaussian type of target-jumps is to keep his fixation in the neighborhood of the mean position. This will degrade the performance of the saccadic system.

Thus, to avoid the prediction by the subject, a nonstationary time sequence should be used. One such sequence, which is suitable to stimulate saccadic eye movements, is the random walk sequence. If this time sequence is used to represent the position of a target, then each target movement may be a single step either to the left or to the right of the present position according to a probability law. Equal probability for moving to either direction was chosen for the first experiment. In the second experiment the target movement has one additional option: to stay at the present position. All three options have one-third probability. The theory of the random walk shows that for an unbounded random walk the position of the target has a gaussian distribution with its mean equal to its starting position, but its variance increases linearly with time. Thus, as time goes by, the probability distribution of the target position becomes closer to a uniform distribution. When they are observed subjectively, every new target position appears to be a new mean position, because it has equal probability to jump in one direction or the other. The subject should find that the best strategy to follow this random walk target motion is to follow every target step because every new position appears to be the new mean position. The strategy of expecting a fixed mean target position should not work here.

There is another advantage of the random walk target movements over the gaussian white noise target movements. The uncorrelated gaussian white noise causes the target to jump to a new position which is uncorrelated to its previous position. As the time interval between two target-steps decreases, that is, the frequency of the target-jump increases, this type of uncorrelated target movement will put the subject in a hopeless situation if he loses track of it, because it does not give him any clue to catch up. Thus, many properties of the saccadic system at the high target rate cannot be observed for this reason. We will come back to this point in the Results section. However, for the random walk target every new target-jump is still in the neighborhood of the previous target position. Even if a few target-steps are too fast to follow, the saccadic system can still catch up with the target in the vicinity of current eye position and start following from there. This advantage, I believe, enables the steady state properties of the saccadic programming system when following a long-sequence, high-frequency target motion to be studied.

However, there exists a practical difficulty in implementing the random walk target movement described above, because the target quickly runs out of the screen. At first glance it seems that an elastic barrier for the random walk target movement at the boundary of the screen can solve the problem. When the target-jump hits this elastic boundary, it bounces back one step. This arrangement keeps the target on the screen, but it increases the predictability of the target motion when it is near the end of the screen. A different scheme was adopted to solve this problem. The one-dimensional random walk target movements were arranged to be on the circumference of a circle with a prespecified radius, instead of being on a horizontal axis as is normally implied when one talks about a random walk. I will call this type of target movements the circular random walk. One step in the circular random walk covers a fixed length of circular arc, either in the clockwise or in the counterclockwise direction. In those experiments described in this chapter, the radius of the circle was chosen to be four degrees of visual angle and the whole circumference was covered by 16 steps. In other words, a single step covered 22.5 degrees of the circular angle which, in the experiments reported here, corresponds to about 1.6 degrees of visual angle. The horizontal and vertical extent of the target was 12 min of arc of visual angle (Fig. 5.2).

As mentioned above, a random walk target movement can be defined by a sequence of velocity impulses. For the circular random walk used in this chapter, the velocity impulses have the weight of either +22.5° or -22.5°, corresponding to a counterclockwise step or a clockwise step. Thus, a single velocity impulse has equal probability to be a positive impulse or a negative impulse and this probability is independent of the rest of the impulses in the sequence. Mathematically, the autocorrelation function of this velocity sequence is an impulse function

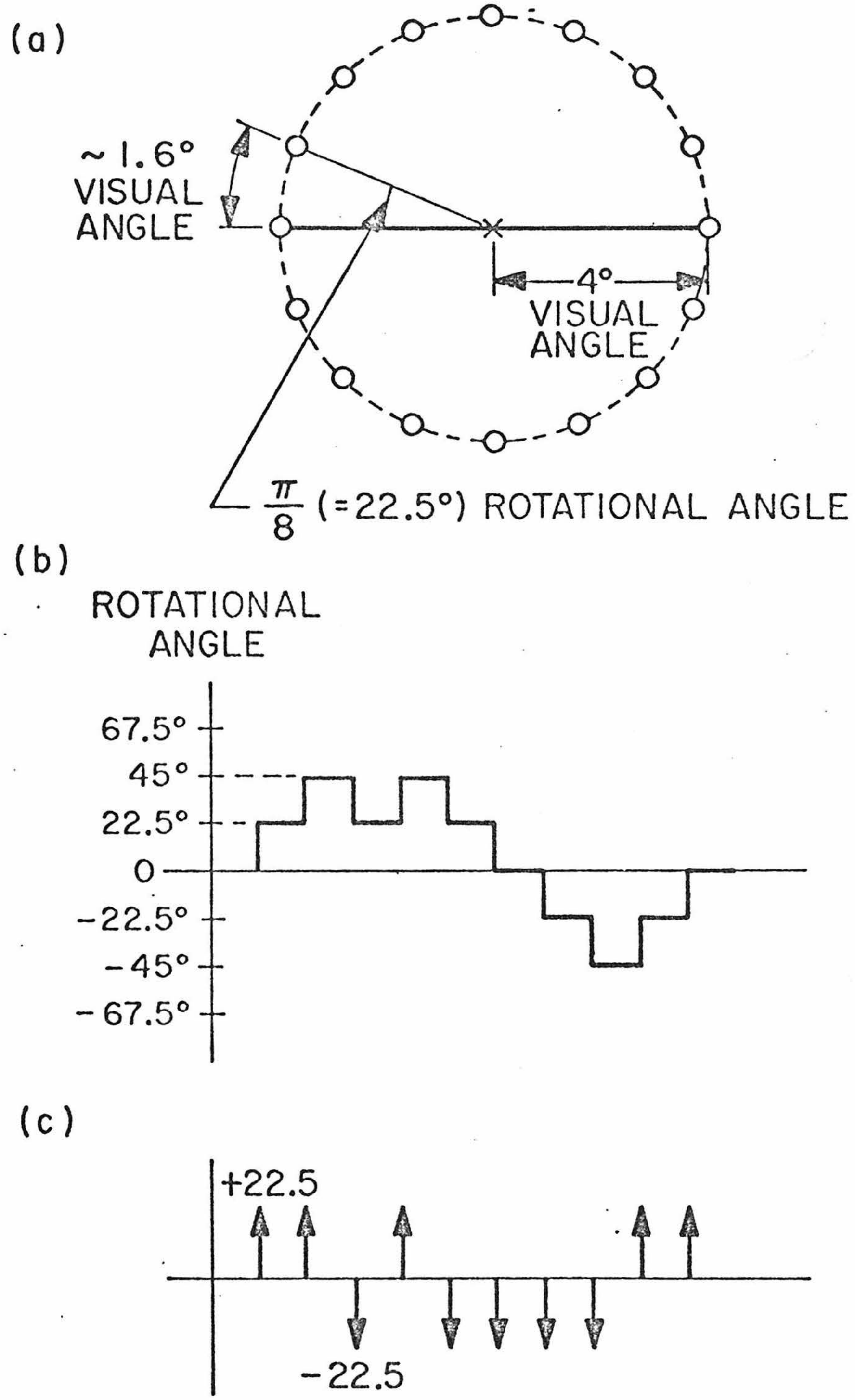


Fig. 5.2. Circular random walk target movement. (a) Its geometry. (b) An example in the position domain. Plotted in terms of rotational angles. (c) Same example in the velocity domain.

occurring at the zero displacement and the power spectrum of this sequence is constant over all frequencies. For a continuous random process, if its velocity has a constant power spectrum, it is best known as Brownian motion. Therefore, this circular random walk target motion can be thought of as a discrete model of Brownian motion.

The circular random walk sequence was generated on-line using a pseudorandom number generator. At each target sample instant, a random number was generated to determine whether this step was to be counterclockwise or clockwise.

Both the horizontal and the vertical components of the subject's eye movements were recorded while he was following the target movements. In the data analysis, the vertical and the horizontal eye movements were combined to generate the angular eye positions on the circumference of the circle. These angular eye positions were in terms of the rotational angle of the circle, which thus became one-dimensional signals. With this transformation the response-stimulus relationship can be analyzed as a one-dimensional function instead of a more complicated two-dimensional function. The detailed shape information of a saccade may be distorted, but the starting time and the finish time of the saccade are invariant. Since the detailed shape information is not important in my analysis, this transformation reduced the amount of data to be analyzed without losing the relevant information. The data analysis schemes for each individual experiment are discussed later.

5.4 Experiment I

This experiment was performed to find out whether or not the saccadic system can follow a long sequence of random walk target movements as well as it does in following the double-step target movements.

5.4.1 Method

The circular random walk target motion described in the last section was used as stimulus. A target-step covered 22.5° of circular angle on the circumference of the circle. The target-jumps occurred at a prespecified rate. Each target-jump had two possibilities: It could move in the clockwise direction or in the counterclockwise direction with equal probability.

If the target-jump occurred periodically, the observer might learn the rhythm and start to predict when the target would move. This is undesirable in the study of the programming strategy of the saccadic eye movements. To avoid prediction by the observer, two values of time interval between target-jumps were used for each trial. During the trial, the next time interval was selected randomly from the two prespecified values. The time intervals used in this experiment were the following pairs: 300/250 msec, 250/200 msec, 200/150 msec, 150/100 msec, 100/50 msec.

Both the horizontal and the vertical eye movements were recorded. The eye positions were converted into the rotational angle on the circle as described in Section 5.3.

5.4.2 Results of Experiment I

There were 200 to 800 target-jumps in each one-minute trial, depending on which pair of time intervals were chosen for that trial.

A large amount of data was produced by even a single run. To analyze the data, it is desired to find some statistics which describe its response behavior. The simplest statistic is the ratio of the number of saccadic eye movements to the number of target-jumps. This ratio was calculated for each pair of time intervals used in the experiment. The average ratios are shown in Table 5.1 for two subjects.

TABLE 5.1

		Subject RW		Subject RH	
Time Intervals	Avg. Target-Steps	Avg. No. of Saccades	Avg. Ratio	Avg. No. of Saccades	Avg. Ratio
300/250	218.5	217	1.00 ± 0.05	209	0.95 ± 0.05
250/200	267	227	0.85 ± 0.08	213	0.81 ± 0.07
200/150	343	250	0.74 ± 0.02	230	0.68 ± 0.01
150/100	481	240	0.51 ± 0.03	228	0.47 ± 0.01
100/50	800	250	0.32 ± 0.02	200	0.25 ± 0.01

When the time intervals were 300/250 msec, the number of saccadic eye movements was about the same as the number of target-jumps. This means that almost every target-step was followed and the saccadic programming system was able to handle the target information at this input rate. As the rate of input information increased, more target-steps were skipped. As Table 5.1 indicates, the maximum number of saccades in the period of one minute was about 250 for subject RW and 230 for subject RH. The average time interval between the two saccades was, therefore, 240 msec for subject RW and 260 msec for subject RH. This may be interpreted as the maximal average capability that the saccades can be generated by the saccadic programming system in response to the unpredictable target jumps.

A comparison between Table 5.1 and the percentage of two-saccade responses in Table 4.2 indicates that more target-steps were skipped when steady state target movements were followed. For example, there were about 57% two-saccade responses when the time interval between target jumps was 100 msec, but only about 51% and 47% of the target-steps elicited responses when the time intervals between two random walk steps was 150/100 msec.

Using the analogy developed in the Introduction of this chapter, the time interval between target-steps can be approximately related to the peak-to-trough time interval in the sinusoidal stimulus. Therefore, time intervals of 300, 250, 200, 150, 100 and 50 msec are approximately equivalent to 1.6, 2, 2.5, 3.3, 5 and 10 Hz, respectively. If we define the gain of the saccadic tracking system as $20 \cdot \log$ (probability) where the probability is obtained from Tables 4.2 and 5.1, the logarithmic gain function for the transient and the steady state behavior of the saccadic tracking system can be plotted as in Fig. 5.3. Note that the gain of the steady state behavior for each time interval pair is plotted as a function of the average value of the two equivalent frequencies. For example, for the time interval pair 300/250 msec, which corresponds to 1.67/2 Hz, the average frequency value of 1.8 Hz is used. This plot showed that the gain for the steady state behavior is lower than the gain for the transient behavior. But it is still greater than the gain function of the oculomotor tracking system shown in Fig. 5.1a. The

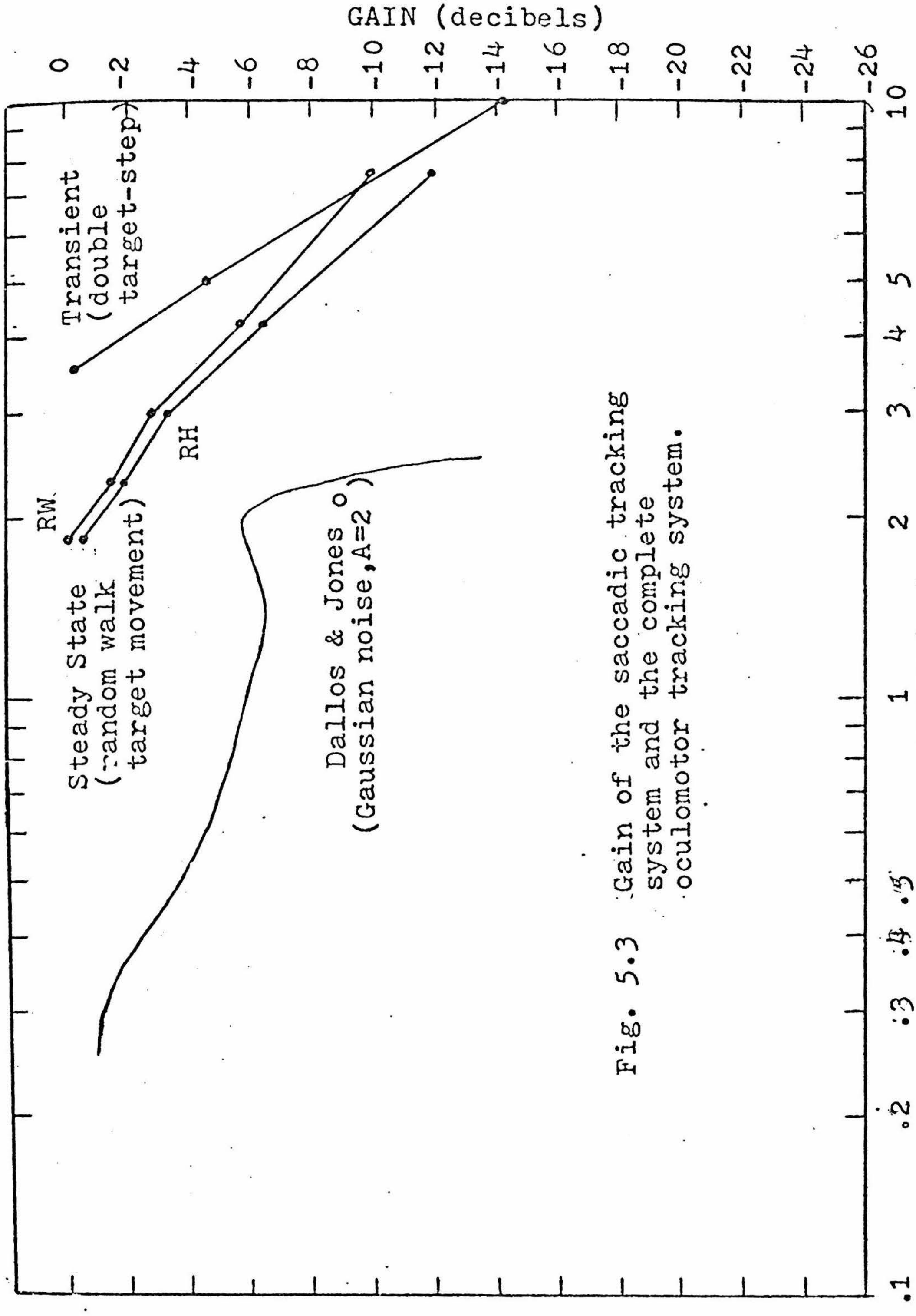


Fig. 5.3 Gain of the saccadic tracking system and the complete oculomotor tracking system.

lower gain of the oculomotor tracking system is probably due to the stimulus used to obtain it. For a random stimulus, gaussian noise instead of random walk target movements were used. Two disadvantages of gaussian random target motion were discussed in Section 5.1. Also, for a single sinusoidal stimulus, as its frequency increases, it seems to have the same effect as the square wave stimulus described in the Introduction of this chapter. Of course, a caution should be made. This comparison is under the analogy described above, which may not be a valid comparison.

This observation tends to support the hypothesis that the tracking performance of the saccadic system is inferior when it follows a steady state random target sequence rather than when it follows only two target-steps. But why is this the case? Are there higher-order effects in the programming strategy of saccadic eye movements which will affect the saccadic response in the steady state target movements but not in the situation consisting of only two target-steps? Experiment II was designed to study this question.

5.5 Experiment II

To study the higher order effects, one may extend the double target-step paradigm used in Chapter IV. For example, to study the third order effect, a three target-step combination can be used. However, this paradigm is very time consuming and only the transient behavior will be involved. A better paradigm is to use the random walk target motion. During data analysis, this long sequence of target movements is broken into many small sequences which consist of only a few target-steps, and the saccadic responses to these small sequences are studied. This paradigm is more economical and, more important, the steady state behavior is studied. However, in order for a random walk sequence to be separated into small sequences, a new type of circular random walk target motion is needed.

5.5.1 Method

The circular random walk target motion was the same as that of Experiment I, except for two modifications. At the instant that the target should jump, it had three equally probable choices instead of two. As before, it could move one step in the clockwise direction or in the counterclockwise direction, but it had the additional choice of staying at the same location. For this new random walk target movement, the presence of the no-jump condition automatically broke the rhythm; therefore, only one time interval was needed for each trial. The time intervals used were 250 msec, 200 msec, 150 msec, 100 msec and 50 msec.

5.5.2 Data Analysis

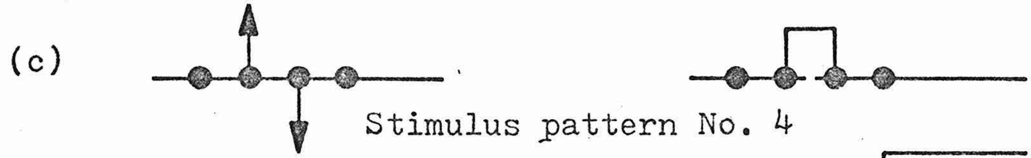
From the random walk target movements, various sub-sequences can be extracted. A sub-sequence is defined as a particular combination of successive target-jumps which are preceded and followed by at least one no-jump. In this analysis, only those sub-sequences which consist of combinations of up to three target-steps are extracted. As discussed before, the target sequence can also be represented uniquely by a sequence of positive or negative velocity impulses. The velocity impulse representation of the seven sub-sequences extracted are shown in Fig. 5.4.

Velocity Position

Stimulus pattern No. 1

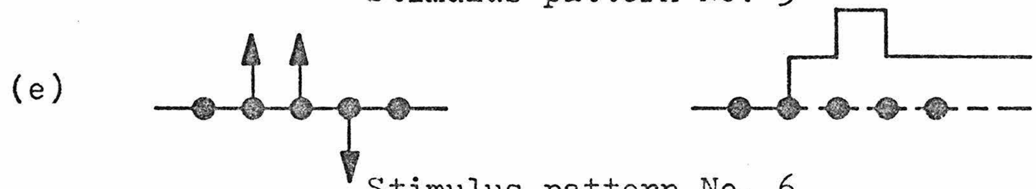
Stimulus pattern No. 2

Stimulus pattern No. 3

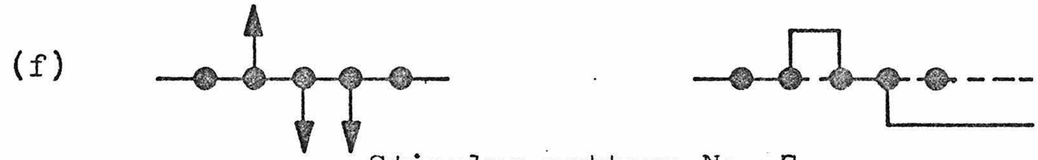


Stimulus pattern No. 4

Stimulus pattern No. 5



Stimulus pattern No. 6



Stimulus pattern No. 7

Fig. 5.4. Position and velocity representation of seven stimulus patterns in Experiment II.

There is only one combination which can be made from a single target-jump if we do not distinguish a clockwise jump and a counterclockwise jump in which only sign differs (Fig. 5.4a). There are two combinations from two successive target-jumps. One combination has two jumps in the same direction and the other combination has two jumps in directions opposite to each other (Fig. 5.4b,c). Similarly, there are four different combinations from three successive target-jumps (Fig. 5.4d,e,f,g).

The purpose of having no-jumps is to let the influence from the previous target-step die out or to give the saccadic programming system a chance to catch up with the beginning of a new pattern, although the probability of this occurring is marginal when the time interval is only 100 msec or 50 msec.

The saccadic eye movement response was first time-locked to the first target-jump of a particular stimulus pattern, then it was added to the accumulated response to that pattern. It is more convenient to work on the velocity of the eye instead of the position of the eye as long as they contain the same relevant information, because the velocity function is independent of the starting position of a saccade.

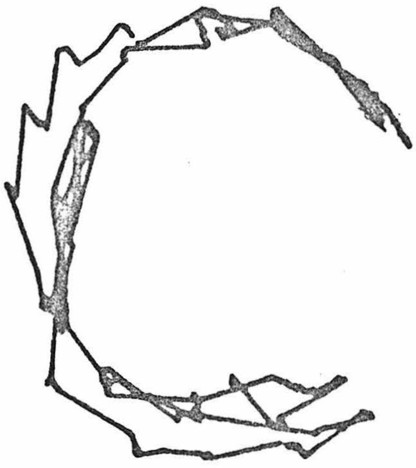
Two-dimensional eye position signals are first converted into the corresponding rotational angle on the circle by taking the arctangent of the ratio of the vertical component of the eye position over the horizontal component of the eye position, as described in Section 5.3. One-dimensional eye velocity signal can be derived from this one-dimensional rotational angle representation of the eye position. The eye velocity function obtained this way is a bell-shaped function with a duration of about 20 msec in this experiment. The peak velocity of a saccade has a monotonical relationship with the magnitude of the saccade (Westheimer, 1954, Cook, 1965).

Since only the initiation time and the magnitude of a saccade are relevant parameters in this analysis, the following data reduction scheme was used to reduce the computational complexity. The bell-shaped velocity function was replaced by a square pulse of height equal to the magnitude of the saccade. The duration of the square pulse was set to be 20 msec. The record was then divided into 20 msec time bins; if a saccade started in a particular time bin, the square pulse was moved to occupy the whole of the bin. Thus time is preserved ±10 msec. The responses to all occurrences of each stimulus pattern were accumulated together, time-locked on the first event of the stimulus.

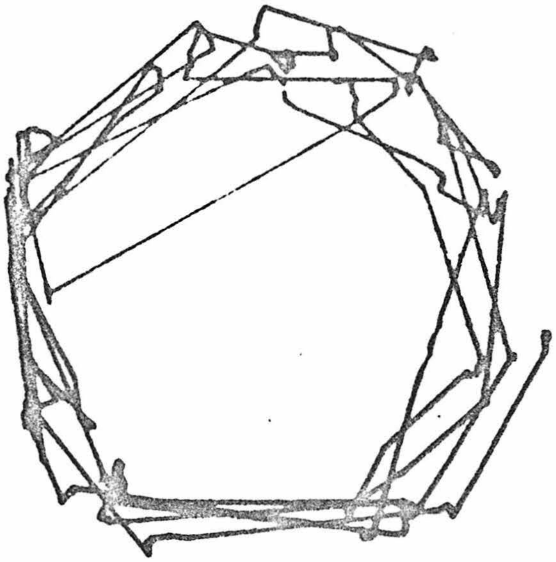
The data analysis procedures can be summarized as follows (Fig. 5.5):

(1) The recorded horizontal and vertical components of the target movements and the eye movements were converted into the one-dimensional rotational angle representation of position on the circle (Fig. 5.5a,b,c).

(2) The one-dimensional target and eye position signals were sampled with a 20 msec time interval. The target jumps were represented by a square pulse with the amplitude of +22.5° or -22.5°, depending on whether the jump was in the counterclockwise direction or in the clockwise direction. The saccades in the eye position signals were detected and were represented also by a square pulse occupying the time bin. The magnitude of the square pulse was the magnitude of the



250 msec
time interval



50 msec
time interval

Fig. 5.5a. Two-dimensional eye movement recording.

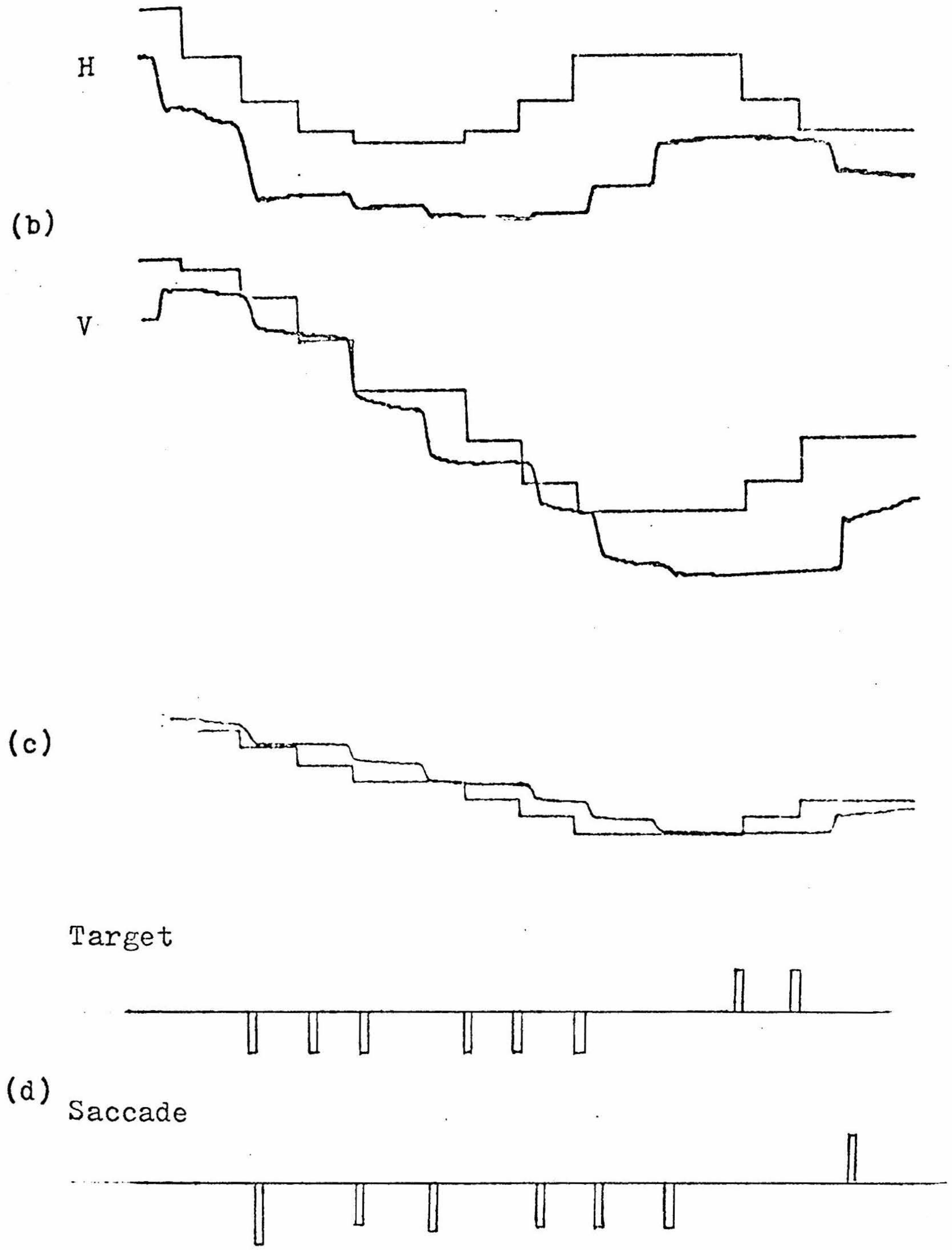


Fig. 5.5. (b) The horizontal and the vertical components of target and eye movements.
(c) Rotational angle representation of target and eye movements.
(d) Square pulse representation of target-jumps and saccades.

saccade (Fig. 5.5d).

(3) The pulse sequence which represented the target-jumps (or target velocity) was scanned to extract each stimulus pattern. When a stimulus pattern was detected, the saccadic pulse sequence, time-locked to the first target step of the pattern, was added to the accumulated response associated with that pattern. The total length of the accumulated response was 1 sec. After all the data were processed, the accumulated response for each stimulus pattern was divided by the total number of occurrence of that pattern. The normalized accumulated responses are shown in Fig. 5.6 for all seven patterns.

The normalized response obtained through this procedure is actually a histogram, since each pulse representing the saccade still retains the information on its magnitude and its sign. Two pulses with opposite signs will cancel each other. The histogram, therefore, represents a quantity proportional to the product of the probability of a saccade to occur within the time bin and its magnitude.

In the data analysis it is sometimes desirable to have a histogram representing only the probability of a saccade occurring within the time bin. This histogram can be obtained by the same procedure except for Step 2, where the magnitude of the pulse representing the saccade was set to +22.5° instead of the magnitude of the saccade. These histograms for the seven stimulus patterns are shown in Fig. 5.7.

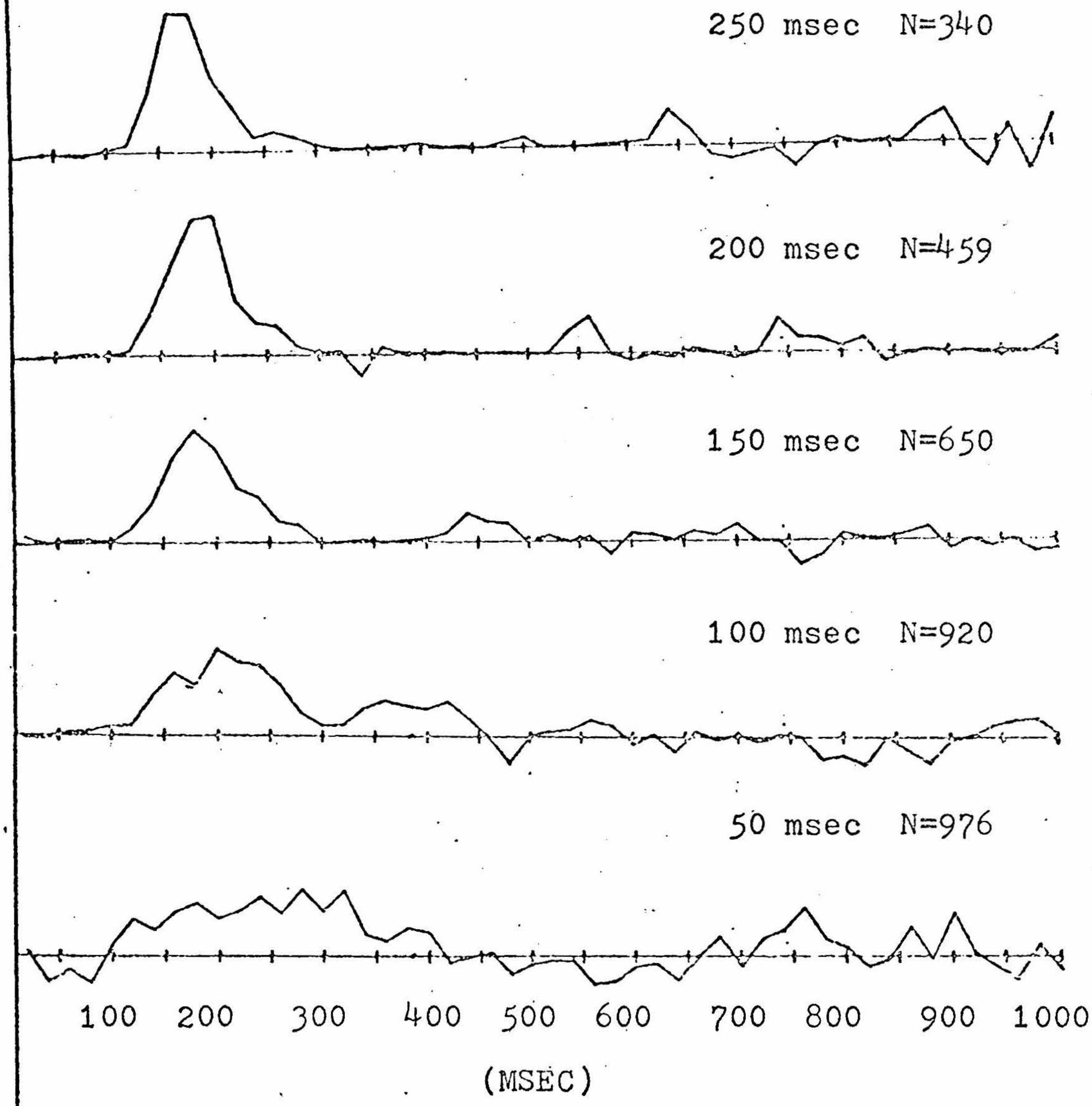


Fig. 5.6a Accumulated responses to stimulus pattern No. 1. Subject RH. The time above each response plot is the time interval between target steps. N is the total number of responses accumulated.

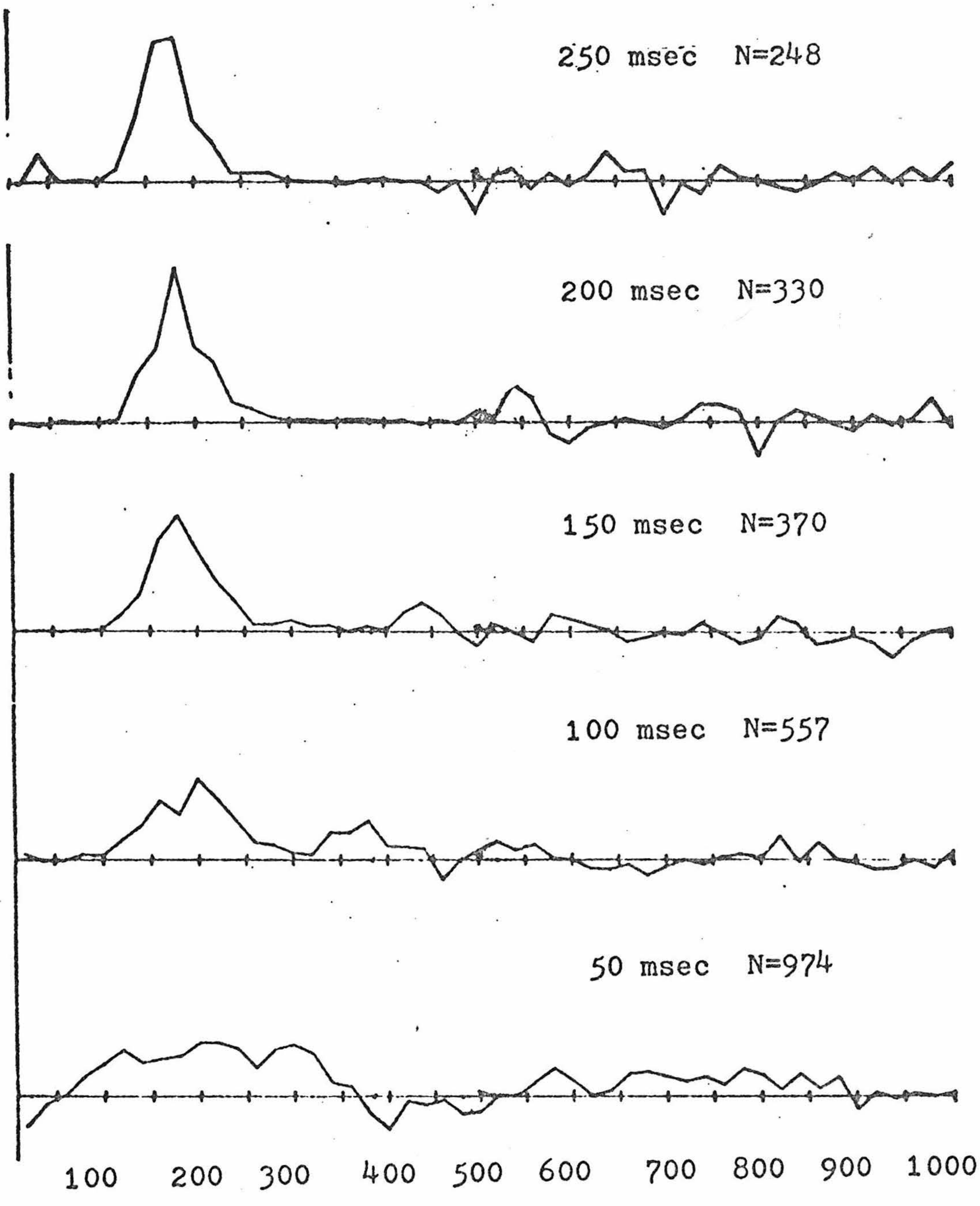


Fig. 5.6b Accumulated responses to stimulus pattern No. 1. Subject RW.

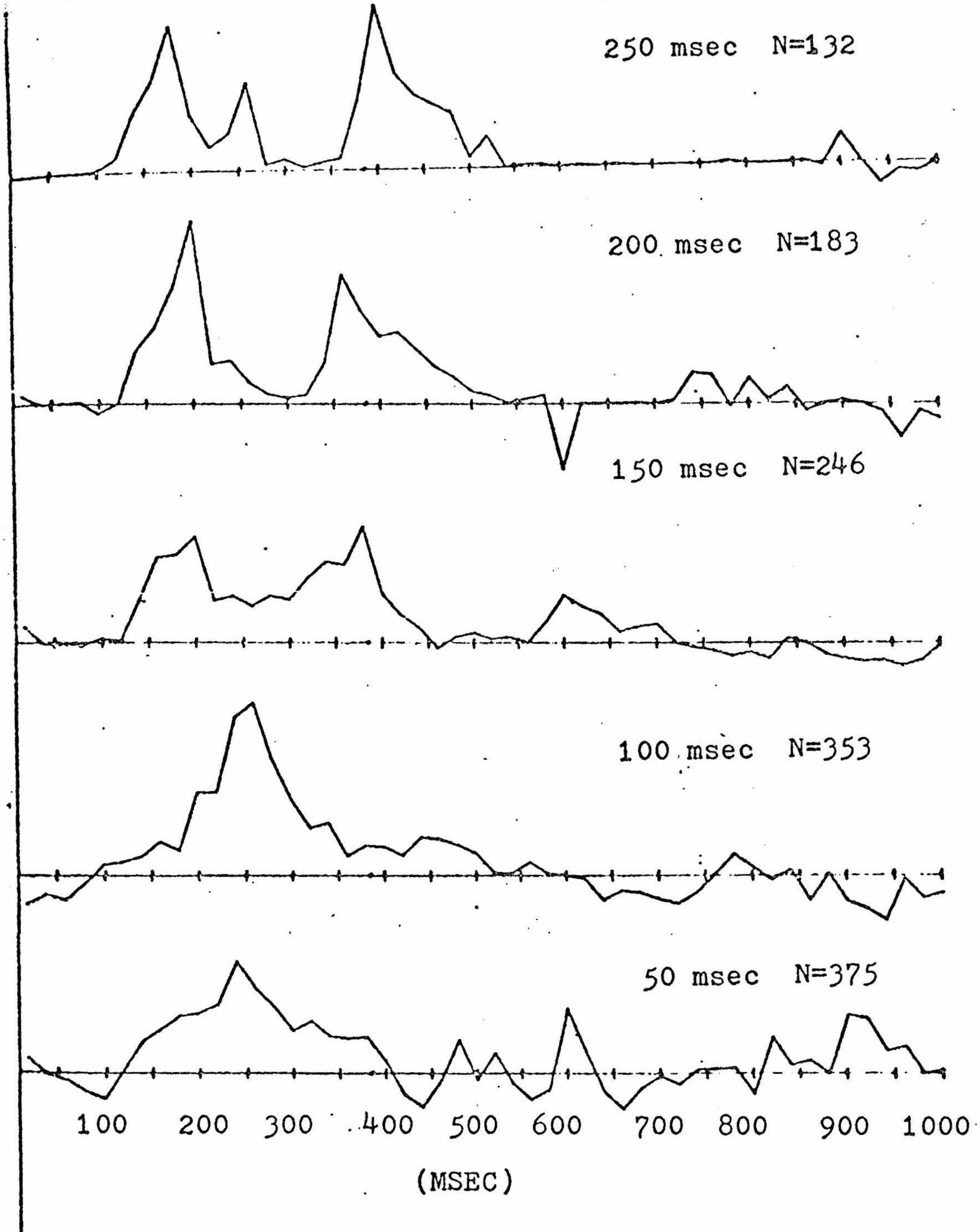


Fig. 5.6c Accumulated responses to stimulus pattern No. 2. Subject RH.

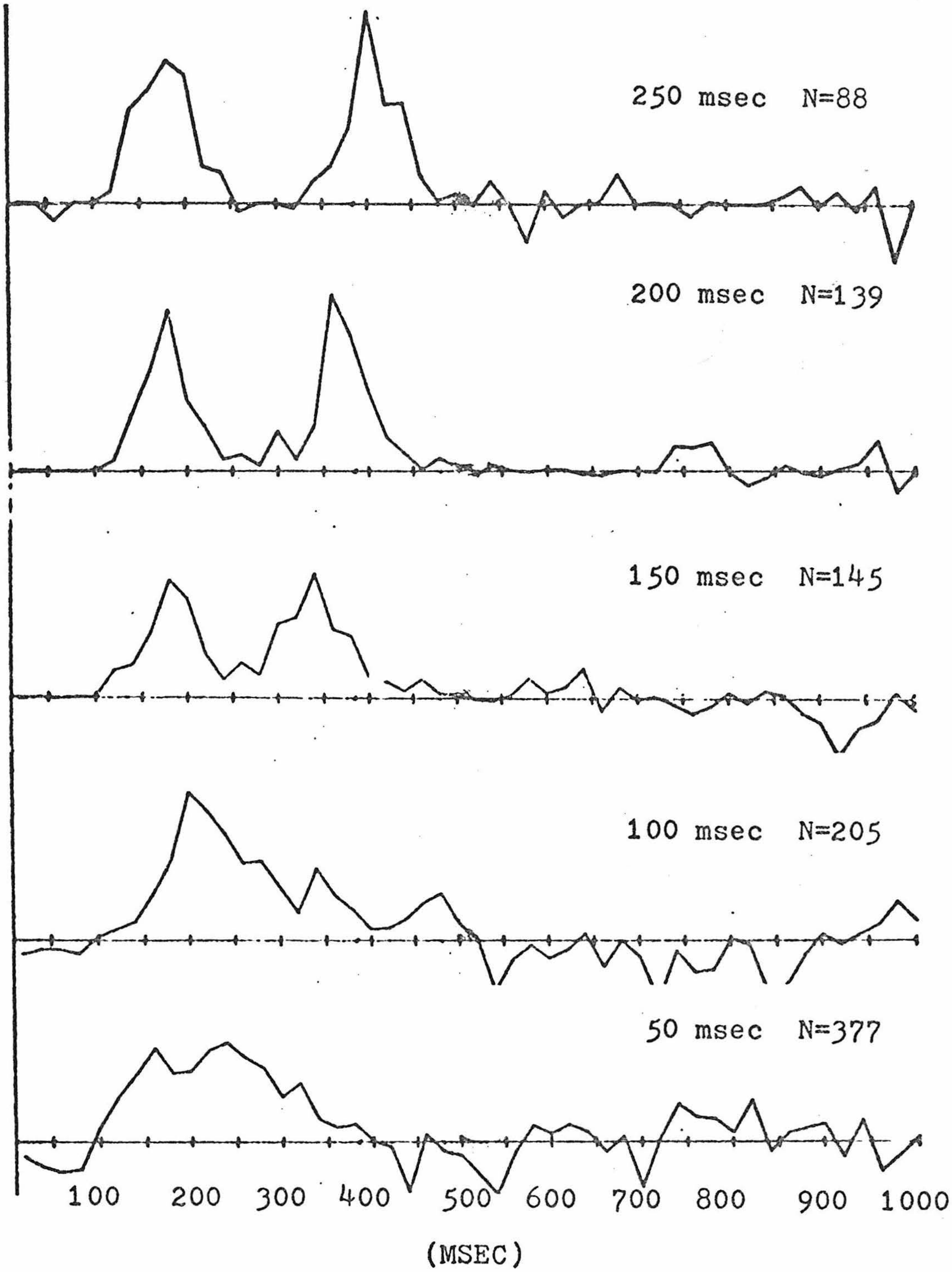


Fig. 5.6d Accumulated responses to stimulus pattern No. 2. Subject RW.

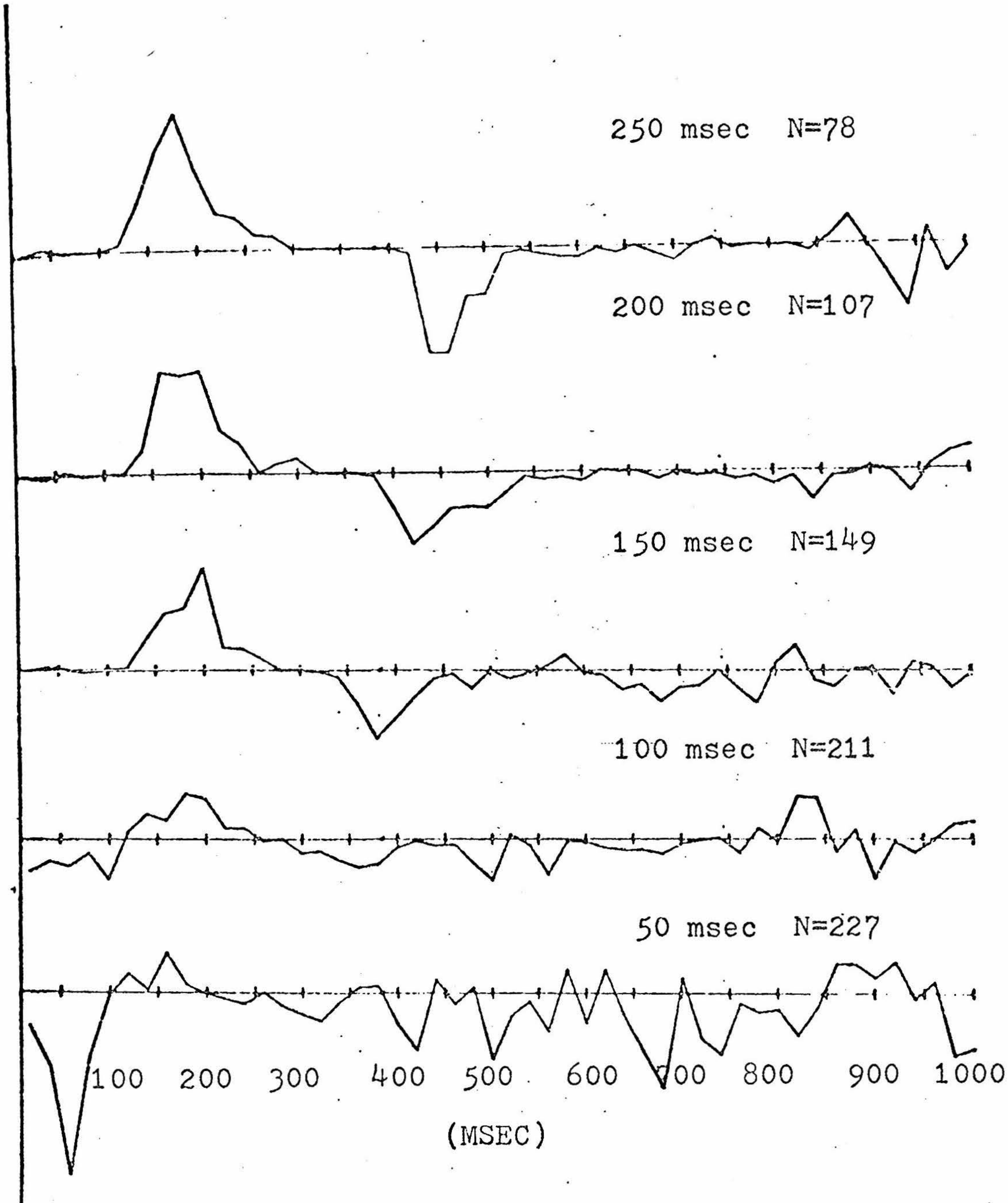


Fig. 5.6e Accumulated responses to stimulus pattern No. 3. Subject RH.

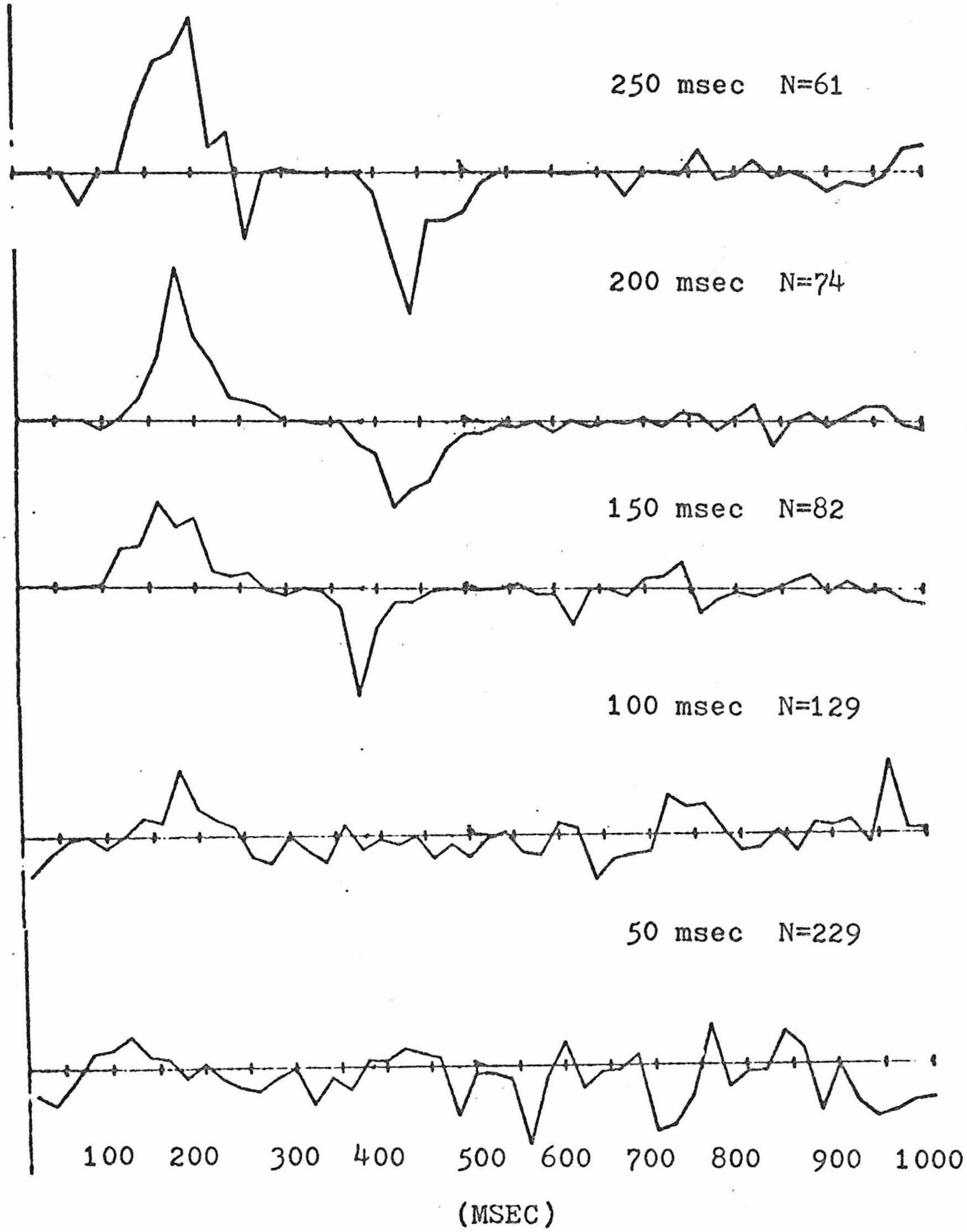


Fig. 5.6f Accumulated responses to stimulus pattern No. 3. Subject RW.

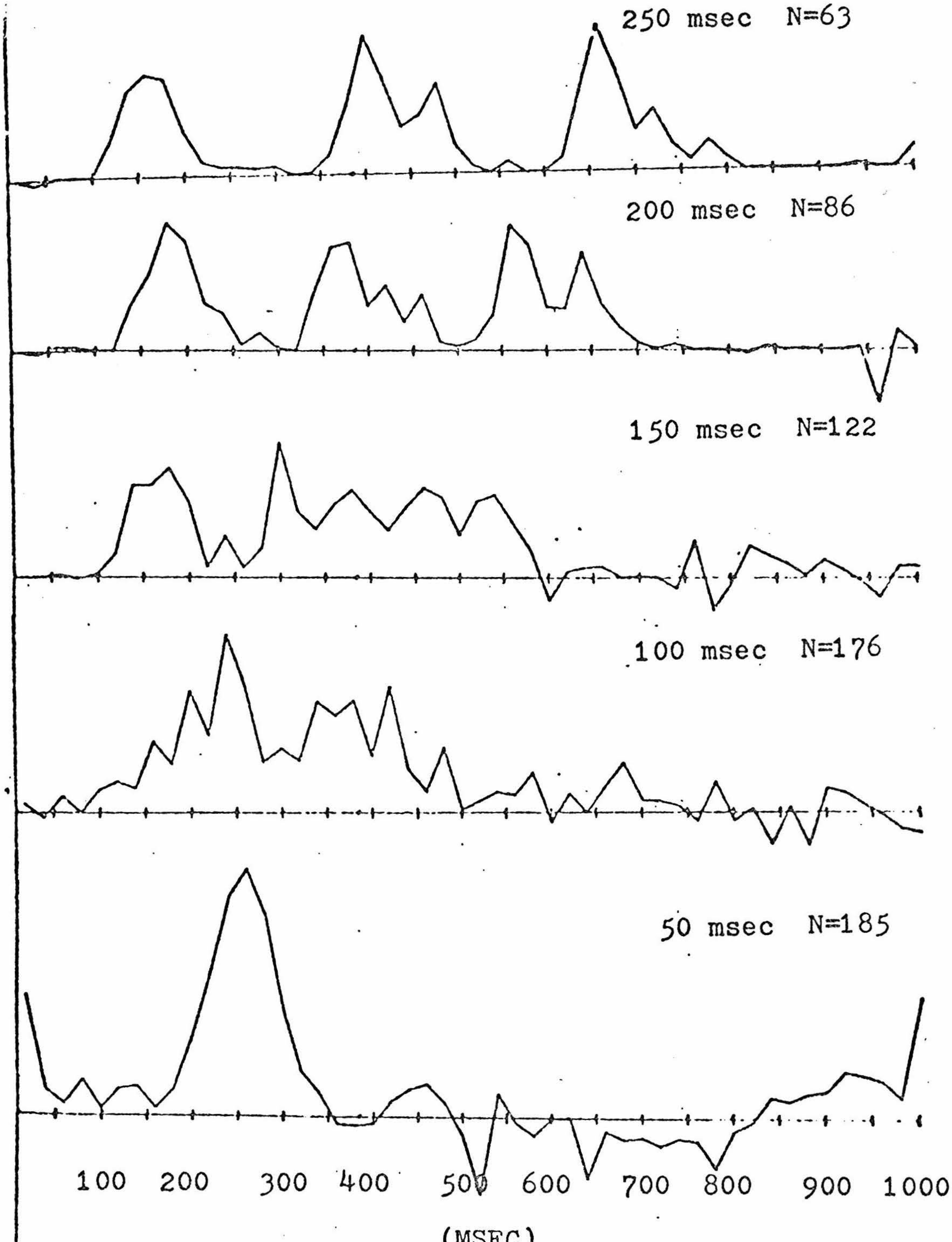


Fig. 5.6g Accumulated responses to stimulus pattern No. 4. Subject RH.

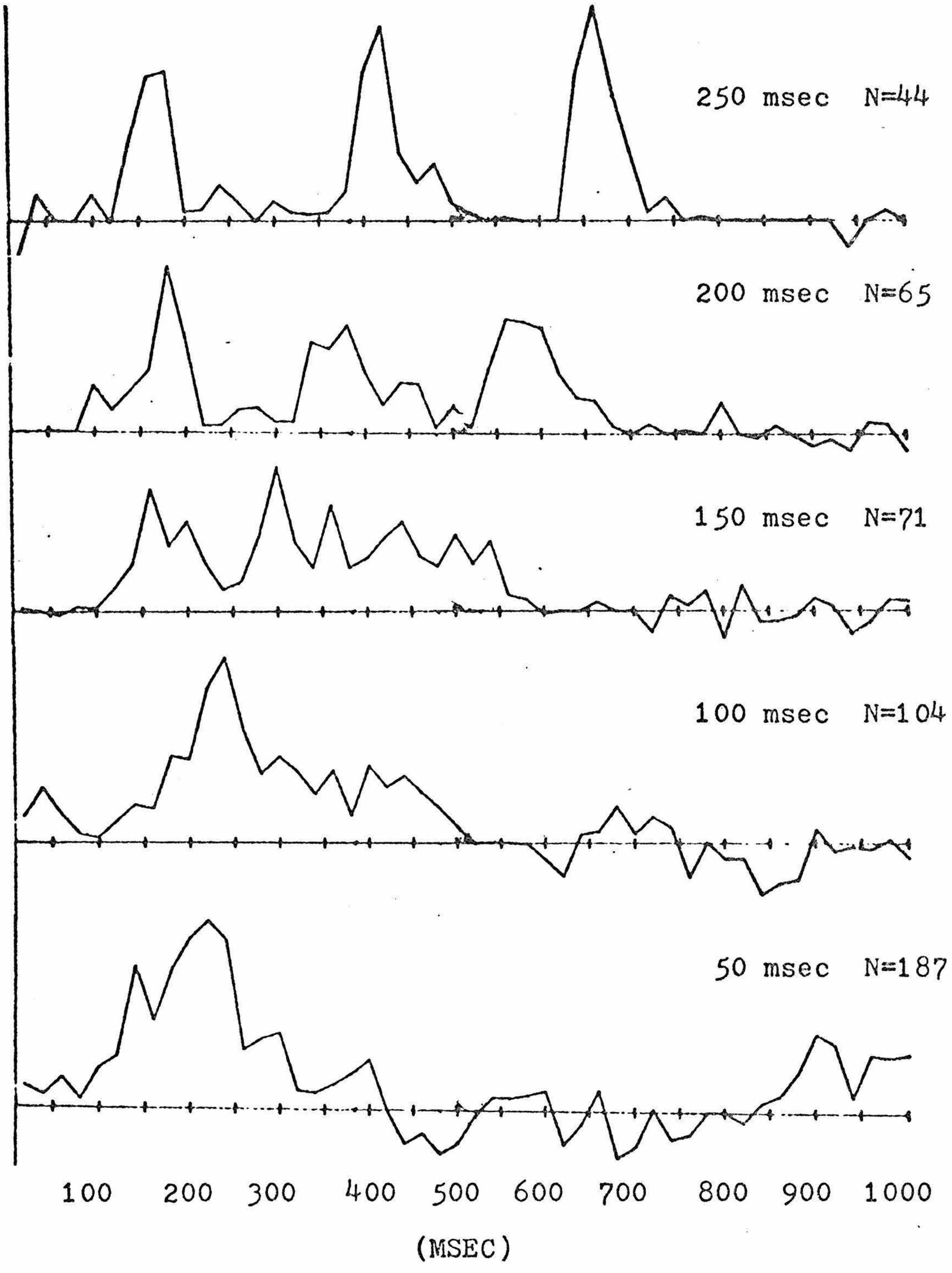


Fig. 5.6h Accumulated responses to stimulus pattern No. 4. Subject RW.

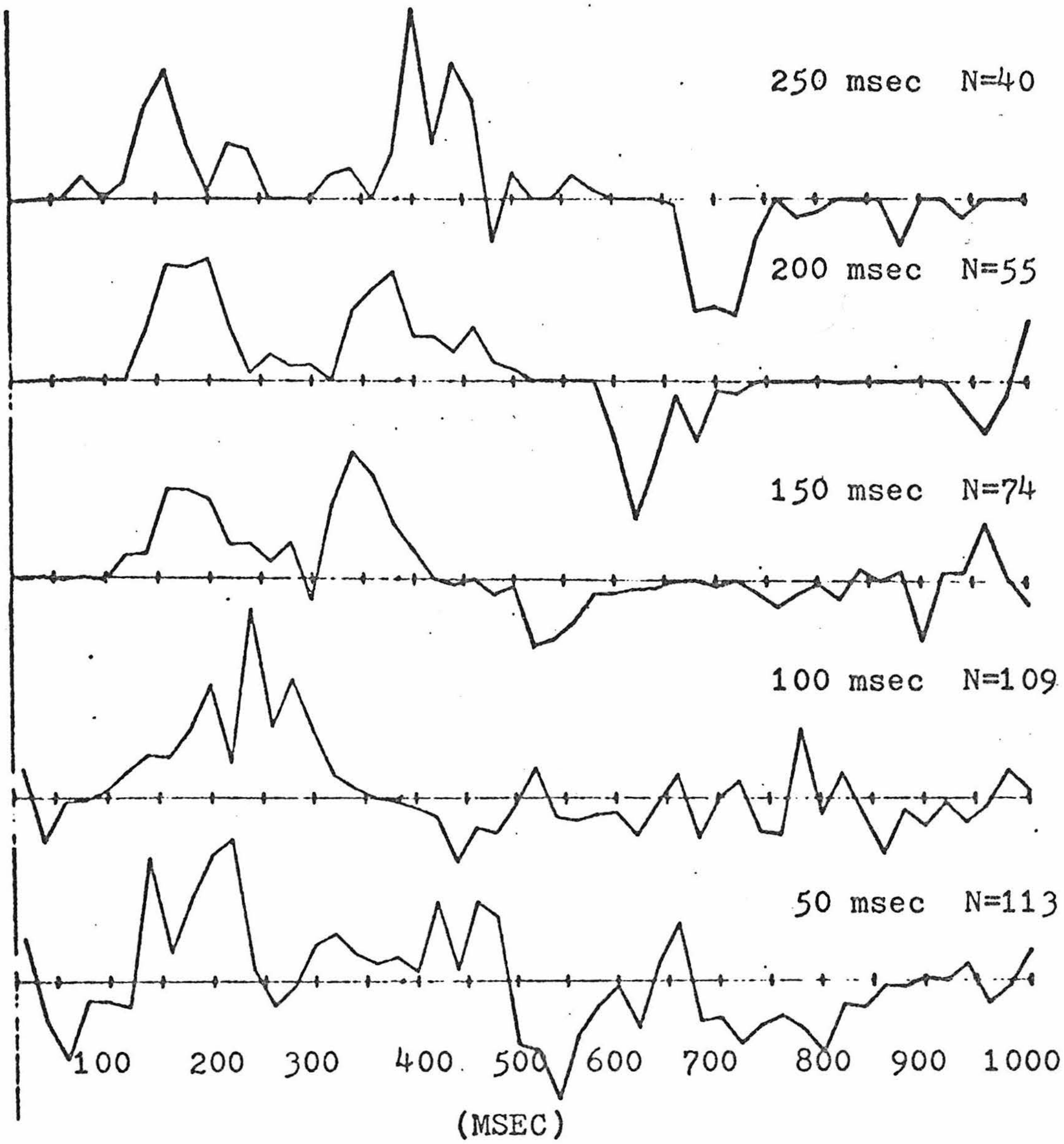


Fig. 5.6i Accumulated responses to stimulus pattern No. 5. Subject RH.

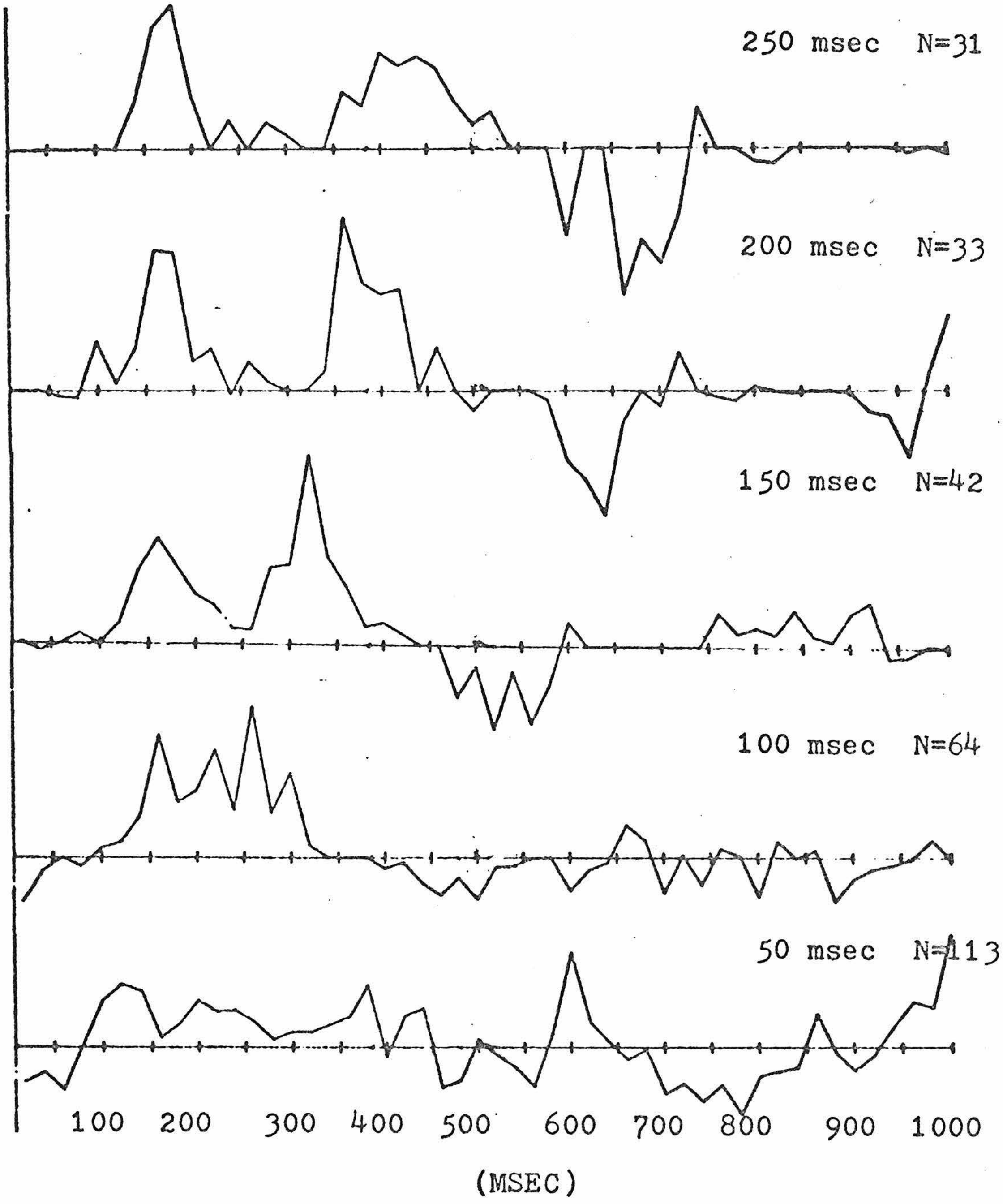


Fig 5.6j Accumulated responses to stimulus pattern No. 5. Subject RW.

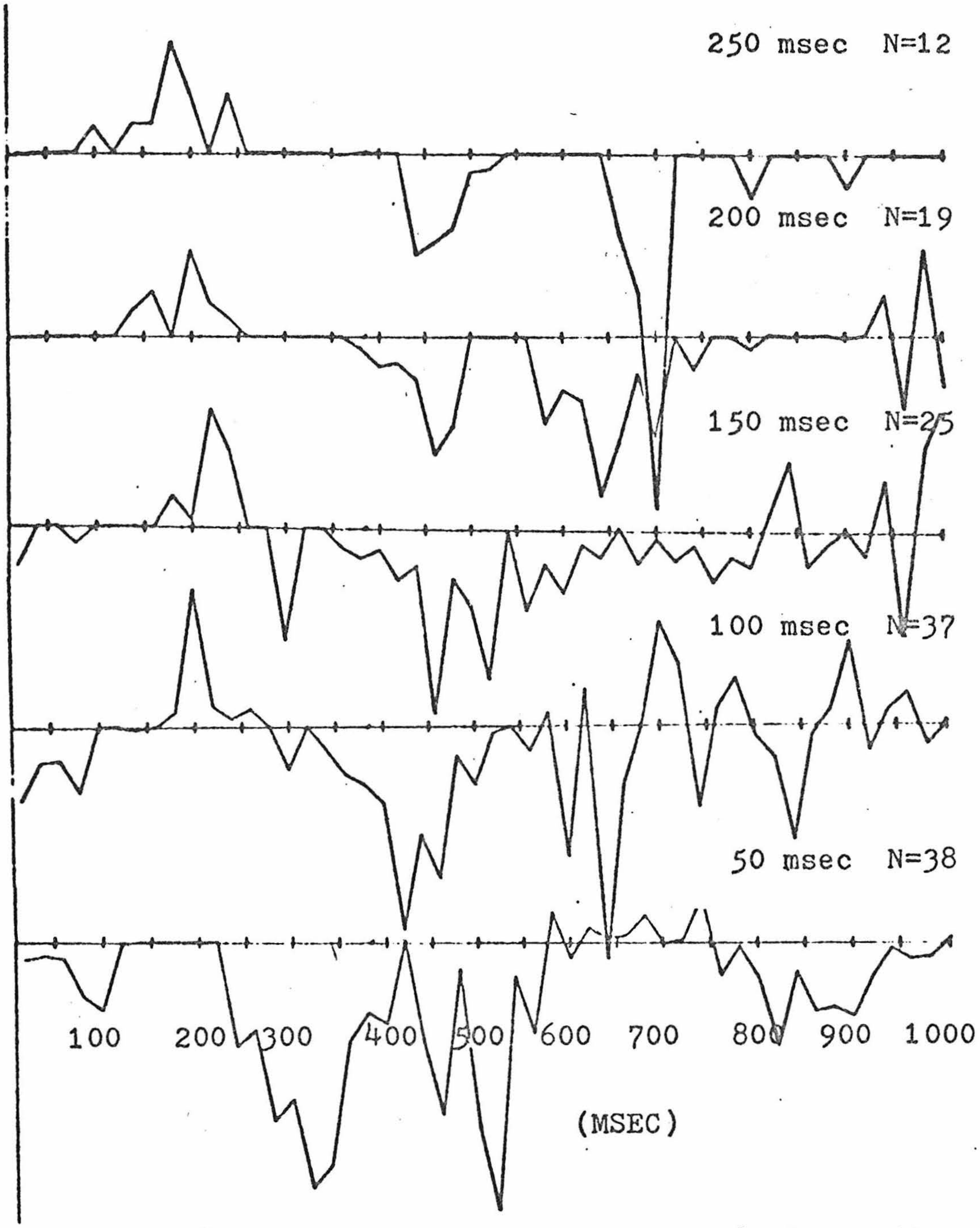


Fig. 5.6k Accumulated responses to stimulus pattern No. 6. Subject RH

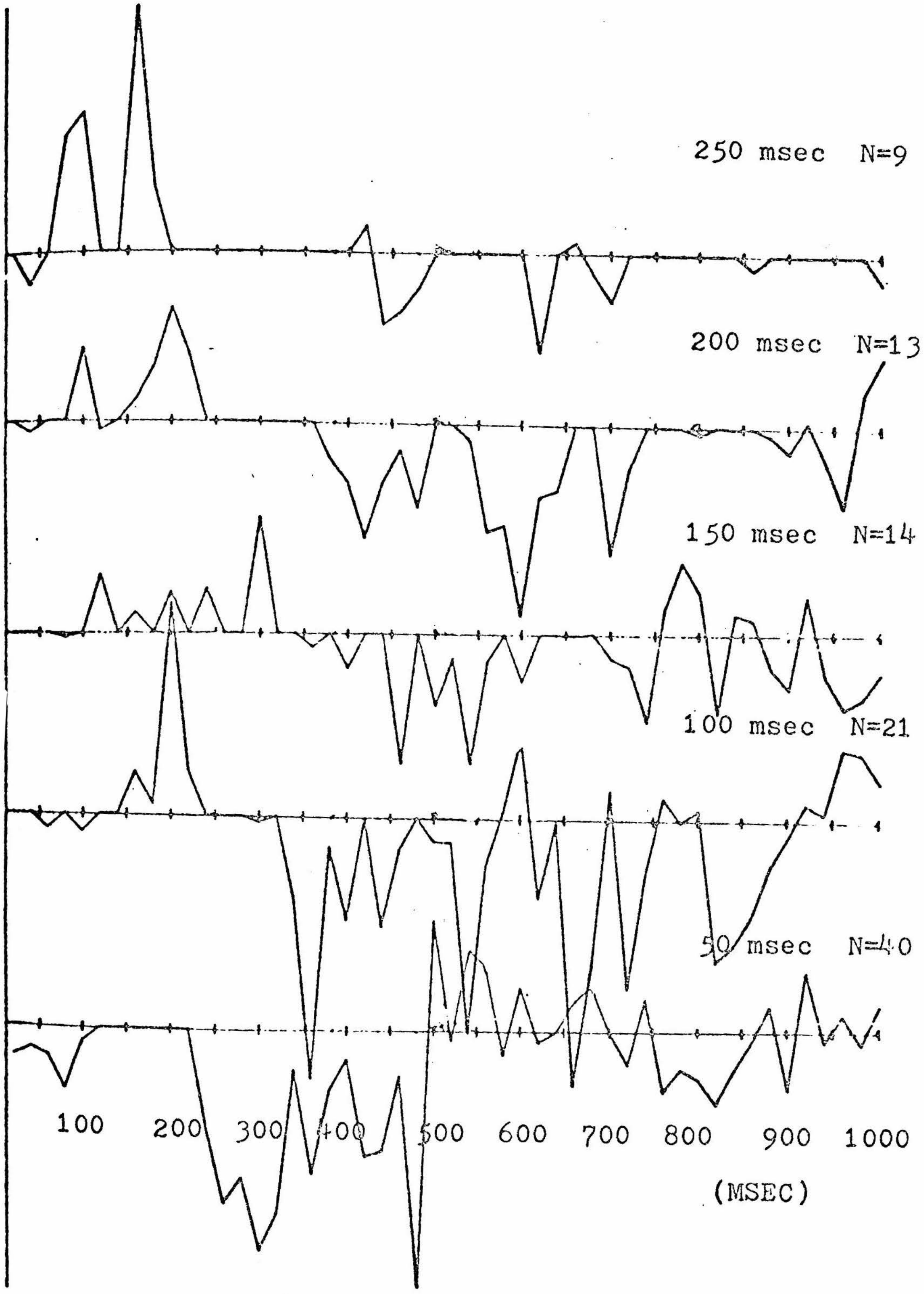


Fig. 5.61 Accumulated responses to stimulus pattern No. 6. Subject RW.

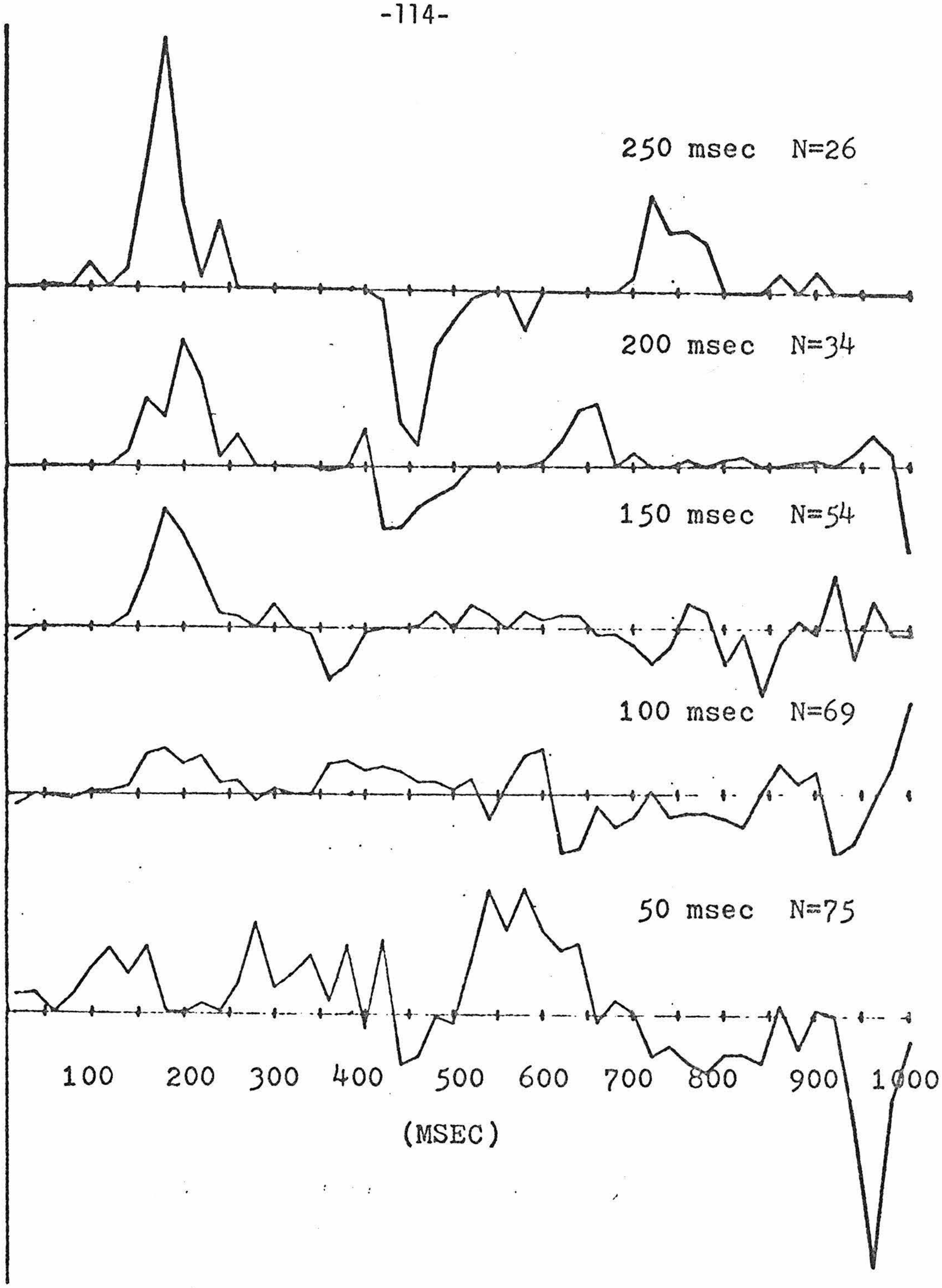


Fig. 5.6m Accumulated responses to stimulus pattern No. 7. Subject RH.

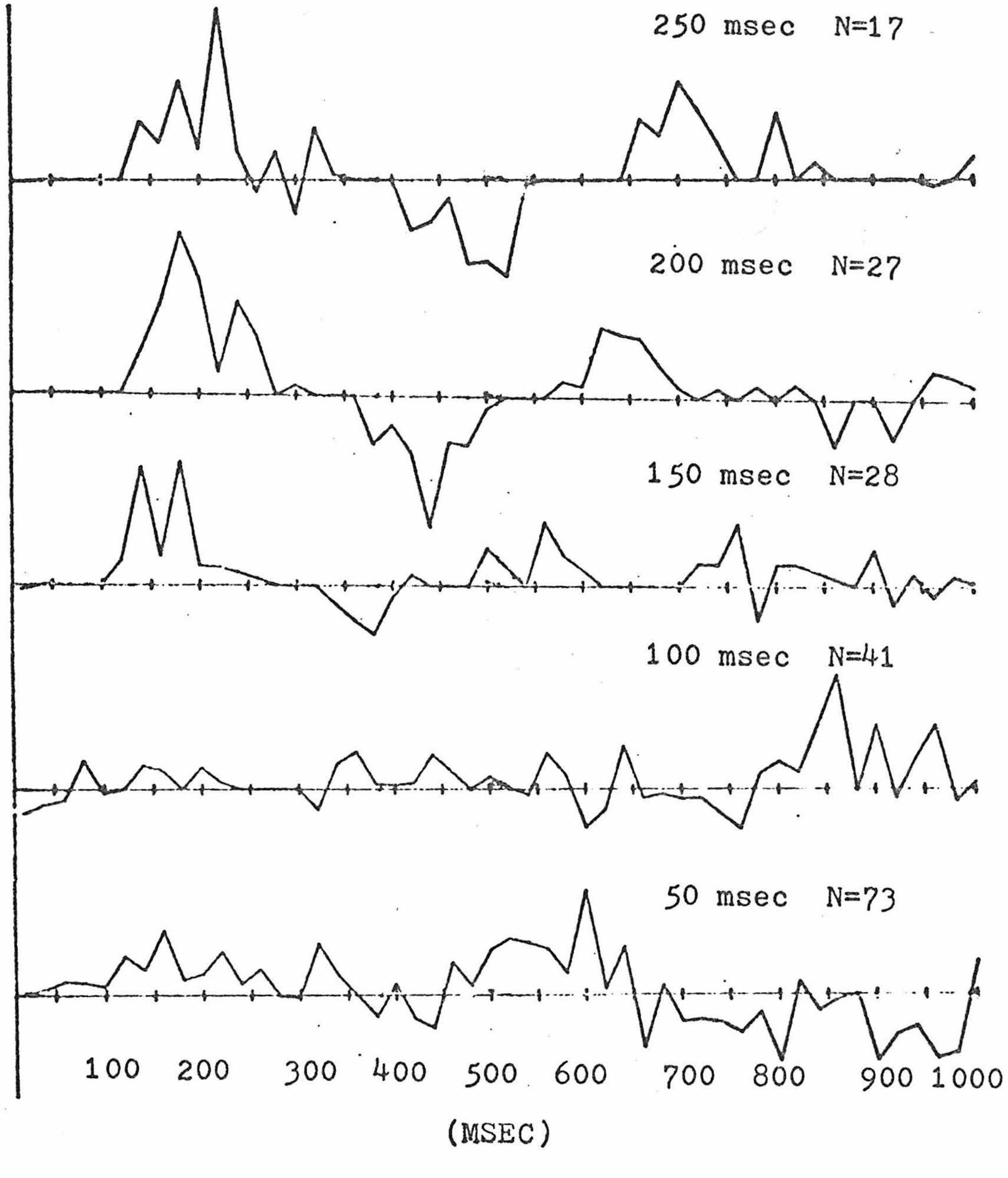


Fig. 5.6n Accumulated responses to stimulus pattern No. 7. Subject RW.

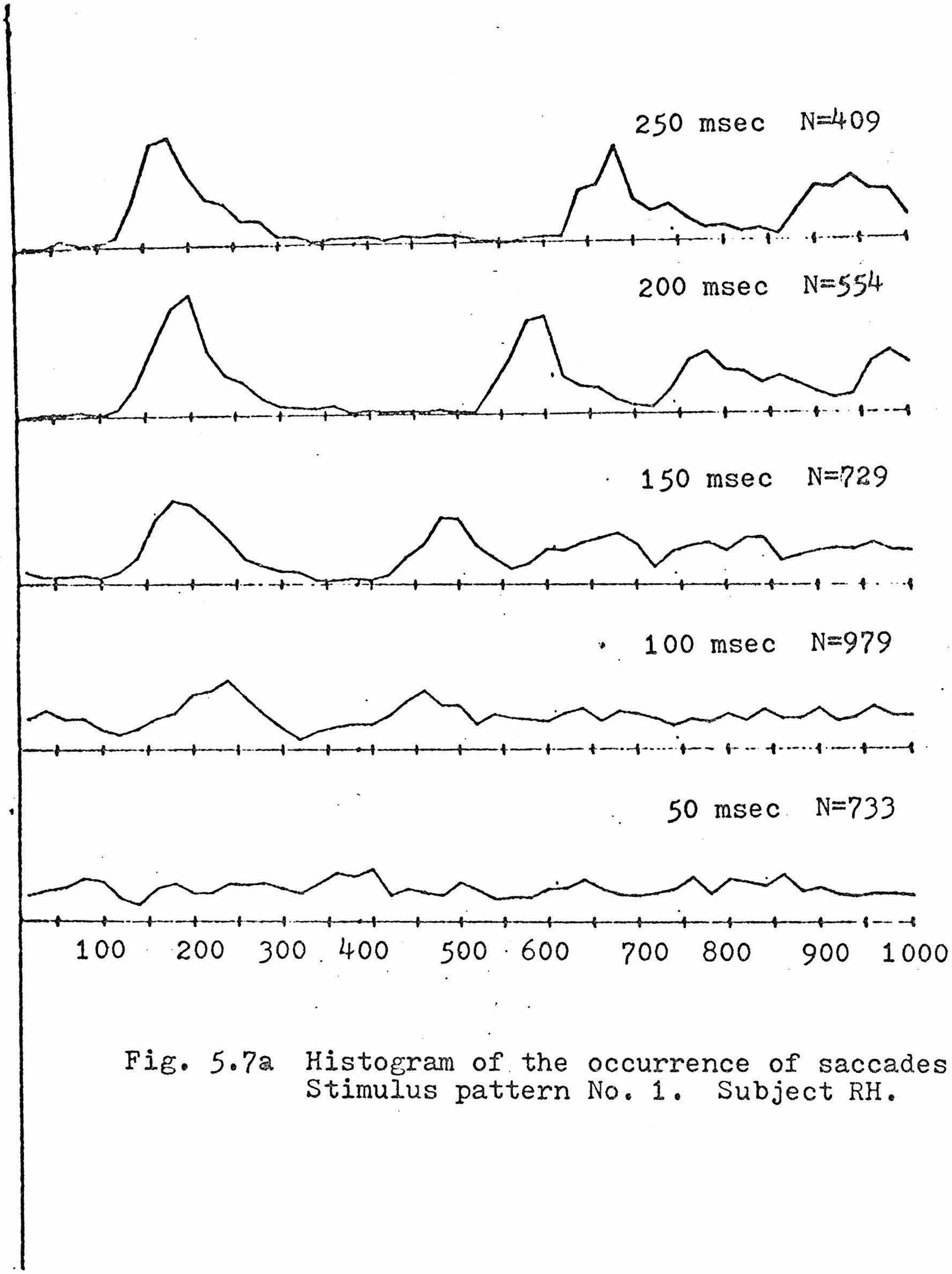


Fig. 5.7a Histogram of the occurrence of saccades.
Stimulus pattern No. 1. Subject RH.

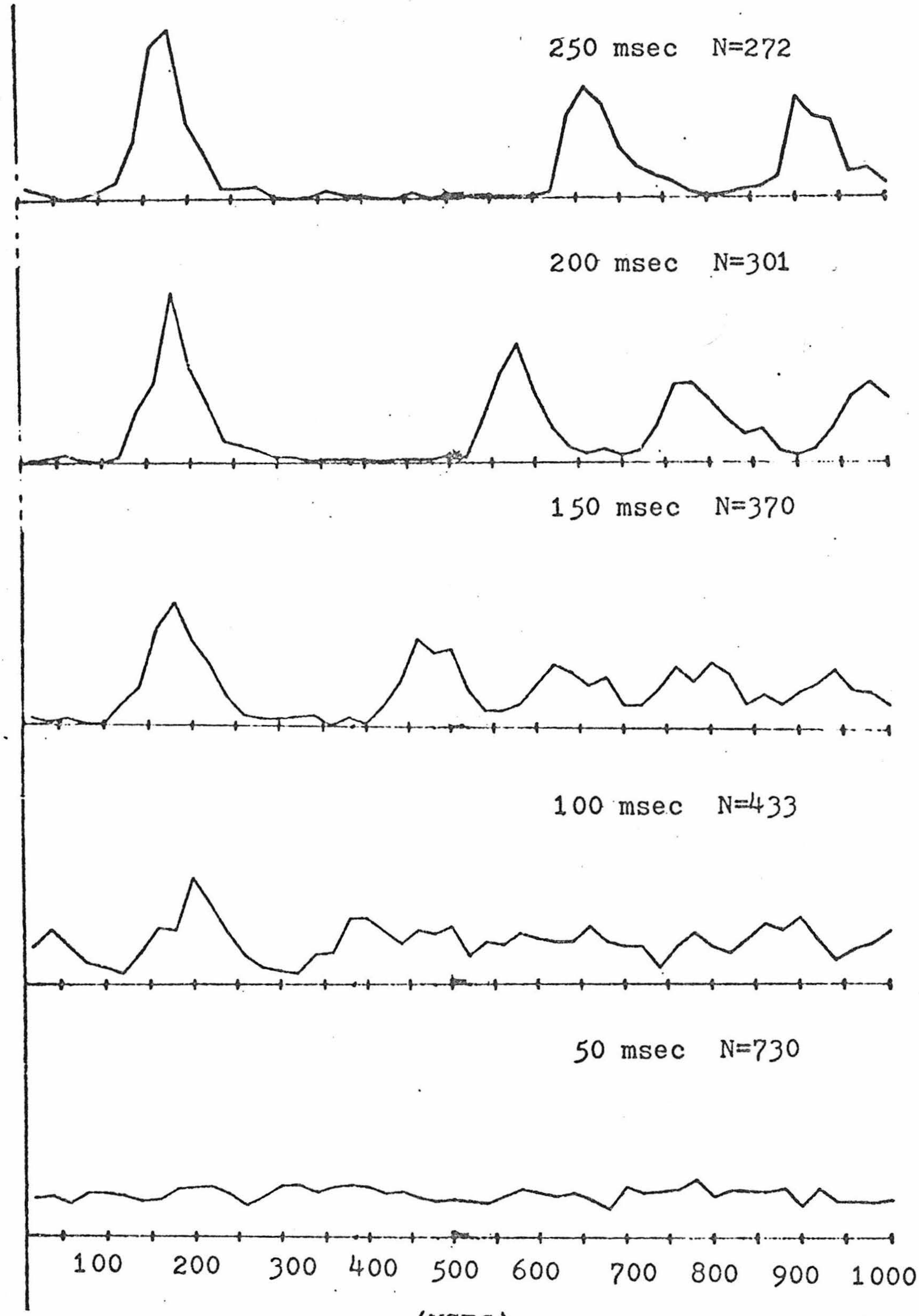


Fig. 5.7b Histogram of the occurrence of saccades. Stimulus pattern No. 1. Subject RW.

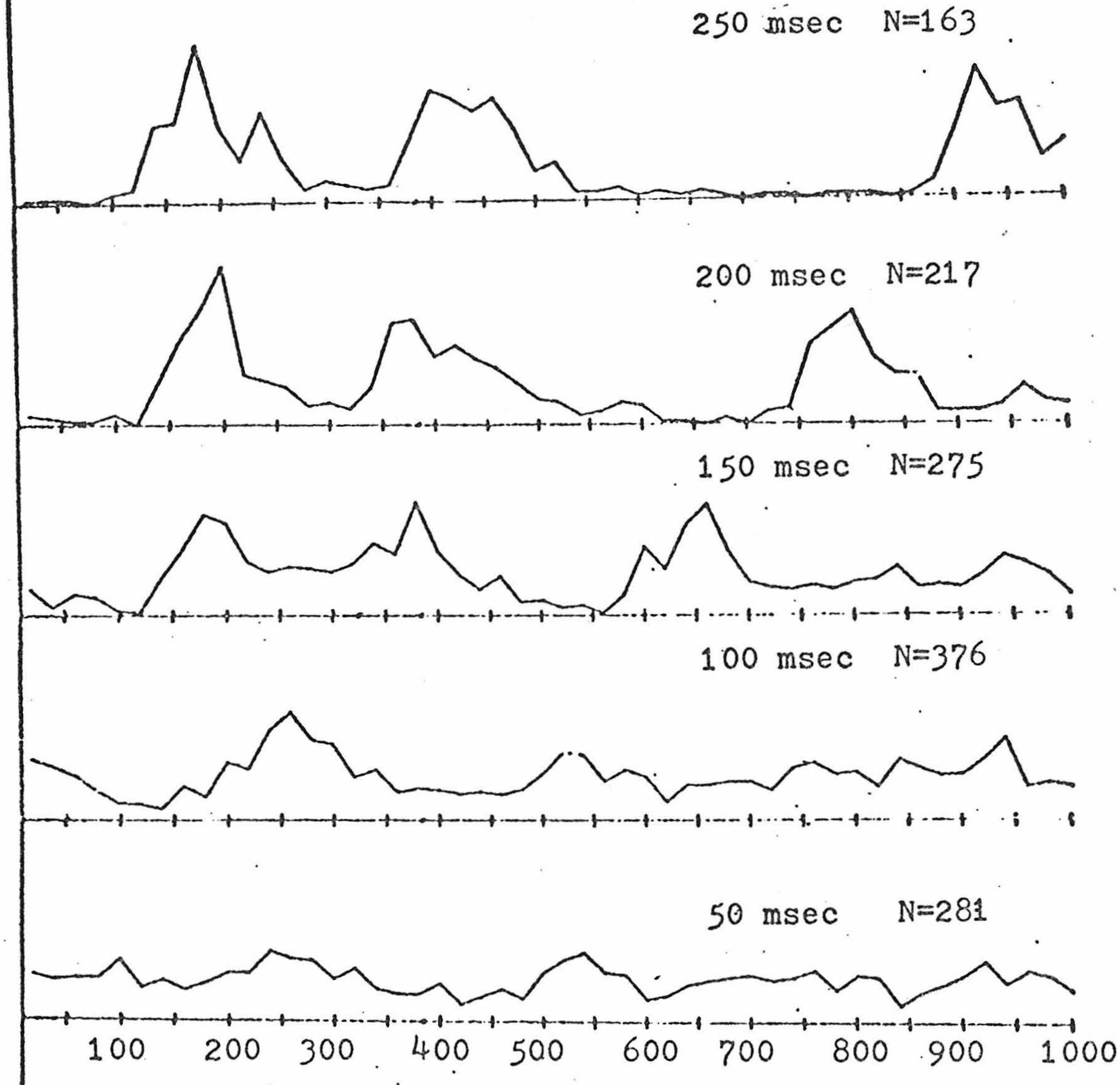


Fig. 5.7c Histogram of the occurrence of saccades. Stimulus pattern No. 2. Subject RH.

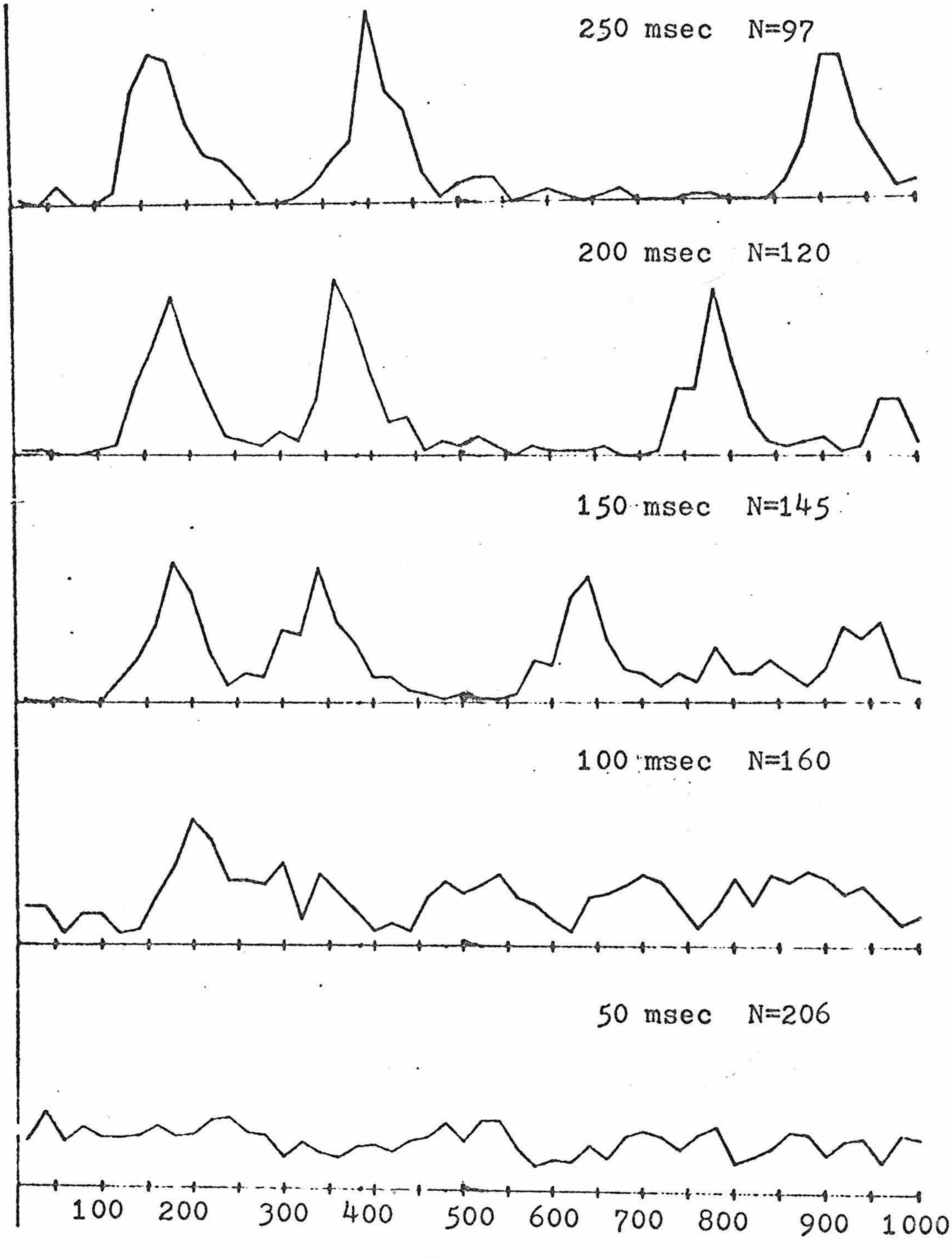


Fig. 5.7d Histogram of the occurrence of saccades.
Stimulus pattern No. 2. Subject RW.

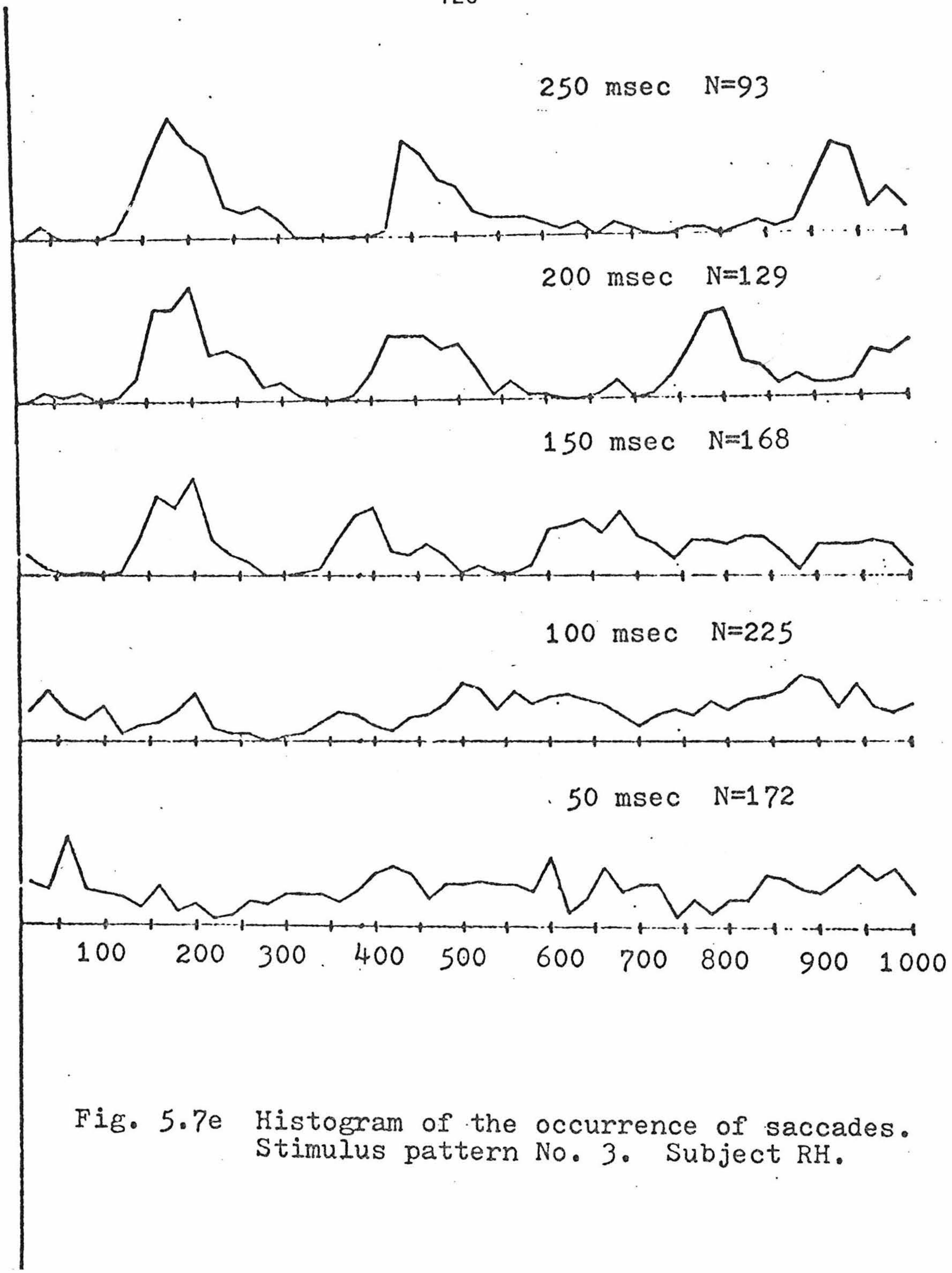


Fig. 5.7e Histogram of the occurrence of saccades. Stimulus pattern No. 3. Subject RH.

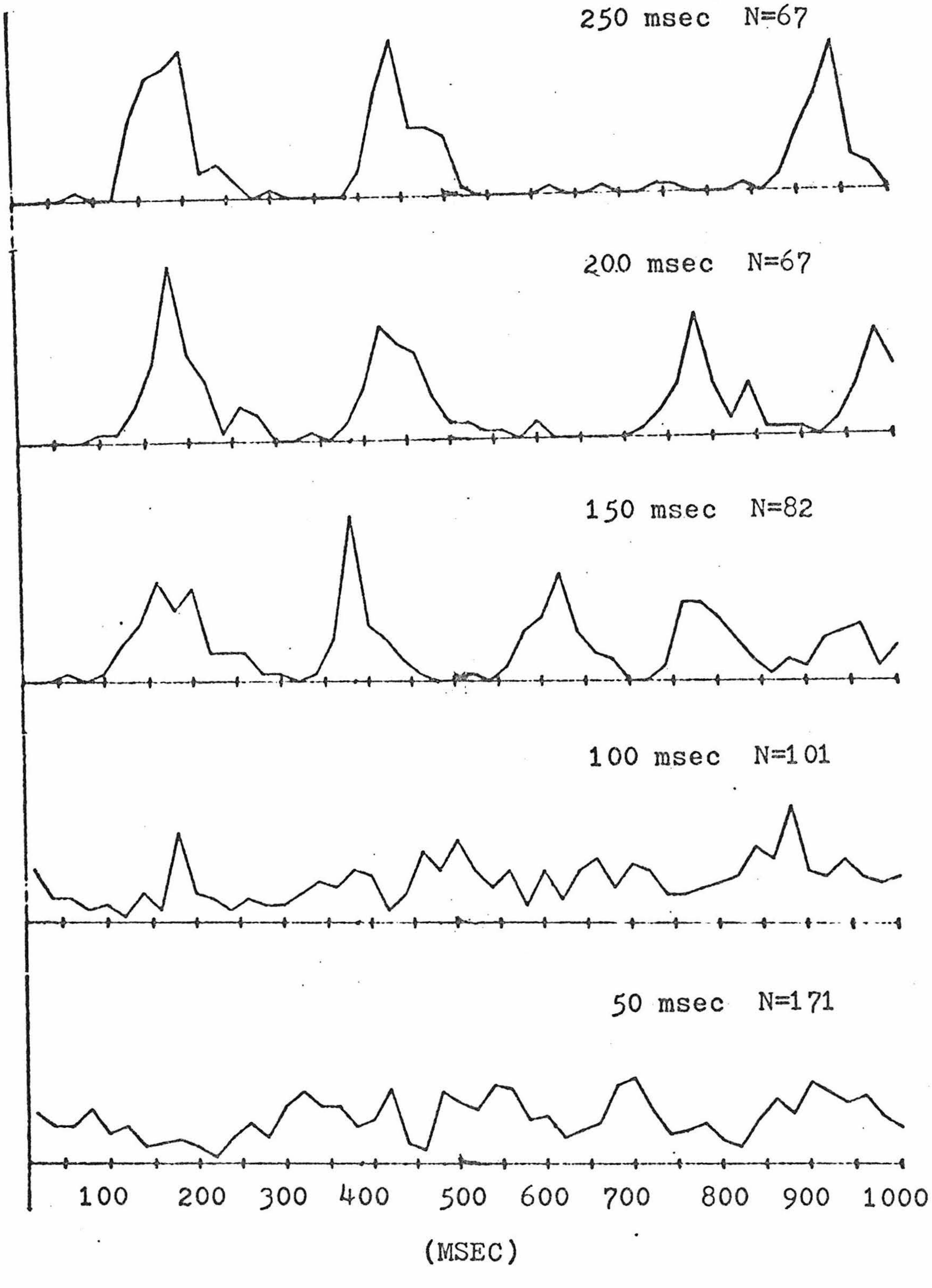


Fig. 5.7f Histogram of the occurrence of saccades. Stimulus pattern No. 3. Subject RW.

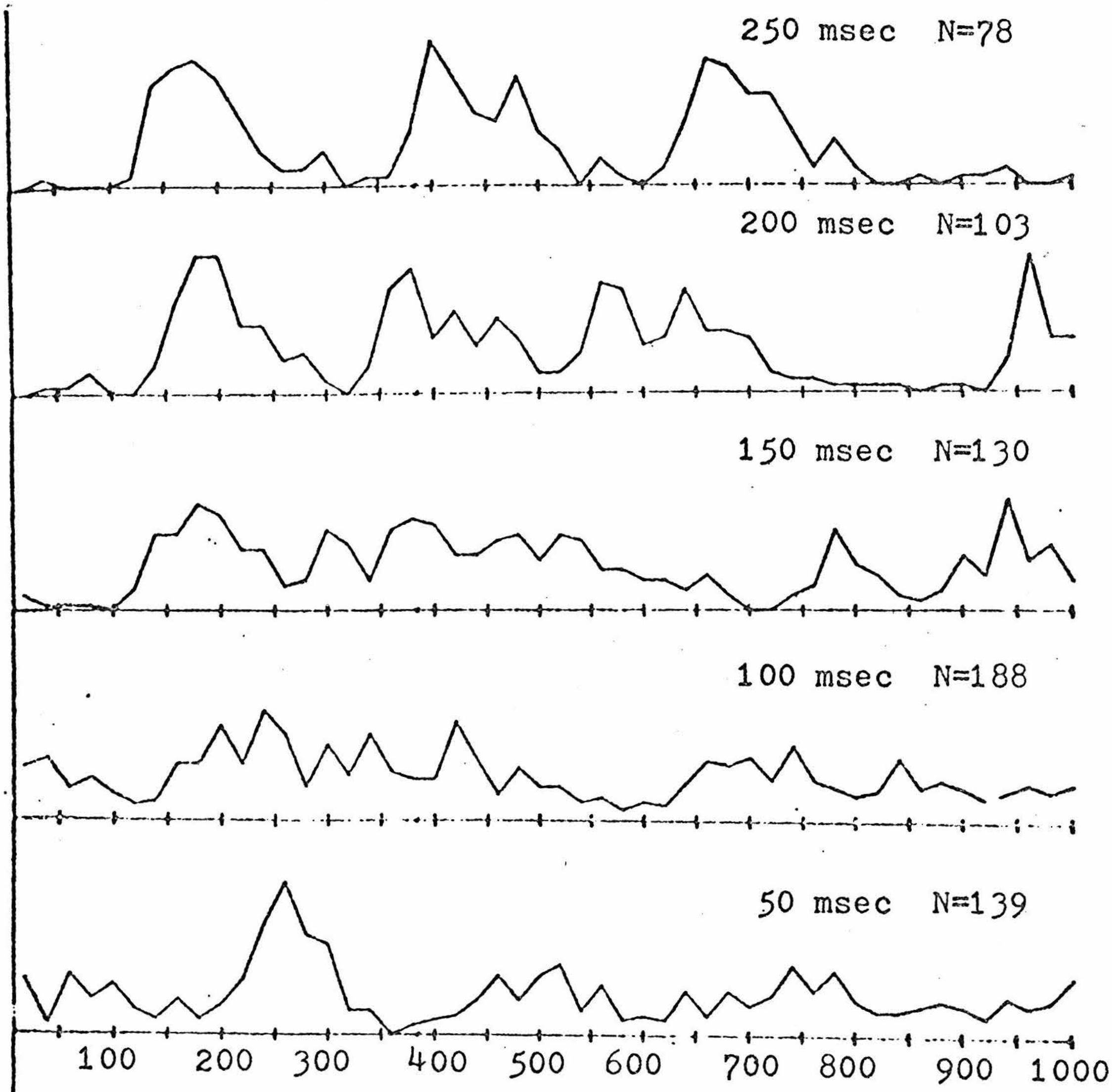


Fig. 5.7g Histogram of the occurrence of saccades. Stimulus pattern No. 4. Subject RH.

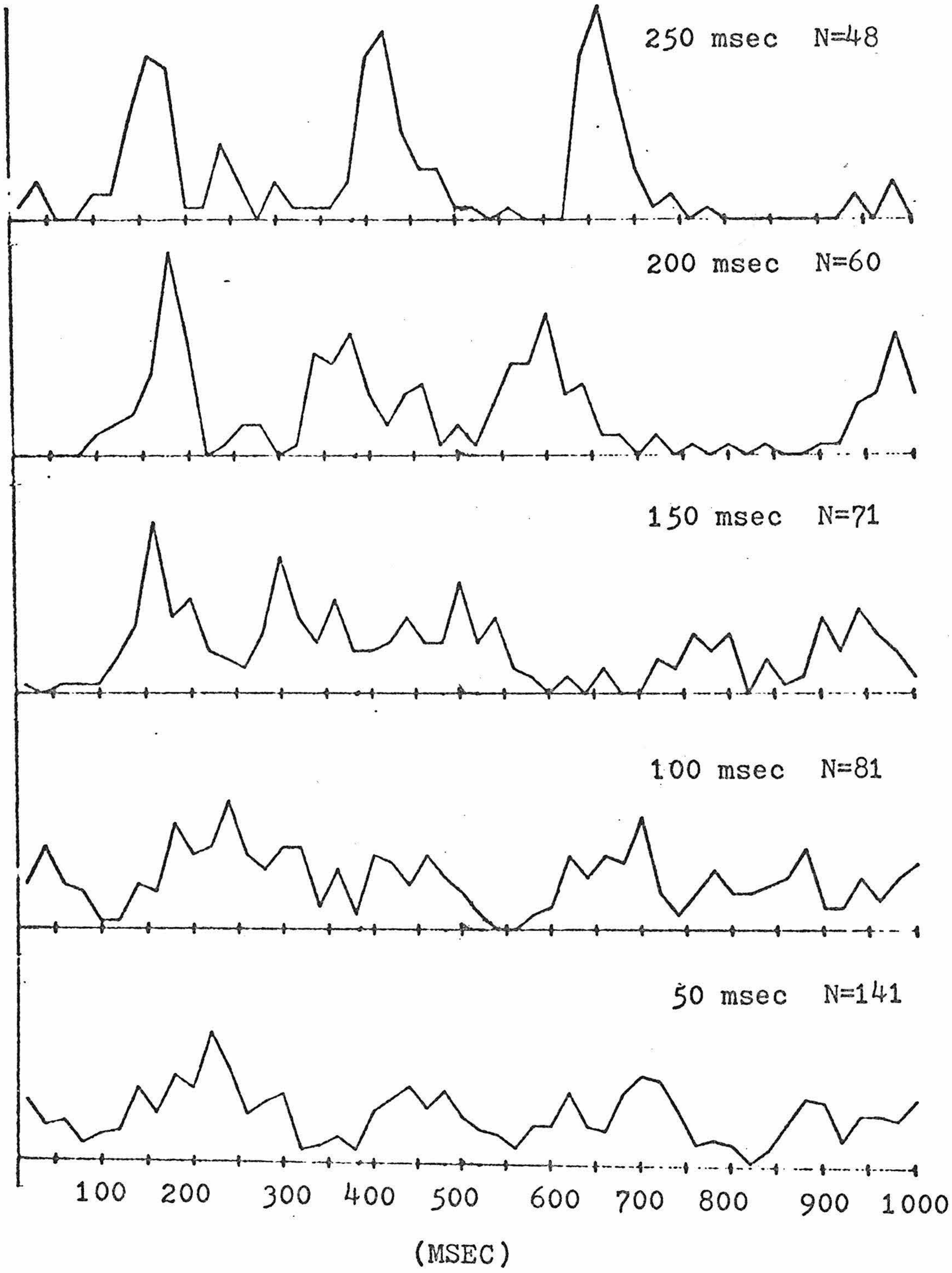


Fig. 5.7h Histogram of the occurrence of saccades. Stimulus pattern No. 4. Subject RW.

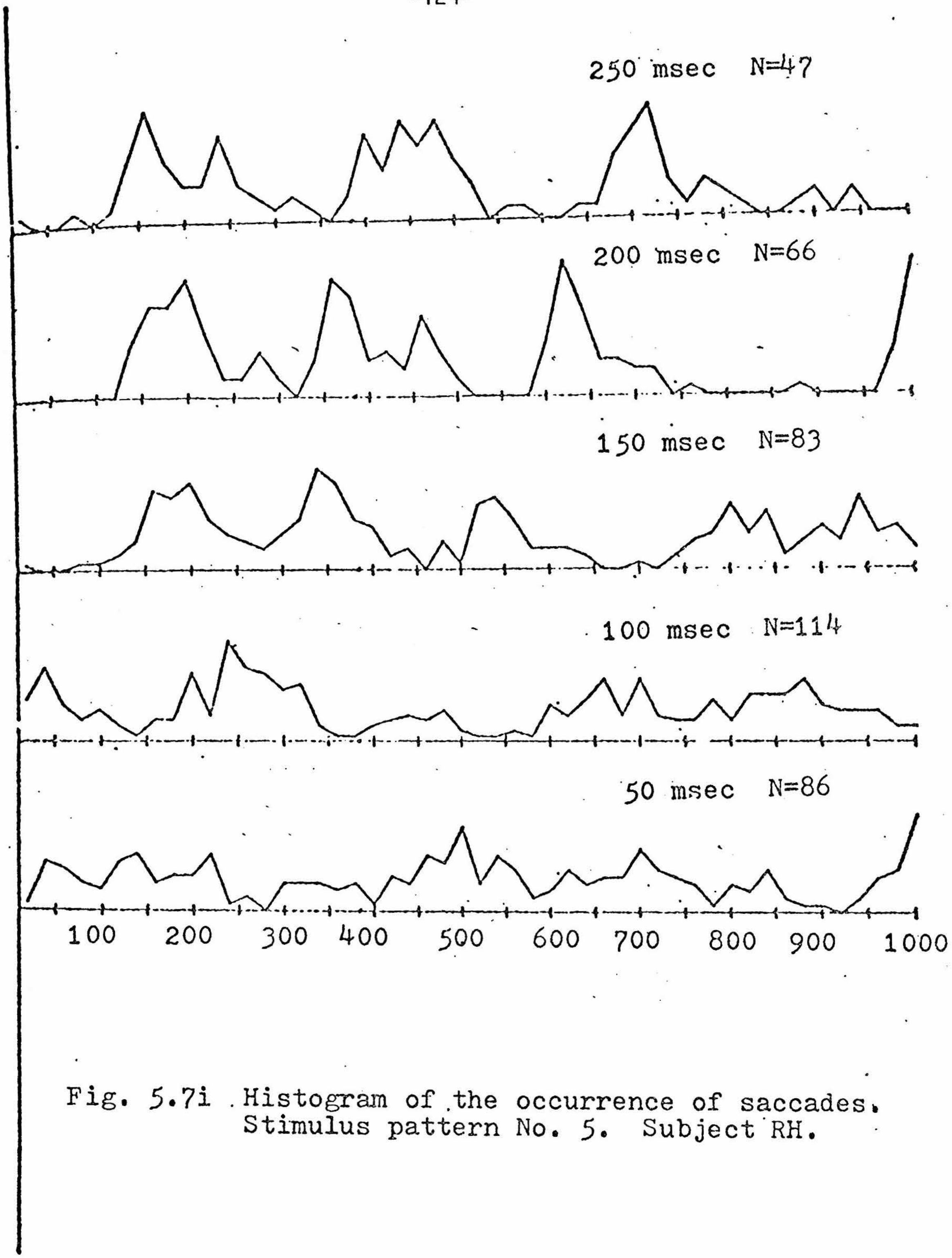


Fig. 5.7i Histogram of the occurrence of saccades. Stimulus pattern No. 5. Subject RH.

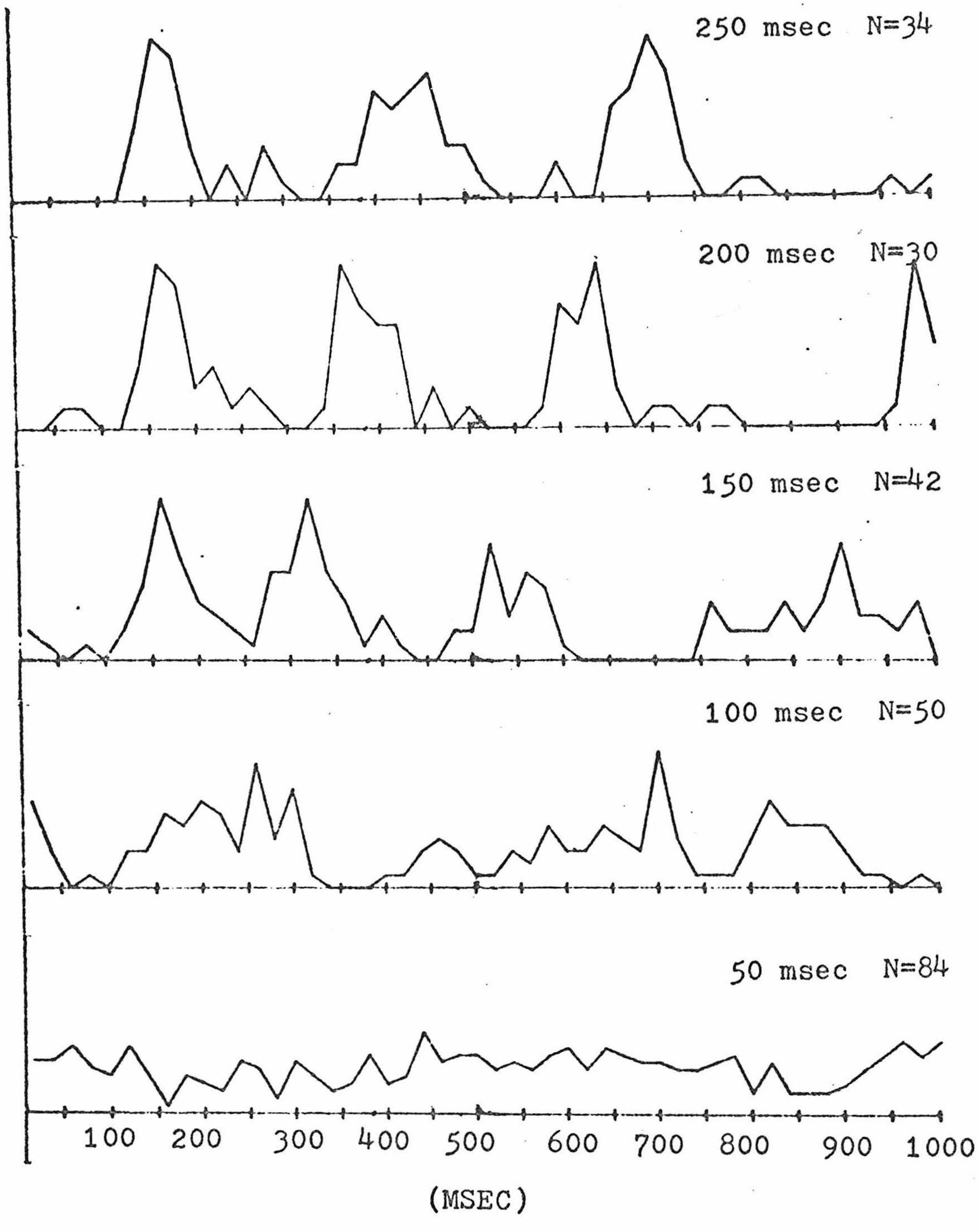


Fig. 5.7j Histogram of the occurrence of saccades. Stimulus pattern No. 5. Subject RW.

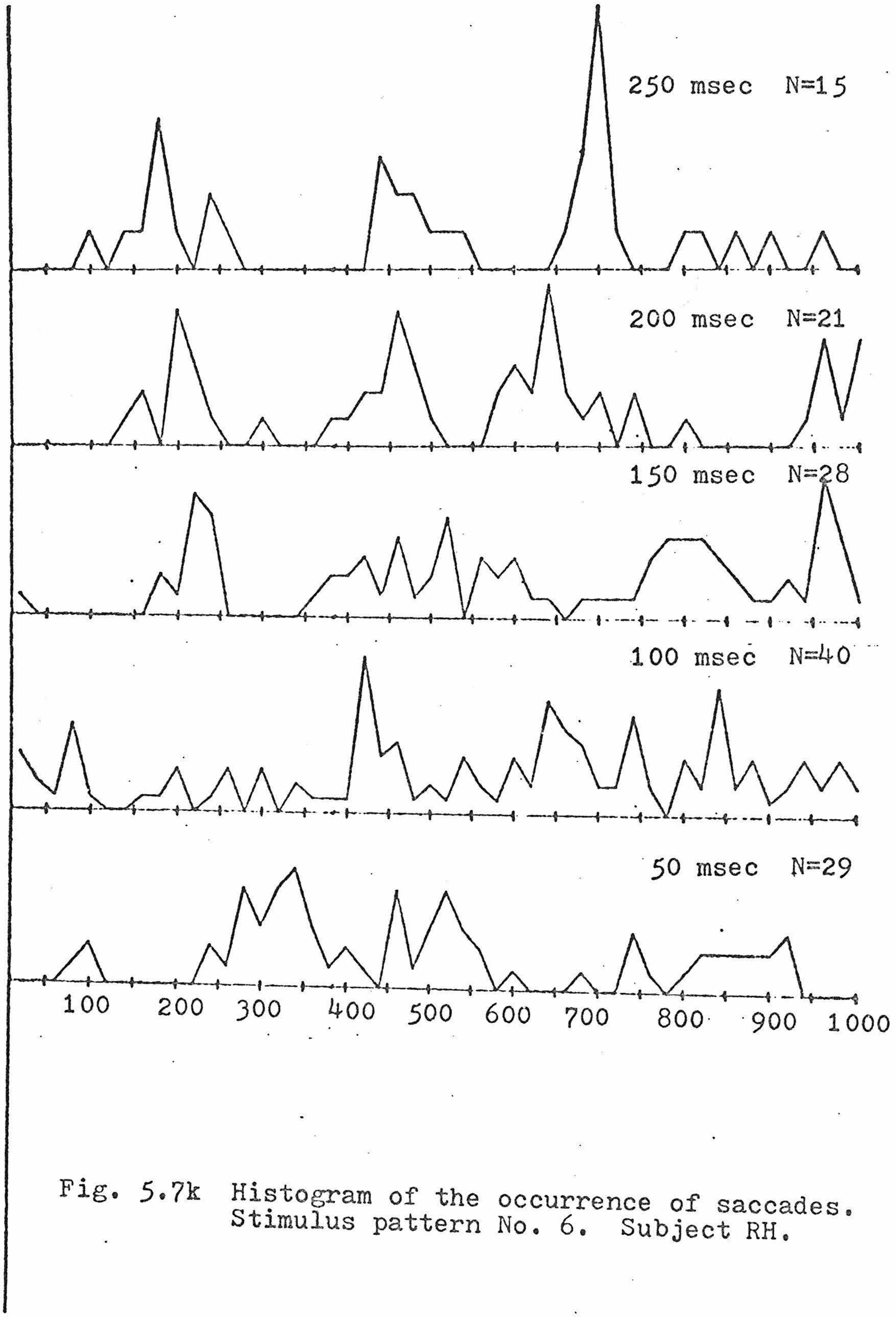


Fig. 5.7k Histogram of the occurrence of saccades. Stimulus pattern No. 6. Subject RH.

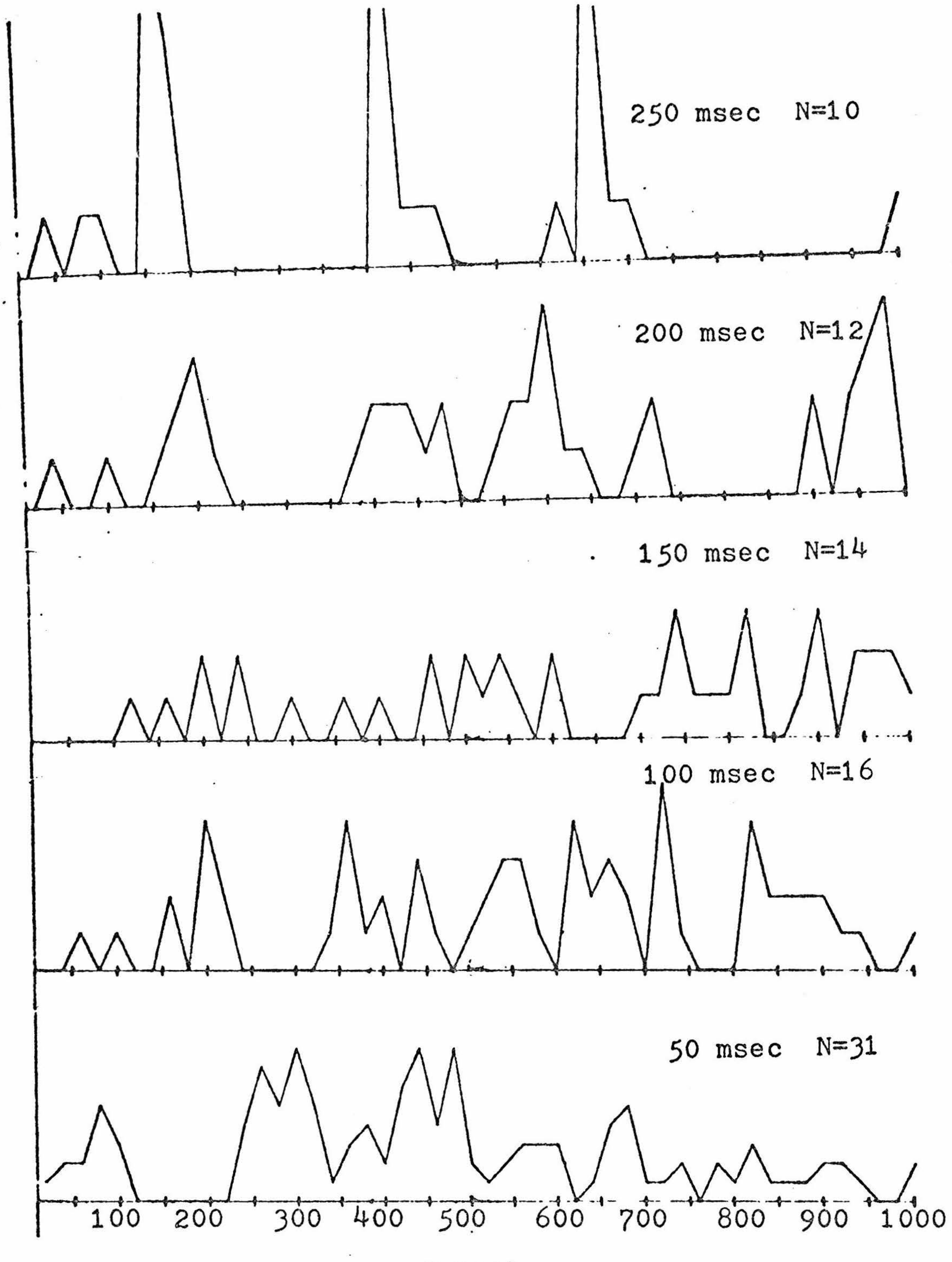


Fig. 5.7 1 Histogram of the occurrence of saccades. Stimulus pattern No. 6. Subject RW.

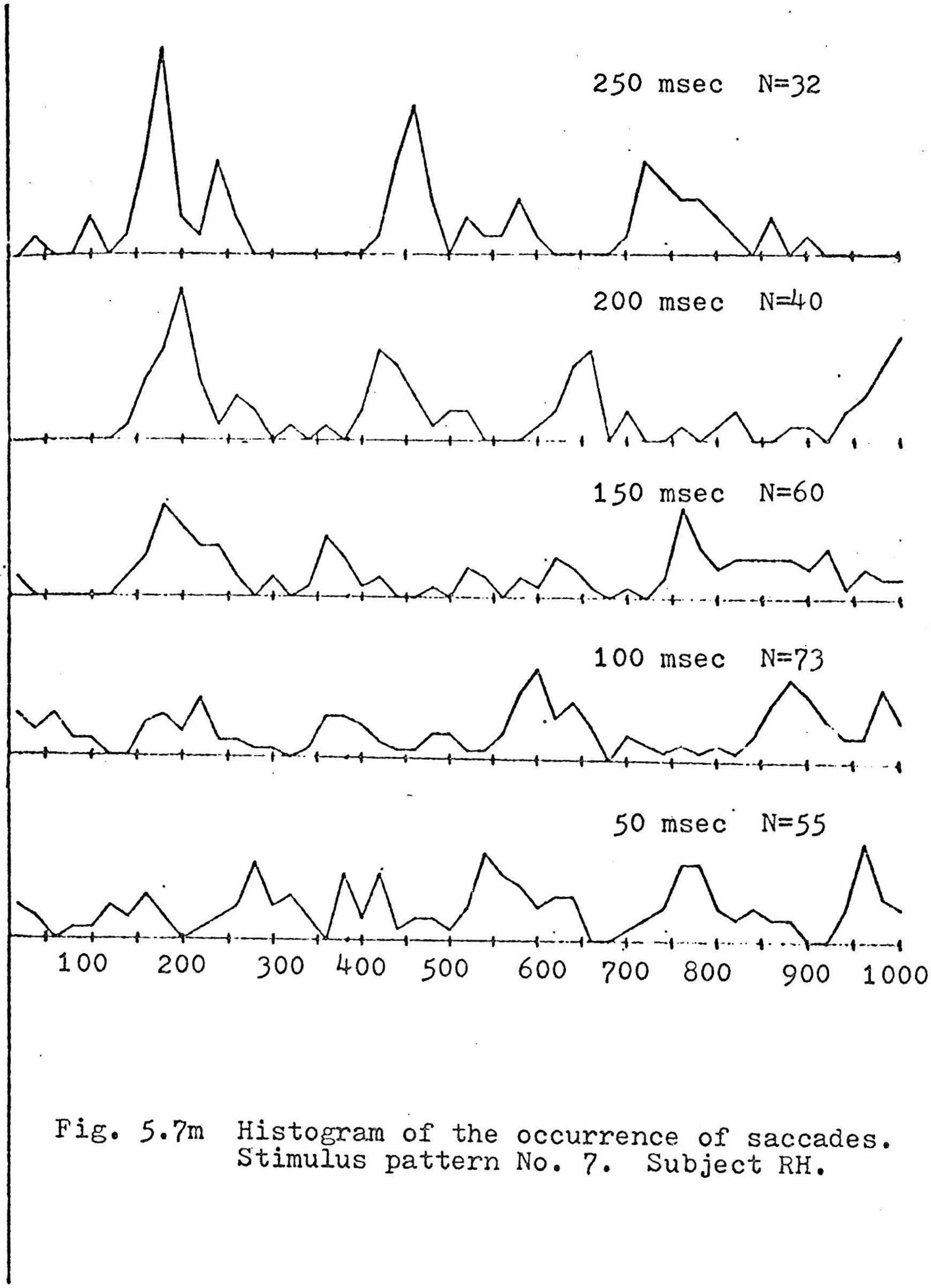


Fig. 5.7m Histogram of the occurrence of saccades. Stimulus pattern No. 7. Subject RH.

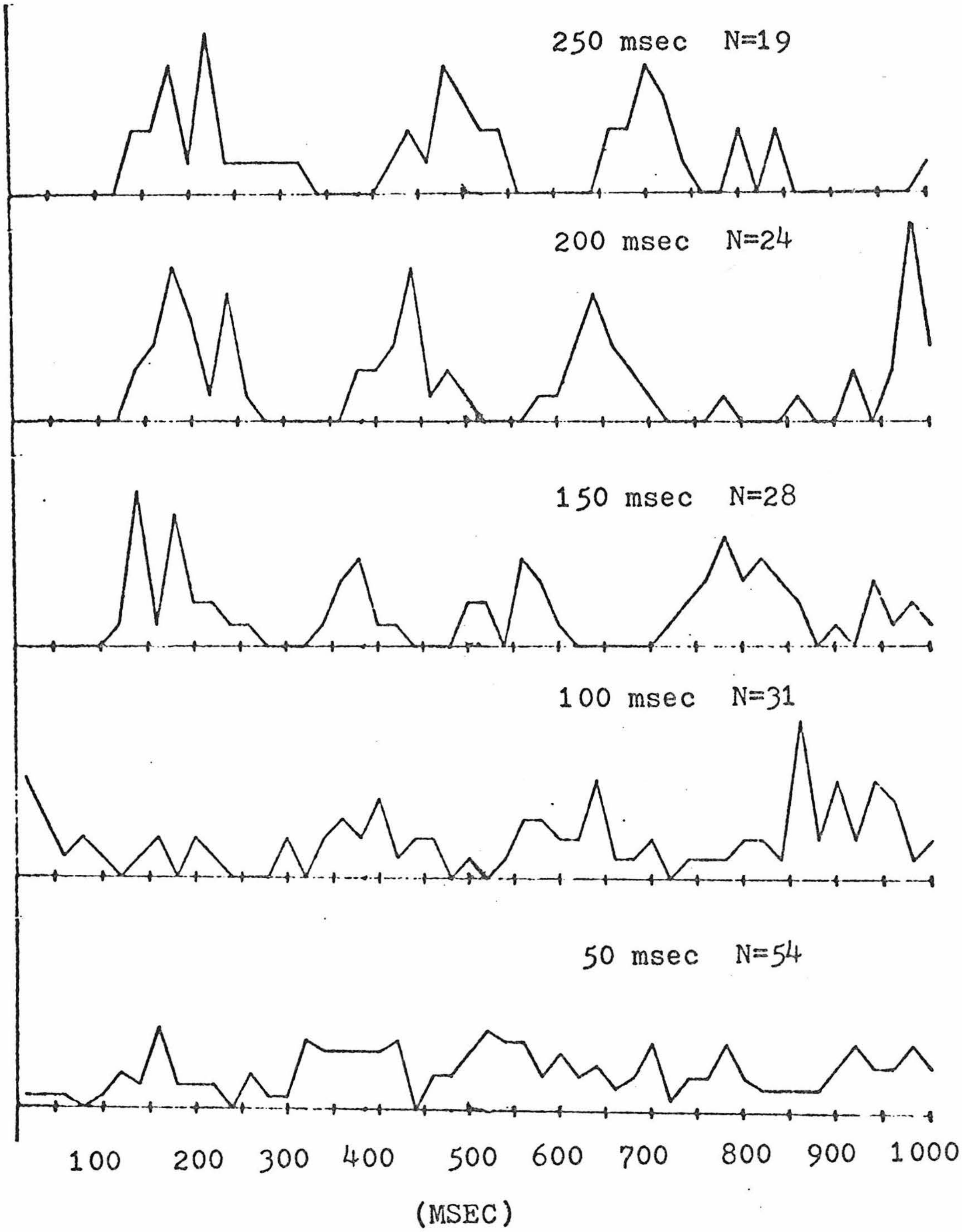


Fig. 5.7n Histogram of the occurence of saccades.
Stimulus pattern No. 7. Subject RW.

5.5.3 Results

Subjects reported an interesting perceptual phenomenon when tracking these target movements. When the time interval was 100 msec, two target spots were often seen to exist on the screen at the same time. They could not distinguish which one appeared first. When the time interval decreased to 50 msec, two or three target spots were often seen to appear at the same time. This phenomenon is very similar to the one reported by Hogben, Julesz and Ross (1976).

As mentioned in the data analysis section, Fig. 5.7 represents a quantity proportional to the probability of a saccade occurring in each time bin, in response to a particular stimulus pattern. Figure 5.6 contains additional information other than pure probability, because the saccadic pulses accumulated have magnitude and sign information. It can be interpreted as the normalized product of the relative frequency of having a saccade in a time bin and its signed magnitude.

The responses to the seven stimulus patterns which are sub-sequences of a continuous target jump sequence, as defined in Section 5.5.2, are discussed below.

5.5.3.1 First order responses

The accumulated responses to the single pulse stimulus pattern (Fig. 5.4a) are shown in Fig. 5.6a,b and Fig. 5.7a,b. For the time intervals of 250 msec, 200 msec and 150 msec, they are bell-shaped functions with the peak located between 150 msec and 200 msec after the target-jump. The majority of saccades have latencies between 150 msec and 200 msec, but there are some saccades with latencies shorter than 150 msec.

Saccades with such a short latency are rare in the study of transient behavior.

When the time intervals decrease to 100 msec and 50 msec, the accumulated responses are no longer bell-shaped functions. In the 100 msec case the response has two lobes (Fig. 5.6a,b) and both lobes are broader and lower. The first lobe represents the saccadic responses to the single target-jump in the pattern. The smaller area underneath this lobe suggests that some target pulses do not elicit a response. The error due to the lack of saccadic response could be accumulated or erased, depending on the direction of the next target-step following the no-jump at the end of each pattern. A step in the opposite direction would erase the error, but a step in the same direction would make the error twice as large. The response to this accumulated error makes up the second lobe. At 100 msec the majority of the saccadic responses seem to have longer latency. The peak of the first lobe is delayed more for subject RH than for subject RW (Fig. 5.6a,b, Fig. 5,7a,b). At 50 msec the occurrence of a saccade seems to be uniformly distributed (Fig. 5.7a,b).

5.5.3.2 Linear model responses

The responses to the stimulus pattern consisting of more than one target-step are compared with the prediction of a linear superposition model. This model assumes that the saccadic system has an infinite information processing capacity and it responds to each target pulse as if it was an isolated single target pulse. The model responses are constructed from the summation of the first order response. The first order response is shifted in time and with a sign change, if necessary, according to the occurrence time and the sign of the target pulses in the stimulus pattern. Then all the shifted and maybe reversed responses corresponding to each target-step are added together and the results are used as the model responses. The model responses are shown in Fig. 5.8 for six stimulus patterns.

5.5.3.3 Second order responses

Two types of second order responses exist (Fig. 5.4b,c).

Stimulus Pattern No. 2: To the stimulus pattern consisting of two target-steps in the same direction, both subjects usually responded with two saccades or one big saccade to cover both target-steps. For the time intervals of 250, 200 and 150 msec, the results are very close to the linear model, that is, two saccades respond to the two target-steps independently. The only discrepancy is that the second lobe in subject RH's response is slightly delayed (Fig. 5.6c,d).

At 100 msec subject RH's response shows only a big peak between 200 and 300 msec. Most saccades occurred around 250 msec (Fig. 5.7c). The time delay between the peak and the second target pulse is about 170 msec, which is about the normal reaction time. The peak in Fig. 5.6c has an area twice as big as that of Fig. 5.7c. Thus it is evident that the saccades occurring around 250 msec have a magnitude sufficient to cover the two target-steps. In other words, when the target-steps are 100 msec apart, the saccadic system in most cases does not respond to the first target-step but to the combination of the two target-steps. For subject RW both Fig. 5.6d and Fig. 5.7d

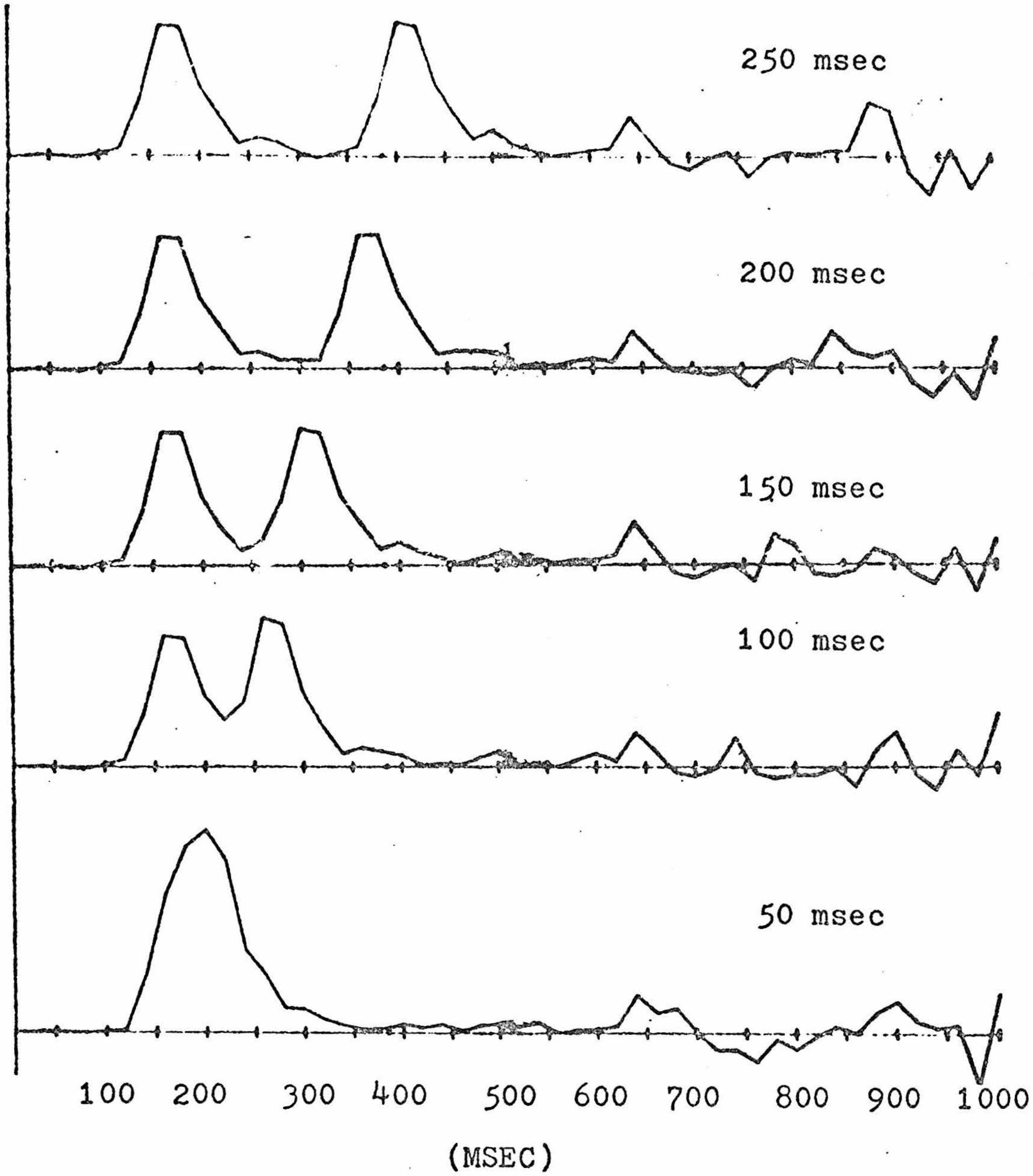


Fig. 5.8a Linear Model Response.
Stimulus Pattern No. 2.

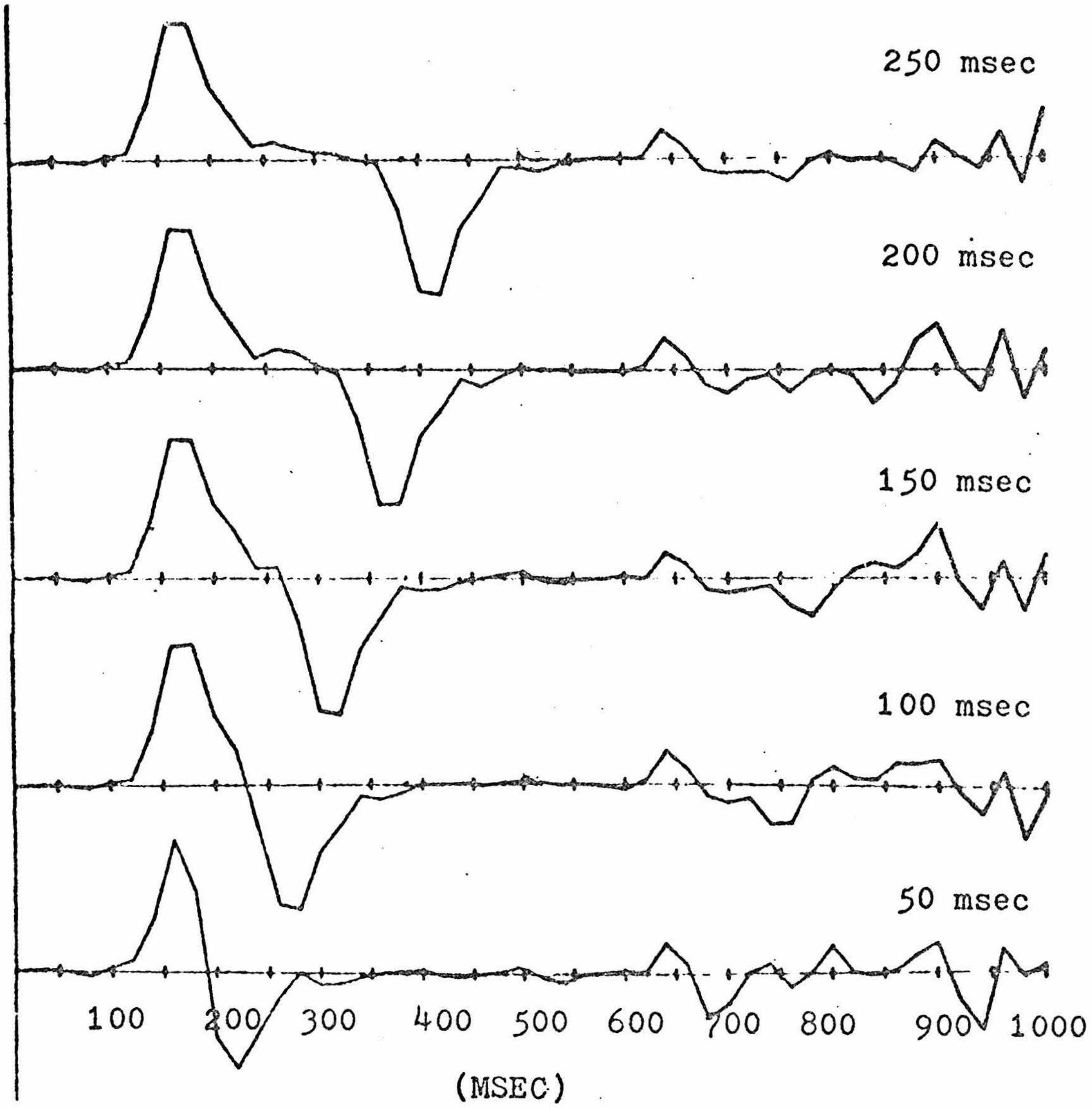


Fig. 5.8b Linear Model Response.
Stimulus Pattern No. 3.

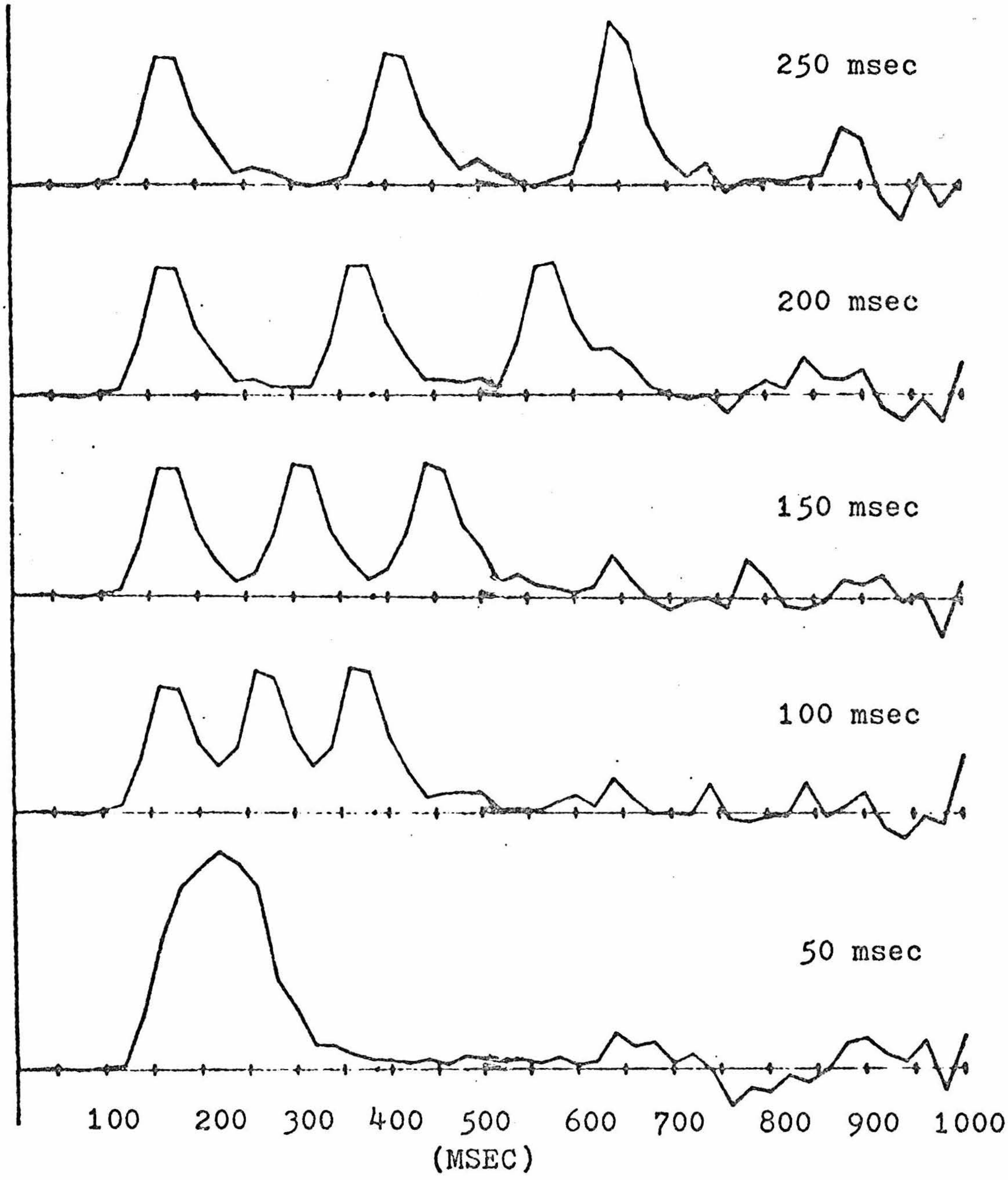


Fig. 5.8c Linear Model Response.
Stimulus Pattern No. 4.

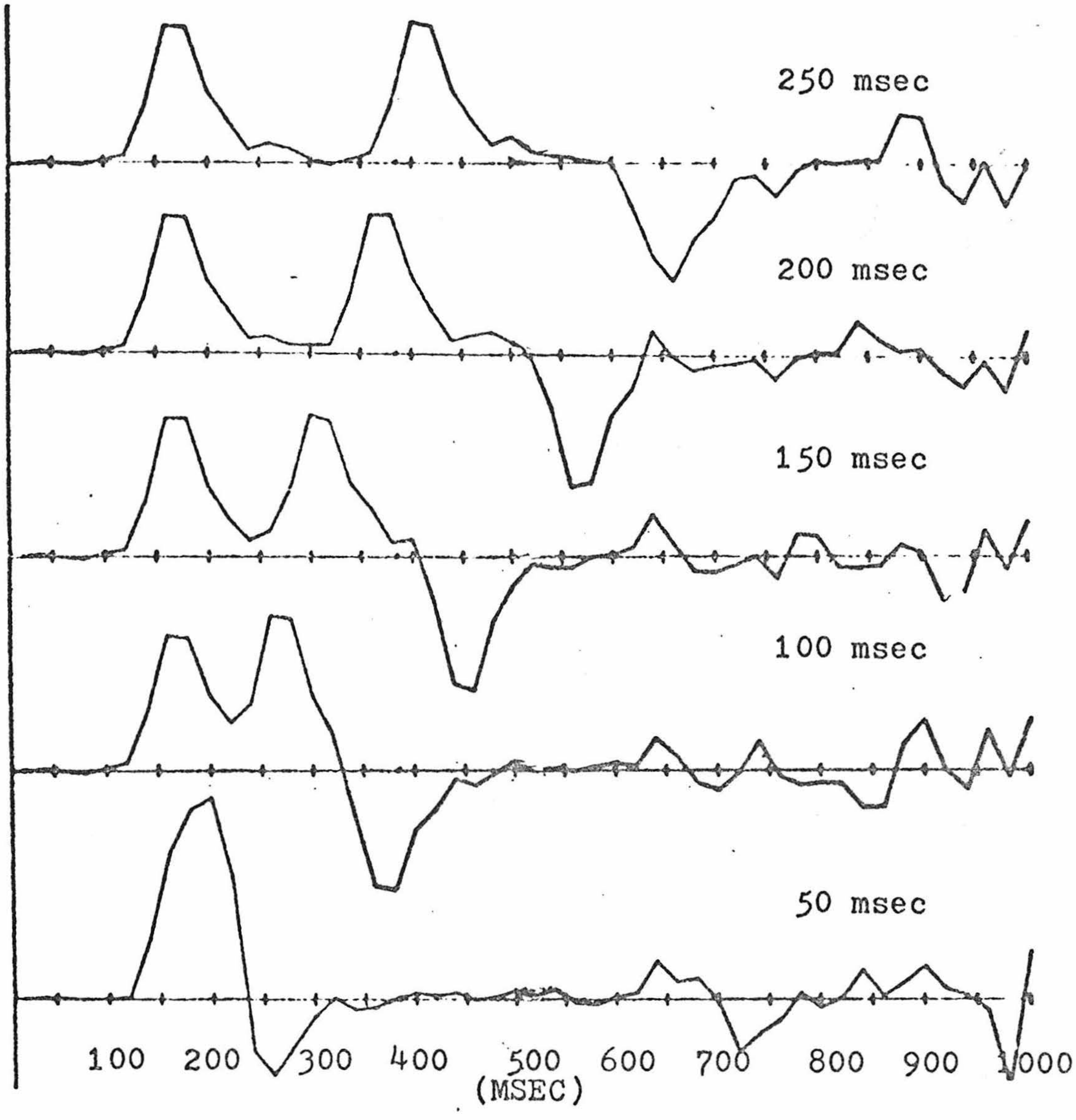


Fig. 5.8d Linear Model Response.
Stimulus Pattern No. 5.

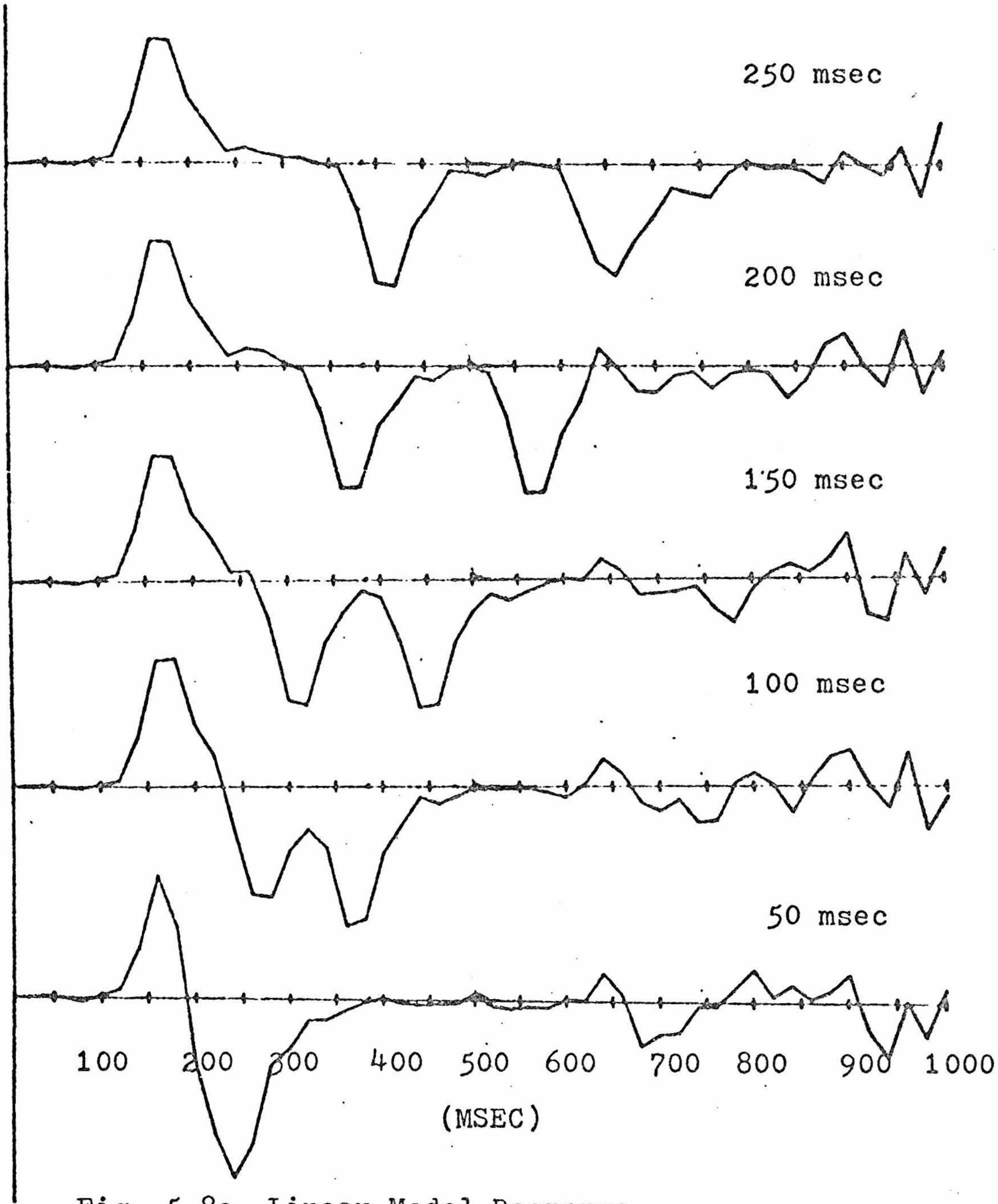


Fig. 5.8e Linear Model Response.
Stimulus Pattern No. 6.

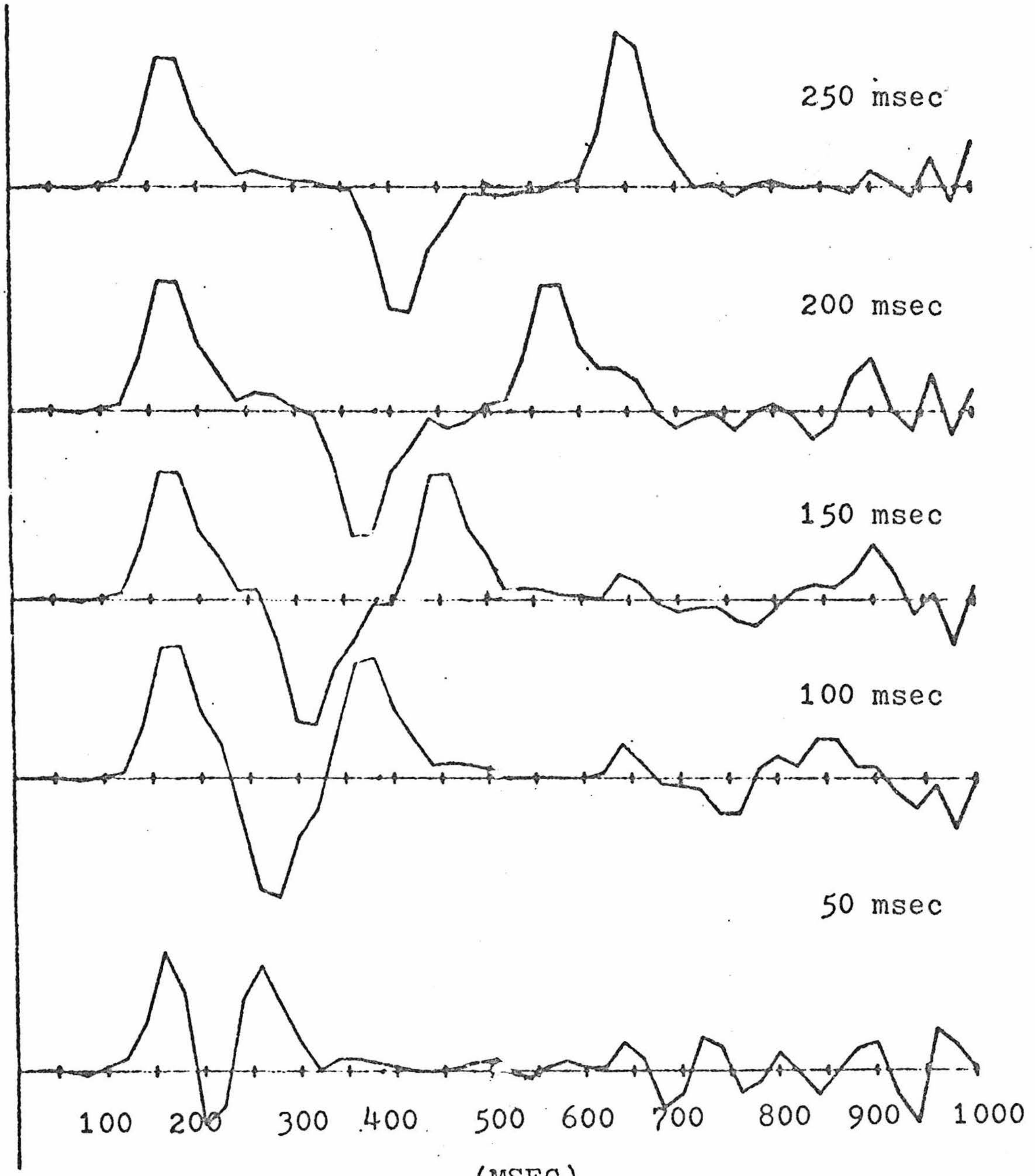


Fig. 5.8f Linear Model Response.
Stimulus Pattern No. 7.

show a broad lobe with about the same area underneath them. The first peak is around 200 msec. This suggests that RW responded to most of the first target-steps. There are also saccadic responses between 200 and 300 msec. The response in Fig. 5.6d has more area in this time interval, which suggests that some of the saccades responded to the combined error of two target-steps.

At 50 msec there is also one lobe with its peak around 250 msec in Fig. 5.6c,d. However, in Fig. 5.7c,d the occurrence of saccades is nearly uniformly distributed. The small peak at 250 msec may be due to larger magnitude of the saccades occurring around that time.

Stimulus Pattern No. 3: The other type of second order response consists of two target-steps in opposite directions. To this type of stimulus pattern one expects to find a response consisting of two saccades in the opposite direction or no saccade at all.

In Fig. 5.6e,f for time intervals of 250, 200 and 150 msec there are two lobes in opposite directions. However, they are different from the linear model response (Fig. 5.8b). First, the second lobe is delayed by about 50 msec, which is also evident in Fig. 5.7e,f. Second, the area under the second lobe is smaller for the time intervals of 200 and 150 msec, and a region of no saccades exists between the two lobes, which is not evident in the linear model response (Fig. 5.8b).

The longer time delay in the second lobe is equivalent of saying that the saccade has longer reaction time if it is in the opposite direction. This suggests that there is a memory in the saccadic programming system which stores the direction of the previous saccade. The smaller second lobe can also be explained by this memory. This will be discussed further in Sections 5.7 and 5.8.

For the time intervals of 100 and 50 msec there are practically no saccades in response to the stimulus pattern; this is reflected in both Fig. 5.6e,f and Fig. 5.7e,f.

5.5.3.4 Third order responses

There are four different combinations of three target pulses.

Stimulus Pattern No. 4: This stimulus pattern consists of three target pulses in the same direction. For the time intervals of 250, 200 and 150 msec the response is similar to the linear model response except that for the 150 msec case the distinction between the last two lobes becomes vague.

At the time interval of 100 msec the response for subject RH vaguely shows two peaks: one around 250 msec and the other at 350 msec. The peaks in Fig. 5.6g are larger than the peaks in Fig. 5.7g. This suggests that RH responded mostly to the combined error of either the first two or the last two target-steps. For subject RW, Fig. 5.7h shows a broad lobe but Fig. 5.6h shows a strong peak around 250 msec and some responses between 300 and 500 msec. The comparison of peaks in these two figures suggests that the saccadic response under this strong peak has a magnitude sufficient to cover two target-steps. It seems that RW responded to the combined error of the first two target-steps strongly.

At the time interval of 50 msec for subject RH there is only one lobe with its peak around 270 msec in both Fig. 5.6g and Fig. 5.7g. The area under the peak in these two figures suggests that RH responded with a single saccade to cover the combined error of three target-steps. The delay of the peak measured from the last target-step is about 170 msec, which is the normal reaction time. For subject RW there is also a single peak between 200 and 250 msec in both Fig. 5.6h and Fig. 5.7h. However, the peak in Fig. 5.6h is about twice as large as that in Fig. 5.7h. This seems to mean that RW responded to the combined error of the first two target-steps. The time delay of the peak when measured from the second target-step is only slightly shorter than the normal reaction time.

Stimulus Pattern No. 5: This stimulus pattern consists of the first two target pulses in the same direction and the third target pulse in the opposite direction. The saccadic responses are shown in Figs. 5.6i,j and 5.7i,j . These histograms show some statistical fluctuations due to the sample size. However, the response is still clear. For the time intervals of 200, 250 and 150 msec the linear additional model is generally applied except for the phenomena of longer delay and smaller area under the lobe associated with the last negative lobe. They are consistent with the observations of the responses to stimulus patterns No. 2 and 3.

For the time interval of 100 msec for subject RH, the combined error of the first two target-steps seems to elicit a single saccade. For subject RW responses to both target-steps are observed. The last negative target pulse corresponds to only a small negative lobe for both subjects. Figure 5.7i,j shows that this smaller negative lobe is due to a fewer number of negative saccades and not to positive and negative cancellation.

For the time interval of 50 msec no significant response above the background level can be extracted.

<u>Stimulus Pattern No. 6</u>: This stimulus pattern has the first target-step in one direction and the last two target-steps in the opposite direction to the first one. The responses are shown in Fig. 5.6k,l and Fig. 5.7k,l. There are large statistical fluctuations due to a very small sample size. The responses extracted from the statistical noise for 200, 250 and 150 msec time intervals are in general consistent with the linear addition model except for the delay phenomenon when changing the direction of saccades. The latency for the second response lobe is longer but not for the third lobe. Therefore the time interval between the last two lobes is shorter than the corresponding time interval between target-steps. This is consistent with what was said before, because the second target-step changes direction and the third target is in the same direction as the second one.

For the time interval of 50 and 100 msec the response is noisy. However, it seems that the combination of the last two steps claims the major response.

<u>Stimulus Pattern No. 7</u>: This stimulus pattern has the first and the third target-steps in the same direction and the second target-step in the opposite direction. The responses are shown in

Figs. 5.6m,n and 5.7m,n. For time intervals of 150, 200 and 250 msec the phenomena of changing direction described before are evident for the second and third response lobes. At 150 msec the third response lobe has practically disappeared. For the time interval of 50 and 100 msec not much response can be observed.

5.5.4 Summary of Responses

For the time intervals of 150, 200 and 250 msec most of the target-steps elicit responses. The responses for both subjects are very similar to the linear superposition of the responses to each target-step independently, except for the phenomena of longer latencies and few responses associated with the target-step which is in the opposite direction to the previous one. These phenomena will be explained by a directional memory in Section 5.7.

When the time interval goes down to 100 msec, the saccadic system seems to lose some sensitivity. For example, to a single target-step both subjects lost some of their short latency saccades. For subject RH only the combined error of two successive target-steps in the same direction elicited a consistent response. Subject RW also had a strong response to the combined error of two target-steps in the same direction but he still responded to a single target-step quite often.

When the time interval decreased to 50 msec, RH only responded to the combined error of three successive target-steps in the same direction with consistency. For RW there is evidence that he often responded to the combined error of two successive target-steps in the same direction.

The response pattern to the random walk target movement with time intervals of 50 and 100 msec seems to be related to the perceptual phenomenon described at the beginning of Section 5.5.3. This relationship will be discussed further in Section 5.6.

5.6 The Relation of the Perceptual Smearing Phenomenon with the Saccadic Tracking Responses

As described in Section 5.5.3, the subjects often saw two target spots on the screen when the time interval between target-steps was 100 msec, and three spots when the time interval was 50 msec. If the target movements had been continuous, this phenomenon would have shown a smearing region in the visual field. Therefore, for the following discussion I will call this phenomenon the "smearing phenomenon" and the arc on the circle which is covered by these two or three target images the "smearing arc." For the target movements described above, the higher is the target rate, the longer is the smearing arc. The size of the smearing arc was the size of 1 to 2 target-steps for the time interval of 100 msec and the size of 2 or 3 target-steps for the 50 msec interval.

If a target jumps back and forth within a small region at a high rate, say having the time interval of 50 msec between two target-steps, the smearing arc may be stationary or oscillate a little, but the centroid of this arc stays nearly stationary. Apparently, this perceptual target movement pattern is not a good stimulus for the saccadic tracking system. From the tracking responses obtained at 50 and 100 msec time intervals, I propose that, in order for a sequence of successive target-steps to be a strong and consistent stimulus for the saccadic tracking system, it must move the centroid of this smearing arc out of its previous smearing region. At the 50 msec time interval, this needs two or three target-steps in the same direction, as illustrated in Fig. 5.9. As for how far away the centroid should be moved from the previous smearing region in order to become a strong stimulus, this depends on individual subjects and the strategy used by the subject during tracking.

Since the size of the smearing arc depends inversely on the time interval between target-steps, one may expect that the product of this time interval and the number of target-steps needed to move the centroid out of the smearing region is approximately a constant. This constant seems to be independent of the size of a single target-step because, for the bigger step size, the size of the smearing arc is proportionally larger. Also, in the experiment by Hogben et al. (1976) a phenomenon similar to this smearing effect was demonstrated when dots were displayed anywhere on a fairly large screen. Therefore, it seems to be a time phenomenon instead of a spatial phenomenon.

This constant will be a threshold which defines a strong and consistent stimulus for the saccadic tracking system in the high target rate situation. This threshold constant was about 150 for RH and 100 for RW if the unit of time interval is 1 msec. For example, when the time interval is 100 msec, one target-step gives the product of 100 (100 x 1), which is below the threshold for RH, but about the level for RW. Two target-steps in the same direction makes the product 200

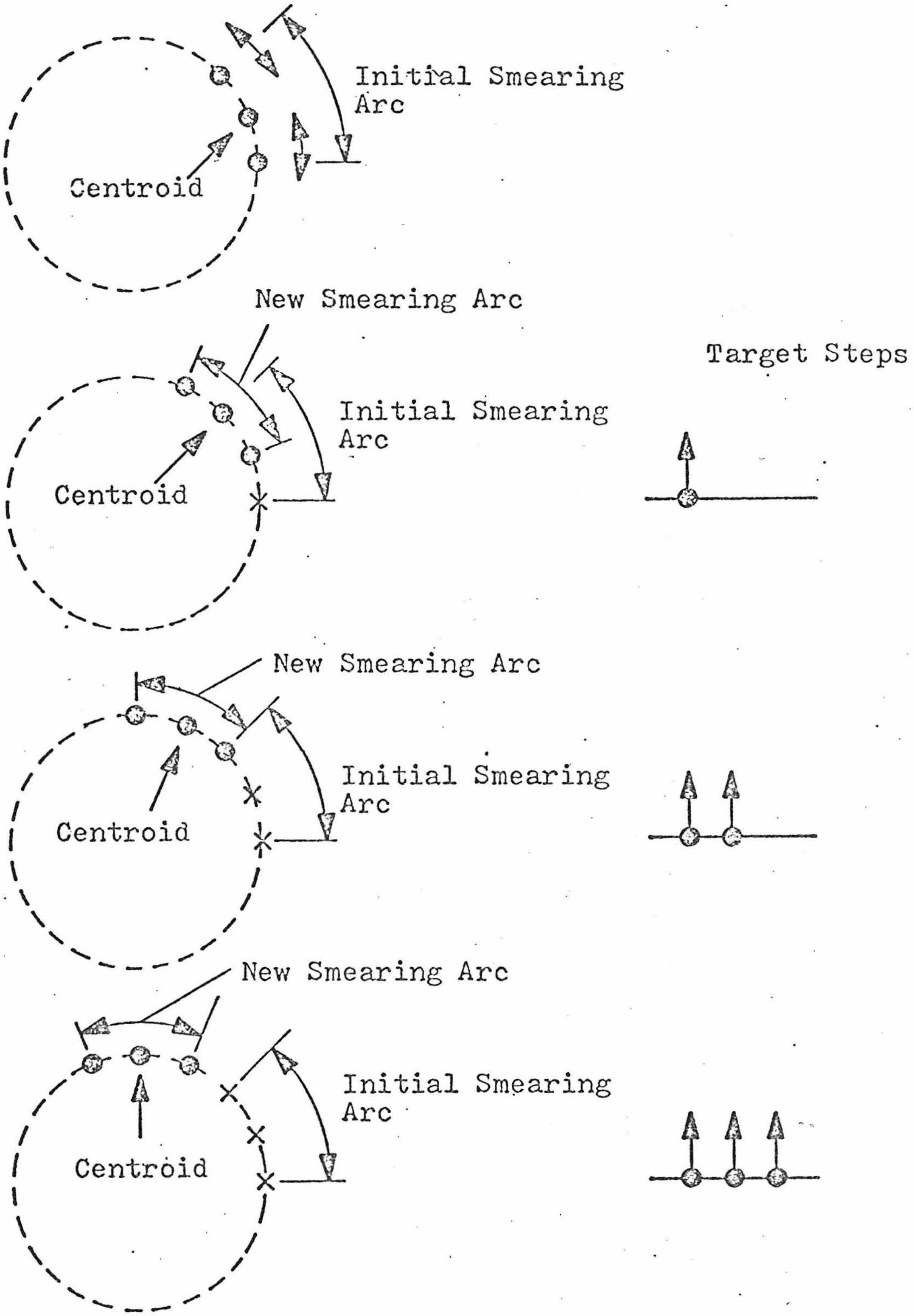


Fig. 5.9. Movement of the centroid of the smearing arc. In this example three target-steps in the same direction moves the centroid completely outside the initial smearing region.

(100 x 2) which exceeds the threshold for RH and becomes a strong stimulus for him. For the time interval of 50 msec, the same calculation indicates that three target-steps in the same direction will be a strong stimulus for RH, but only two target-steps in the same direction are necessary for RW.

This perceptual smearing effect seems to occur in the detection process which detects the target error for the computation process. It seems to be a good strategy in terms of the statistical behavior of target motion. At a high target rate the target error produced by target-steps under the threshold value may be wiped out by new target-steps very soon. Therefore, those target-steps are not worth tracking anyway.

However, at 50 msec there are saccades occurring randomly with a time from 250 to 350 msec between them, even when the threshold is not exceeded. It seems that the system will lower its threshold if there has not been a saccade for 250-350 msec. This makes the system look like a sampled-data system, but it actually is not. For those combinations of target-steps exceeding the threshold, the combined error is responded to consistently. The sampled-data model would predict that every single step in this combination should elicit a response with equal probability, which is not the case. Therefore, I propose this threshold adjusting mechanism to explain the results at the high target rate situation.

5.7 Directional Memory in the Saccadic Programming System

From the experiments described in Chapter IV and this chapter, two results have related to the direction of the previous saccade. The first one is from the double target-step experiment described in Chapter IV. If the saccadic programming of the initial target-step is cancelled, the reaction time of the reprogrammed saccade depends on the intended direction of the cancelled saccade. It takes more time to process a reprogrammed saccade when it is in the opposite direction to the cancelled saccade than when they are in similar directions. The explanation offered is the following: When a saccadic program is cancelled by the detection of new incoming information, the partial results of the direction of the saccade are stored in the brain. If the new saccade is in the opposite direction, all the stored information has to be modified. The programming system must erase the storage first and start over. The total erasing takes about 40 msec.

The second result is from the circular random-walk target motion experiment described in this chapter. This experiment showed that not only the partial results produced by the cancelled saccade can influence the reaction time of the reprogrammed saccade, but also the direction of an executed saccade can affect the programming of the next saccade in a similar way. If a saccade is in the opposite direction to the previous one, its reaction time is longer than the normal reaction time. This directional influence is observed even when these two saccades are 250 msec apart. Supposing that two target-steps are 250 msec apart, the saccadic system responds to the first target-step with a latency of about

200 msec, and about 50 msec later the second target-step appears. If the second-step is in the opposite direction to the first one, the total programming time of the second saccade is about 40-50 msec longer than the first saccade. Therefore, information about the direction of the previous saccade is passed on to the programming processes of a new saccade even when the previous one is already finished.

We recall that the reaction time of the second saccade in the two-saccade response of the double target-step experiment (Fig. 4.8) is always 30-40 msec longer than the normal reaction time when measured from the onset of the second target-step (i.e., $\overline{RT}_2$-ISI). This is consistent with what was said in the last paragraph, since either the second target-step was in the opposite direction to the first one, or there was an angle of 112.5° between the directions of the two target-steps (refer to the geometry of the target presentation in Fig. 4.1a).

Since the effect and the amount of extra time are comparable in the above three results, it is reasonable to assume that they all share the same memory mechanism. The memory is used to store the results of the direction programming. I will call this memory "directional memory" in the later discussions. In the brain, there is a long-term memory mechanism which is responsible for our knowledge, experience, and other memorizing behavior. This memory mechanism is not well understood. On the other hand, there is a very short-term memory mechanism called iconic memory. This memory stores all visual input information for a short period. The information in this memory decays very rapidly. Before it decays the information can be retrieved by the other mechanisms (Sperling, 1963). I propose that the directional memory mechanism has properties lying between those of the two memory mechanisms above. Only the processed results are stored, and the direction of a saccade is stored in a coded form. The directional coding scheme uses a portion of common representation for nearby directions. Therefore, the programming of a new saccade need only change the portions which are different, if its direction is close to the previous one. The decay time of the directional memory is longer than the iconic memory. The data suggest that directional memory can last at least 250 msec. Furthermore, the contents of directional memory can be retrieved and also can be selectively erased. The erasing is necessary if a saccade is reprogrammed in a different direction or if a new saccade is in a different direction from the previous one and the directional memory has not decayed. The time for erasing the whole content is about 40-50 msec. This is responsible for the difference in the reaction time between those saccades which require erasing the total directional memory and those which do not. The erasing time is not negligible compared with the saccadic programming time.

What is the advantage of having such a directional memory? This memory will reduce the reaction time of a saccade if it is in exactly the same direction as the previous saccade. Although in my experimental design, there are no two target steps in exactly the same direction, Komoda _et_ _al_. (1973) have reported shorter reaction times for reprogrammed saccades which are in the same direction as the cancelled saccade in the double target-step experiment. From the survival point of view, this mechanism facilitates the tracking of fast moving objects in the real world, since fast moving objects seldom change course. In terms of coding theory, it corresponds to the so-called predictive encoding technique which encodes the information as the deviation of the actual information from the predicted information by a preselected model. This scheme is efficient if the information can be approximately predicted by a model, but is inefficient otherwise.

The saccadic programming system seems to use a model which predicts that a sequence of saccades occurring in a short time interval usually move in the same direction.

5.8 A Third-Order Effect on the Saccadic Tracking Behavior Related to the Directional Memory

When the target–jump changes direction, some asymmetry in the number of saccadic responses was observed; this did not exist in the responses to the double-step target movements. If the time interval is greater than 100 msec, a pair of target–jumps in opposite directions will elicit two saccades in opposite directions, which are represented by two lobes in Fig. 5.6e,f and Fig. 5.7e,f. In Fig. 5.6e,f two lobes have different signs. Let us refer to the first lobe as the positive lobe and the second lobe as the negative lobe. If this pair of target-steps forms a double target-step experiment, these two response lobes should always have the same area underneath them in a plot like Fig. 5.7e,f, which represents the probability of a saccade occurring. This is because the saccadic system can only respond to this pair of target-steps with either two saccades or no saccades. However, in the steady-state experiment the negative lobe has a smaller area underneath it than the positive lobe. It is evident when the time interval is 150 msec (Fig. 5.7e,i,m) and less evident for the time intervals of 200 and 250 msec. This asymmetrical phenomenon can be explained by a third-order effect. If a target jumps in the opposite direction to the previous target-step, the programming process in response to the target-jump has to erase the direction memory of the previous saccade and introduce an extra 40-50 msec in its total programming time. It was shown in Chapter IV that the longer the reaction time, the more probable it is that the saccade will be cancelled by new incoming information. The whole effect requires three target-steps: the second target-step has to be in the opposite direction to the first in order to increase its reaction time, and it needs a third target-step to cancel the second saccade.

Let us use the responses with a time interval of 150 msec as an example. For the stimulus pattern No. 3, there are only two target-steps followed by a no-jump, hence the third target-step arrives 300 msec later than the second target-step. Normally, it would be unlikely for this third target-step to cancel the second saccade unless there was some extra processing time to delay the occurrence of the second saccade. The response in Fig. 5.7e,f showed slightly fewer saccades in the second lobe. The same argument can be applied to explain the smaller negative lobe in the responses to the stimulus pattern No. 5 (Fig. 5.7i). For the stimulus pattern No. 7, both the second and the third target-steps change directions. The saccades in response to those two target-steps become more susceptible to being cancelled and the responses in Fig. 5.7n demonstrate this argument.

The third-order interaction may be a major contribution to the inferior performance of the steady-state saccadic response, compared with the double target-step tracking response, when the time interval between target-steps is 150 msec or more.

5.9 Conclusion

From the results of Experiment I, it can be concluded that the behavior of the saccadic system when tracking long sequences of target-jumps is different from the behavior when tracking only a combination of two target-jumps. A higher percentage of the target-jumps elicit responses when the target movement consists of only two steps. The steady-state gain of the saccadic tracking system is closer to that of the complete oculomotor tracking system which is made up of both saccadic and smooth pursuit systems.

Experiment II studied the saccadic responses to a set of stimulus patterns similar to the double target-step stimulus but as a steady-state behavior. It also investigated whether or not some higher order effects exist. In fact, a third-order effect, which involves the presence of three target-steps, was observed and was related to the directional changes in the target-steps and directional memory (Sec. 5.7, 5.8). If there is no direction change, the saccadic response is close to the response predicted by a linear superposition, continuous processing model when the time intervals are 150, 200 and 250 msec.

This is comparable with the responses in the double target-step experiment which had 90 percent of two-saccade responses for the time interval of 150 msec.

For the time intervals of 50 and 100 msec, the strong and consistent stimulus for saccadic eye movements is defined empirically by a relationship of the target rate and the number of target-jumps. A sequence of target-steps is a consistent stimulus only if the product of the time interval between target-steps and the number of successive target-jumps in the same direction exceeds a threshold value. Two subjects had different threshold values.

The inferior response performance of the steady-state tracking responses for the time intervals greater than or equal to 150 msec can be explained by the third-order effect discussed in Section 5.8. But for the time intervals of 50 and 100 msec, the inferior performance seems to be caused by the smearing effect in the detection process as discussed in Section 5.6.

VI. THE MODEL

A model, in my belief, is a concise way to summarize data. It should link together all data and hypotheses and provide a concise way to display their relationships. It should help us to understand the system as a whole, and it should also be a tool helping the experimenter to design new experiments to test a specific hypothesis.

To summarize the data and the hypotheses described in the last two chapters, I now propose an information processing model for the saccadic programming system. A host of models have been proposed to describe the behavior of saccadic eye movements and other types of eye movements. Most of them have been control system models with emphasis on the reproduction of the correct shape of a saccade. Two representations of these models are described first. The model proposed here is unique in that it lays emphasis on the information processing that occurs during the latent period of saccadic tracking eye movements.

6.1 Previous Control System Models

The existing control system model of saccadic eye movements can be represented by the following two configurations. The first one is the revised sampled data model proposed by Young et al. (1968) (Fig. 6.1a). In this model, the sampling interval is a stochastic variable with the average value of 200-240 msec. The likelihood of occurrence of different types of responses to double target-step movements can be correctly predicted on the basis of random delay between inputs and samples. The output of the impulse sampler is integrated to generate a step signal. The sampled error will elicit a saccade only if it

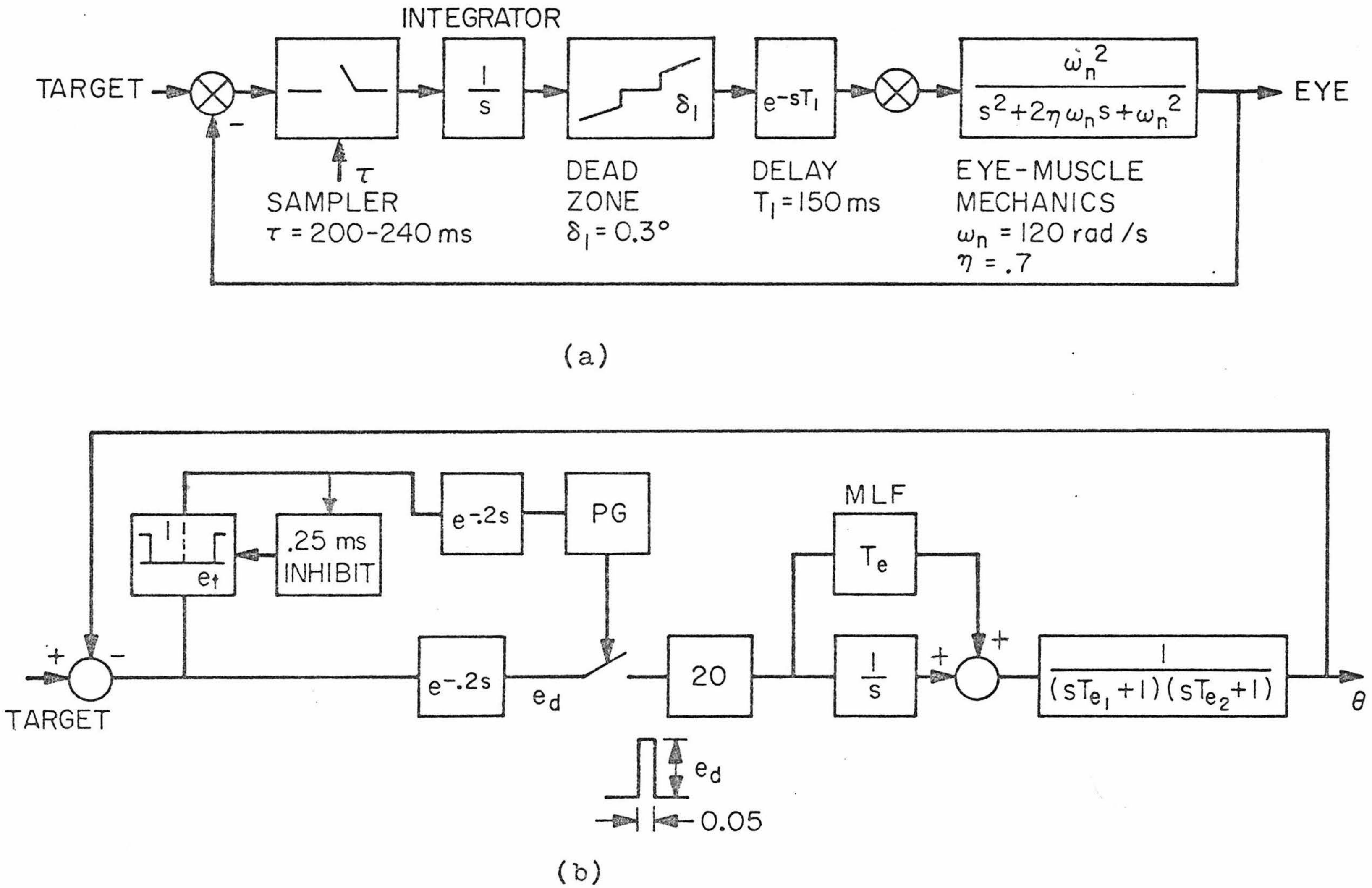


Fig. 6.1. (a) Young's revised model of the saccadic tracking system.
(b) Robinson's model of the saccadic eye movement control system.

exceeds a threshold (δ_1). The threshold has an average value of 0.3 to 0.5 degrees. This, they argued, is associated with the foveal angle. The latency of saccadic eye movements range from 150 msec to 360 msec, which is represented by a time delay. Eyeball and muscle dynamics are modelled by a second order linear approximation. According to Young et al. this model responds to transient input in excellent agreement with experimental data. However, the average sampling interval of 200-240 msec is not compatible with the experimental result in Section 4.3.3.5, which suggested an approximate 100 msec refractory period.

The second model was proposed by Robinson (1973) (Fig. 6.1b). This model is a modification of the first one. It includes the premotor circuitry reviewed in Section 2.2. In this model, the retinal error signal goes through two pathways. The upper pathway decides whether a sample should be taken. The sampling concept is that motor circuitry samples the output of information processing stages of the brain rather than that the brain samples its input. In this model the retinal error signal first goes through a threshold device; however, there is probably no dead zone for saccadic eye movements, or at best, it is very small. Subjects can make saccadic responses to $3\sim5$ min arc target-steps (Haddad and Steinman, 1973). According to Robinson, the dead zone observed is actually a psychological threshold set unconsciously by the subject. Error signals which are greater than the threshold activate a pulse generator after a time delay of 200 msec. It also inhibits the input signal for the next 250 msec. The pulse generator will generate a pulse of 50 msec duration, which closes the sampler for that time interval, and the retinal error occurring 200 msec ago is sampled by the motor circuitry. The retinal error signal, which is now in pulse form and corresponds to the eye velocity, is amplified (with gain 20) and integrated by the neural integrator. The output of the integrator is the eye position signal, to which is added a feed-forward velocity pulse signal coming from the input of the integrator. The pulse signal will move the eye to its final position and the position signal will keep it there. The plant, or the mechanics of the extraocular muscles and the eyeball , is modeled again as a second-order approximation. The time constants Te_1 and Te_2 are in the order of 200 msec and 7 msec, respectively. Te is the ratio of gain of the feed-forward path and the gain of the neural integrator. This ratio determines the relative proportion of eye velocity signal to eye position signal in the pulse-step innervation to motorneuron. Te should be close to Te_1; this approximately cancels the pole generated by (STe_1+1) in the transfer function of eyeball mechanics. If Te is not Te_1, the saccade will undershoot or overshoot.

This model predicts a simple step response, but it does not predict the response to the double target-step movement. Although this model can be modified artificially to include another decision branch to respond to the second target-step (Robinson, 1973), it is not a general model. In addition, the duration of the velocity pulse is set to 50 msec and therefore all the saccades generated by this model have a duration close to 50 msec, which is not the general case either. The

250 msec inhibition prevents the activation of the pulse generator during the latency (200 msec) and the duration of a saccade (50 msec). Although this inhibition is not the same as sampling input information it still conflicts with the results of about 100 msec refractory period in the system. The contribution of this model is the incorporation of the premotor circuitry, which simulates the neural activities before it reaches the motorneurons. Both models effectively used 200 msec delay to cover the major activities in the saccadic programming. From the discussion in the previous two chapters, it is clear that a lot of activities must occur during this 200 msec latency before the command signals are sent to the premotor circuitry. An information processing model is proposed to cover those activities.

6.2 The Model of the Saccadic Programming System

A block diagram representation of a model for the control of saccadic eye movements is shown in Fig. 6.2. In this diagram the heavily outlined blocks represent the brain processes and the other blocks are memory buffers. Also, the routes for information flow are displayed in heavy lines and the control signals are in ordinary lines.

We assume that the target is a bright area which moves on the retina. In the first place, certain parameters of this target must be detected by the visual system. It has already been shown by Hogben _et al._ (1976) that visual detection processes involve the storage of raw input data in a short term memory. This memory has a decay time that depends on the nature of the detection processes involved; for example,

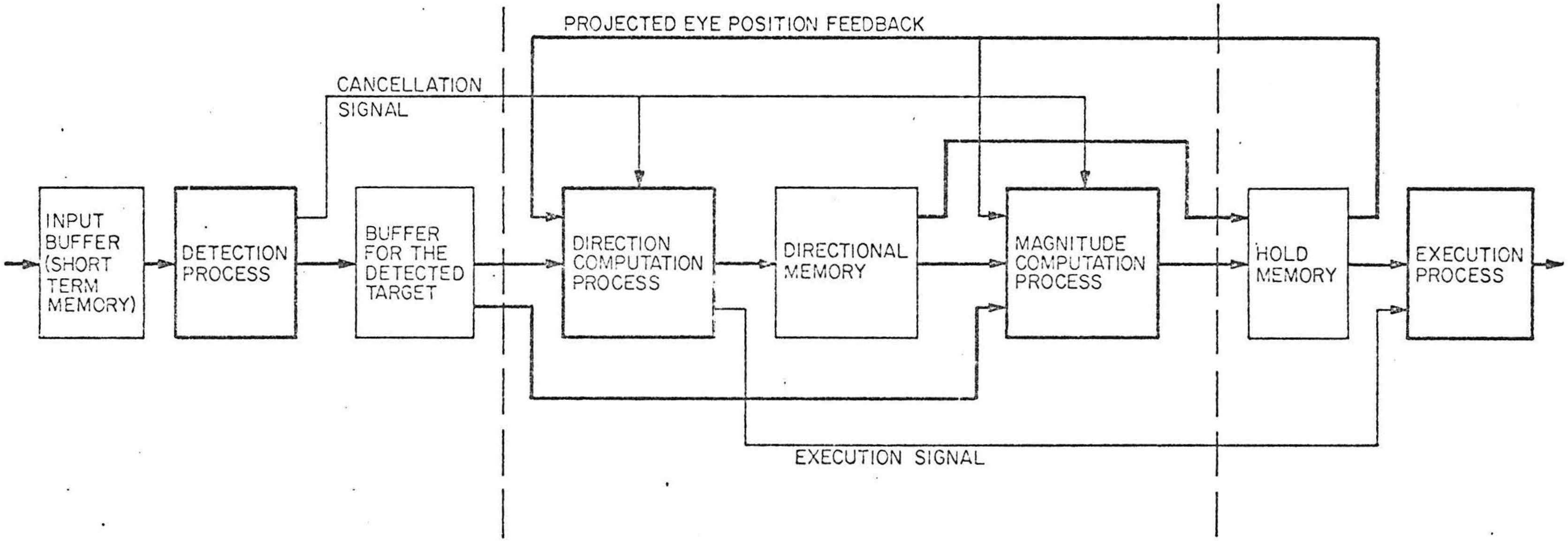


Fig. 6.2. The information processing model of the saccadic programming system.

the decay time is 120-140 msec for brightness detection, but only half this value for detailed position detection.

In this model, I propose that the results of the primary detection process are next transferred to a second buffer and the information contained there then becomes available to the processes which calculate the magnitude and direction of the saccade. This conclusion is drawn from the data shown in Fig. 4.8. That is, the reaction time for the second saccade of a double saccade response is constant for ISI below 100 msec, but increases linearly with ISI thereafter. This refractory period of about 100 msec, I claim, is the time interval during which the current programming processes wait for the completion of the computational processes of the previous saccadic eye movement. Thus, if the direction and magnitude computation processes are in a refractory period following a previous calculation, the detected new input information appears to be held in a buffer until the computation is over; otherwise, the computation should start immediately or the detected information will be lost.

We have presented evidence above to support our claim that the computation of saccadic direction and the computation of saccadic magnitude are separate processes and the computation of direction finishes before the computation of magnitude. Although magnitude computation requires the results of direction computation, it can start before direction computation is complete. The argument is rather indirect and stems from the observed results of the intermediate saccade response; we suggest that there is a stage in the saccadic programming processes after which the direction of the saccade cannot be changed by new target information, but the magnitude of the saccade can still be reduced. If magnitude computation is serial with direction computation and starts after the completion of direction computation, then the reduction of the magnitude should be a smooth function of ISI. However, we find that the intermediate saccades are either reduced to values greater than or equal to 50% of the correct magnitude, or they are suppressed altogether. We interpret this to mean that there is time overlapping between these two computation processes and the direction computation finishes first; by that time a saccade of at least half magnitude has been programmed.

The results of the direction computation are also put into a memory buffer. This is the directional memory discussed in Chapter V. The results remain in this memory when the saccade is cancelled, or even when the saccade is executed. This directional memory has the function of facilitating the programming of the next saccade if it is in the same direction as the previous one.

In addition to the results of the detection process, the computational processes should have access to information about the current eye position or the projected eye position, which is the result of the previous computation. The latter information is necessary if the computation of the second saccade starts before the previous saccade is executed, because computation of the direction and magnitude of a saccade cannot be meaningful until the starting position is known. We have given evidence that two saccades can be programmed in parallel if the time interval between the two target steps is at least 100 msec. This evidence is shown in Fig. 4.8; the programming of the second saccade in the two-saccade response takes about the same amount of time for those ISI's greater than or equal to 100 msec. This feedback path is modeled by a hold memory which holds the programming results of direction and magnitude computation. It is cleared when the new saccadic command arrives.

The results of these computational processes activate the lower-order neural circuit which converts the magnitude program for the appropriate motorneurons into the final innervation pulse trains.

Two control signals are included for the synchronization and information flow control between processes. One of the control signals is sent by the detection process to the computational processes to notify the computational process that a new target step is detected. The other control signal is sent by the directional computation process to activate the lower-order execution process.

Some conjectures can be made to correlate this information processing model with neurophysiological results and models. The final result of the saccadic programming system is the innervation pulse train sent to the motorneurons which innervate three pairs of extra-ocular muscles. The computation of the direction of a saccade can be considered as the process to determine which ones should be agonist and which antagonist. It also has to balance the secondary effects of the muscles called into play.

The computation for the magnitude of a saccade should determine the signals controlling the generation of a velocity pulse train for each motorneuron involved. The velocity pulse train is the proposed original saccadic control signal for the motorneuron in the second model described above (Robinson, 1973). The parameters of this velocity pulse train to be programmed are frequency and duration. The frequency of the velocity pulse train determines the maximum eye velocity during a saccade and the duration of the velocity pulse train controls the duration of a saccade. The combination of these two parameters determines the magnitude of a saccade. Previous studies have shown a repeatable relationship between the peak velocity of the eye and the magnitude of a saccade, and also between the duration and the magnitude of a saccade. This puts a constraint on the magnitude computation and removes the only degree of freedom in programming the frequency and duration. The velocity pulses are fed into the final common path through an integration which converts the velocity signals into position signals, and also through a direct path. This produces the pulse-step firing pattern of the motorneuron observed during a saccade.

What coordinate system should the computational processes work on? In order to program two saccades in parallel, it is necessary for the directional computation process to work out the target position in head coordinates instead of retinal coordinates, because the wrong direction will be generated if the direction of the second saccade is computed before the first saccade is completely executed and only the retinal error (or the retinal coordinate) is used.

A similar conclusion was reached by Robinson (1975) from the study of the spino-cerebellar degenerated patients who had slow saccades and were able to change the direction in midflight. Nakayama also pointed out that the head coordinate has to be employed in order to obey the Listing law after refixation.

The magnitude process must also work in head coordinates for the same reason. In addition, it requires the magnitude of the vector difference of the target position and the initial eye position to determine the correct combination of the frequency and the duration of the velocity pulses which will satisfy the relationship mentioned above.

6.3 Pipeline Processing vs Full Parallel Processing

As mentioned before, the saccadic programming system is capable of programming two saccades simultaneously. In the above model, I propose that this parallel processing is done in a pipeline fashion. The system consists of three processing units, or three pipes; they are, the detection process, the computation process, and the execution process. Different target information can be processed by each unit simultaneously. For example, while the system is computing the direction and the magnitude of a saccade, the execution process can execute the previously computed saccadic program and the detection process can detect new target information.

This pipeline-structured parallel processing is different from full parallel processing which is normally implied when parallel processing is mentioned in psychology. In full parallel processing, there should be many processing structures like the one shown in Fig. 6.2. Each of them could process a target-step independently of the others, except that the processing speed would depend on how many processing structures were activated. Because the brain has limited processing power, the more parallel processes are activated, the slower they are.

If the saccadic programming system is a full parallel processing system, one would expect the reaction time of the first saccade in the two-saccade response to be longer than the normal reaction time to the single target-step; but they are about the same. One may argue that programming two saccades does not slow down the processing speed of the system. However, the reaction time of the second saccade in the two-saccade response is about 30 to 40 msec longer than the normal reaction time, which contradicts this.

Also, the reaction time found in Fig. 4.8 is against full parallel processing, in which each process has its own processing unit and the processing of the second saccade does not need to wait for the completion of the computation process of the first saccade. In this case, no refractory period should be found.

Revewing the evidence, pipeline processing seems to be adopted by the saccadic programming system. The advantage of a pipeline parallel processing system over a full parallel processing system is the saving in neural circuitry.

6.4 Explanation of the Responses in the Double Target-Step Experiment in Terms of the Model

How can we use this model to explain the three different types of saccadic responses? We assume that the information can flow in this block diagram as in a pipeline, but only one saccade can be processed by each individual process at a time.

If new target information arrives in the first memory buffer before the first target-step is detected, the first target-step is then ignored and the reprogrammed saccade response is observed.

When the second target step is detected, a control signal is sent out to the computational processes. If the programming for the first saccade is still at the stage of computing the direction of the saccade, this control signal will stop the computation and cause the computation process to examine the new content in its input buffer. If this new saccade requires a different set of motorneurons, the partial results from the old program have to be cancelled. The time spent in cancellation corresponds to the extra time needed to reprogram a saccade in the opposite or perpendicular direction. If the new saccade is in a direction similar to the cancelled one, the previous partial program can still be used but with certain modification. In both cases, the initial saccadic program is cancelled and only the reprogrammed saccade response is observed.

If the control signal caused by the detection of the second target-step arrives after the completion of the direction computation, the initial saccade cannot be cancelled, because the execution signal has already been sent to the execution process.

However, in the case that the control signal from the detection process arrives before the magnitude process is complete, the magnitude program is impeded. We assume that the magnitude program of a saccade is generated gradually. Since the old content of the input buffer is erased by the parameters of the new target-step, the magnitude process completes its magnitude program with the intermediate value. An intermediate two-saccade response is generated in this case.

If the control signal from the detection process arrives after both computational processes are complete, it can immediately start the computation of the new saccade even when the old saccade is still being executed at the same time. This generates the full two-saccade response.

The conditions which generate different classes of saccadic eye movement responses can be summarized by the following relationships of the processing times of individual processes.

Assuming that Tdet, Tdir, Tmag, Tex are the processing times of the detection process, the direction computation process, the magnitude computation process and the execution process, respectively, also that subscripts 1,2 indicate programming for the first and the second target-steps, thus we get

(1) Reprogrammed saccade response if

$$ISI < Tdet_1$$

or

$$Tdet_2 + ISI < Tdet_1 + Tdir_1$$

(2) Intermediate two-saccade response if

$$Tdet_1 + Tdir_1 < Tdet_2 + ISI < Tdet_1 + Tdir_1 + \Delta T$$

where $\Delta T \geq 0$ is the time difference between completion of the direction and magnitude computation processes.

(3) Full two-saccade responses if

$$Tdet_1 + Tdir_1 + \Delta T < Tdet_2 + ISI$$

With this model, it is possible to estimate Tdet, Tdir and ΔT from experimental data. The following are assumed:

(1) Tdet, Tdir, ΔT and Tex are independently normally distributed

(2) $Tdet_1 \simeq Tdet_2 = Tdet$, $Tdir_1 \simeq Tdir_2 = Tdir$

The following stochastic equations can be derived from the above relationships:

$$Tdet + Tdir + \Delta T + Tex = RT \qquad (1)$$

$$\mathrm{Prob}(Tdet > ISI \text{ or } Tdir > ISI)$$

$$= \mathrm{Prob}(Tdet > ISI) + \mathrm{Prob}(Tdir > ISI) - \mathrm{Prob}(Tdet > ISI \text{ and } Tdir > ISI)$$

$$= \mathrm{Prob}(Tdet > ISI) + \mathrm{Prob}(Tdir > ISI) - \mathrm{Prob}(Tdet > ISI) \cdot \mathrm{Prob}(Tdir > ISI)$$

= Probability of reprogramming saccades at that particular ISI. (2)

$$\mathrm{Prob}(Tdir + \Delta T < ISI)$$

= Probability of full two-saccade responses at that particular ISI (3)

These stochastic equations cannot be solved analytically, but the mean value of the distributions can be estimated. Since there are only three constraints for four random variables, one variable has to be estimated independently. The mean of Tex was guessed at around 20 msec, from studies involving electrical stimulation of superior colliculus in monkeys (Robinson, 1972). The other three variables were estimated by computer simulation. The simulation procedure is shown in the Appendix. The mean values of those variables which produced minimum square error between the model prediction and the observed data of one subject are:

$T_{det} = 57$ msec

$T_{dir} = 88$ msec

$\Delta T = 35$ msec

$T_{ex} = 20$ msec

6.5 Explanation of the Random Walk Target Motion Experiments in Terms of the Model

The results of Experiment II of Chapter V show that the saccadic responses are very similar to the prediction of a linear superposition model when the time intervals are 250, 200 and 150 msec, except for the instance of changing direction. This result is consistent with the model response. It is assumed in the model that the programming processes for those target steps which are separated by a time interval longer than the refractory period of the system (about 100 msec) can go through this pipeline without any delay. The histograms of the model responses show separate lobes for each target step and normal time delay for each lobe, if all the target steps are in the same direction. Thus the model responses coincide with the observed responses, with only one slight discrepancy; namely, for subject RH, the peak of the second response lobe of stimulus pattern No. 2, when the time interval is 150 msec, is slightly delayed; otherwise it is still quite similar to the model response.

The longer latency associated with changing direction can be explained as the need to erase the directional memory in the model because the previously stored direction program is completely useless in this case. Erasing takes finite time. Because of this extra time spent in erasing, the programming time of the direction computation will be longer and it provides more opportunity for this saccade to be cancelled by the detection of a new target step, according to the programming strategy described in the last section.

This explains the phenomenon that fewer saccades are observed when they are in a direction opposite to the previous saccade. This phenomenon is evident when the next target-step arrives within 150 msec, less evident when it arrives between 200 and 300 msec, and only slightly evident if it arrives later than 300 msec. This is roughly consistent with the model prediction of the responses of the double target-step experiment.

The target rate dependent nonlinearity associated with the time intervals of 100 and 50 msec can be explained by the model as the change of detection threshold for the target error due to the perceptual smearing effect which is discussed in Section 5.6. The theory of changing detection threshold is speculated from the observations that only those combinations of target-steps which move the centroid of the smearing arc outside its initial smearing region elicit consistent saccadic response, and the responses to the rest of the target-steps seem to be random and spaced at least 250 msec apart. The theory goes as follows. The saccadic programming system raises the detection threshold to avoid overloading the system at this sustained high rate, since a small number of target-jumps may return to the initial position very soon. In the meanwhile, if there has not been a saccade for a period of time (probably 250-350 msec) it will lower the threshold to let a target error less than the previous threshold go through. This dynamic threshold setting theory seems to explain the responses for the time intervals of 50 and 100 msec.

6.6 A Qualitative Discussion of the Optimality of the Saccadic Programming Strategy

The human brain can be considered as an information processing machine with a tremendous capability but very slow speed (consider how long it takes to add two numbers). Due to its slow speed, there are many situations in the real world where the input information arrives at a rate higher than the processing speed of the brain. In fact, in all the experiments described so far, we have produced a situation in which the target jumps at a rate close to or higher than the tracking limit of the saccadic eye movements system, and we have studied how the system copes with this situation. It is found that different strategies are employed to encounter different target situations. Before we discuss the optimality of those strategies, we have to define a performance index to measure the optimality. In the tracking situation, the performance index is naturally how well the saccadic system tracks target movements. This usually means the average real time response or the average time delay until the target error is reduced to less than some acceptable minimum value.

It is interesting to compare some techniques used by a man-made information processing system with the saccadic programming strategy. In a man-made system, buffering is the most common technique used to cope with a transient overshoot in the rate of input information. It stores all the incoming information which cannot be processed at the time when it arrives. When the input rate drops, the system can catch up with all the stored information. This technique does not lose any input information but it does not help the real time response of the system because there is always a backlog of information in the buffer. It is clear that this technique is feasible only when the high rate situation is transient and it does not require too much memory. I postulate that a limited buffer is used in the saccadic system (Fig. 6.2) to store the detected target information before the computational processes become available.

Another technique is sampling, which samples the input information at a fixed rate and ignores all the information between samples. This technique sacrifices the information between samples to gain real time response. It provides a pretty good tracking performance, if the rate of target jump is not much higher than the sampling rate. Otherwise, the tracking error can be very large because many target jumps may appear between the sample and the onset of the response. A modified version of this technique is found in the strategies of the steady state tracking situation.

When the saccadic system tracks two-step target motions, the programming strategy described in Section 6.4 has better real time response. If the time interval between two target-steps is greater than

150 msec, the processing speed of the saccadic programming system is fast enough to process the target jumps immediately after they arrive. When the time interval decreases to less than 100 msec, the refractory period of the system becomes a bottleneck. If the buffering strategy were used, the newly detected information would wait in the buffer until computation of the previous target information is finished. This technique introduces extra delay. The reprogramming strategy used by the saccadic system has a better real time response. When a new target-step is detected, the processing status of the previous saccade is examined. If it is still at or before the completion of the direction computation, the saccade in preparation is cancelled and the new target information continues to be processed. If direction computation is complete, the saccade in preparation will be executed. There is reason to believe that this strategy is optimal statistically in terms of having minimum time delay in regard to the current target position. Since cancellation takes finite time, and the more program to be cancelled, the longer it takes, there must be a stage such that cancellation after this stage takes more time than just to let the program finish. This optimal dividing point seems to be at the end of direction computation.

However, when this high rate goes on for a long time, the optimal strategy used by the saccadic programming system to track transient target motion becomes impractical. The incoming information may saturate the detection process or the system would spend most of its processing time busily doing fruitless programming, since each would soon be cancelled by the next detected target step. To save the saccadic system from overworking in this situation, a dynamic threshold adjustment strategy may be employed. The detection process raises its target error threshold for a saccade to be generated, but if there has not been a saccade programmed for 250 to 300 msec, the detection process lowers its threshold again because the system is idling. This strategy seems to be based on the statistical behavior of the target movements. If a target error is small enough and the target rate is high, there is a good chance that the target will return to the current eye position in a very short time compared with the programming time of a saccade. It is difficult to judge how optimal this strategy is under the sustaining high rate situation, but it is clear that it has an advantage over the reprogramming strategy used in the transient situation.

VII. THE PERFORMANCE OF THE SACCADIC EYE MOVEMENTS USING PERIPHERAL ACUITY CUE

7.1 Introduction

Almost all the studies of the control of saccadic eye movements which exist in the literature fall into two extremes on the scale of complexity of information processing. At one extreme, there are experiments using a simple spot as stimulus target and subjects are asked to track the movements of this target spot. Only an initial detection process is needed in such a task. The relationships between the detection process and the computation processes for a saccadic eye movement have been discussed in the previous three chapters of this thesis. At the other extreme there are studies of the control of saccadic eye movements during reading (reviewed by Tinker, 1958) and on the saccadic scan patterns when viewing a picture, etc. The information processing involved in these tasks is extremely complex. It may include detection, discrimination, pattern recognition and cognition. The results of these studies are difficult to interpret and are not repeatable in many cases.

I felt that some work should be done between these two extremes in the complexity of information processing. In our quest for understanding the control of eye movements occurring in one's everyday life, an experimental approach which progresses in an orderly way along the scale of complexity should be a logical one. To produce such a scale is difficult and may be formidable. However, the existence of this scale is not essential. The most important idea is a step-by-step approach instead of a long-jump approach. In this chapter, I will describe two experiments which move one step toward a more complex target. The information processing chosen is acuity discrimination. It is not known what role acuity discrimination plays in controlling eye movements. In this chapter, I hope to find how well the saccadic system can use the peripheral information to program the eye movements under controlled laboratory situation. From the results, how important a role peripheral acuity plays in controlling our saccadic eye movement in the real world may be inferred.

7.2 Brief Review on the Acuity Studies

Visual acuity was classified by Riggs (1965) as the identification of four different tasks:

(1) Detection: The task is to detect the presence or absence of a test target such as a dot or a line.

(2) Recognition: The most commonly used task is to recognize the Snellen letters.

(3) Resolution: The test targets used for measuring resolution threshold include a pair of dots or lines, gratings, checkerboard pattern, and a broken ring (Landolt c).

(4) Localization: This task is usually called vernier acuity which requires a subject to discriminate differences in the spatial position of segments of a test target.

The physical and physiological variables which affect visual acuity have been reviewed by Westheimer (1965) and Lit (1968). The variables include luminance, contrast, color of test target, exposure, duration, flickering of test target, target orientation, adaptation state, refractive state and accommodative state of eye, eye movements, retinal locations, age, presence of drugs, etc.

Most types of visual acuity are highest in the fovea for photopic vision, and drop quickly as the retinal location of the test target is moved toward periphery. The peripheral acuity has been compared with cone density as a function of eccentricity. These two functions show similar shape; however, the relationship breaks down at the far periphery. At the far periphery, large refractive error also occurs, but it has been shown that the refractive error cannot completely explain the degradation of acuity in the far periphery (Millodot *et al.*, 1975).

It is generally thought that the size of receptive fields or the the density of ganglion cells is more likely to be the anatomical basis of the degradation of peripheral acuity. The data on the size of receptive fields and the density of ganglion cells as a function of eccentricity for a human subject are sparse, and do not permit meaningful comparison with the acuity data.

As eccentricity increases, visual acuity becomes less affected by the luminance of the target or background (Mandelbaum and Sloan, 1947; Kerr, 1971) and by the adaptation state (Fick, 1898).

There are large acuity differences between the horizontal and vertical meridians of the retina. If equal acuity curves (isopters) are plotted in the visual field, the shape is oval. They are flattened above and have greatest extent in the temporal direction on the horizontal meridian. However, differences between the temporal and nasal horizontal meridonal acuities are small (6 to 5 ratio, cited by Low, 1951).

7.3 Experiment I

This experiment represents a first attempt to study how the saccadic programming system utilizes peripheral acuity information. First, we would like to know how well a subject can use peripheral acuity to direct his saccadic eye movements under laboratory conditions. In this experimental condition, the saccadic system has to discriminate acuity information and choose the correct target to respond. This is different from the previous experiments which used a single spot target as stimulus, where the subject's action is "detect and go." The decision process involved in this experiment is much more complex. The saccadic system has to interface with the peripheral acuity system. How is it done?

Peripheral acuity drops quickly as the eccentricity of the test target increases. Does the accuracy of a saccadic eye movement in choosing the correct target also drop quickly when using a peripheral acuity input? If the eye movement system gets input from the so-called "acuity system," the answer to the above question will be positive. If one believes that the eye movement system has its own acuity subsystem and obtains some privileged information from the peripheral retina, then the accuracy of the eye movements may be better than that predicted by peripheral acuity. Although few people believe in the latter theory, no one has disproved it for the eye movement system yet; on the other hand, some scattered reports suggest that some privileged information goes to the oculomotor system.

This experiment compares the accuracy of saccadic eye movement responses with peripheral visual acuity measured in the same experimental conditions. The result of this experiment also provides baseline information about how far the saccadic system can use the acuity information to direct eye movements to a target with a certain level of accuracy. From this information, one may be able to infer how useful a role acuity information can play in directing our everyday eye movements.

7.3.1 Method

A computer generated pattern similar to Landolt c was used as a test stimulus. This pattern is shown in Fig. 7.1, which is a matrix-dot simulation of a Landolt c. The gap of the c could have one of four orientations: up, down, left and right. Three different sizes of gap were used: 2, 4, and 6 min of arc.

At the beginning of each trial a c-pattern was displayed at the center of the screen. The subject was instructed to fixate at the c monocularly and to note its gap orientation. His eye positions were monitored by a computer program. When the program determined that the subject was looking at the c, it displayed two other c-patterns in the periphery. One c had the same gap orientation as the center c and the other had a different gap orientation. The former is called the target and the latter the decoy. They could appear at three eccentricities

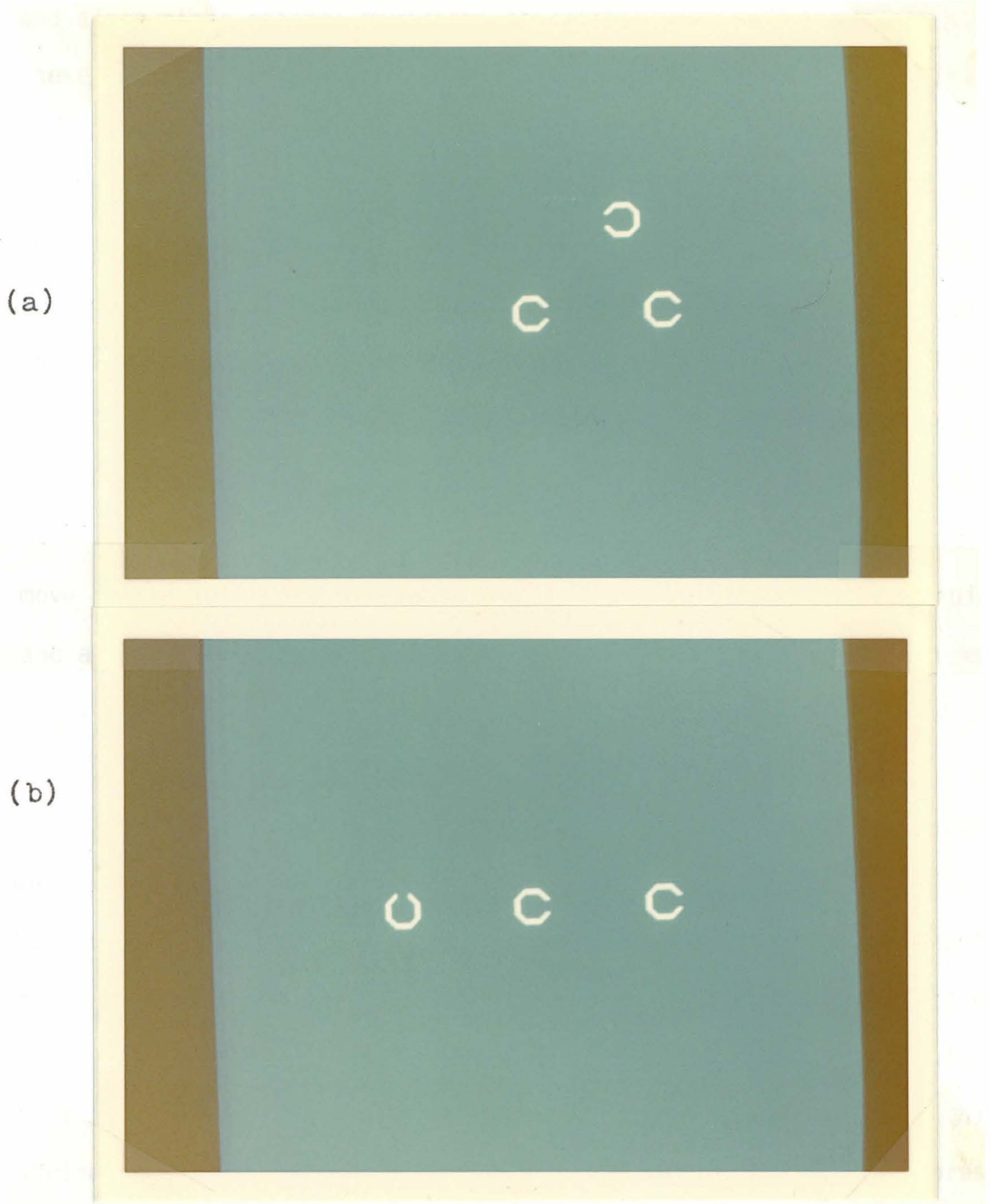


Fig. 7.1 Photograph of Landolt-c like stimuli in (a) adjacent presentation, and (b) opposite presentation. Picture taken from COMTAL screen, which has same matrix-dot configuration as the plasma screen.

and along eight retinal meridians associated with each eccentricity. These 24 locations can be represented by the vertices of three octagons, all centered at the central fixation c. Before each presentation, the computer program first chose one of the three prespecified radii, then chose two vertices from the appropriate octagon. There were adjacent and opposite presentations. In the adjacent presentation target and decoy were displayed at two adjacent vertices of the octagon. In the opposite presentation they appeared at either the two vertices on the horizontal axis or the two vertices on the vertical axis (Fig. 7.1).

When target and decoy appeared, the subject was instructed to move his eye fixations from the center fixation c to the target quickly and accurately. The reaction time of his first saccadic eye movement and its end position were registered by the computer. If the end position was in the vicinity of the target, it was counted as a hit.

In the adjacent presentation, eight possible pairs of locations were grouped into four visual fields: left (L), right (R), top (T), and bottom (B). The left visual field consists of two pairs of adjacent vertices which contain the vertex on the left horizontal axis as part of the pair. The right, top and bottom visual fields were defined likewise, except that each of them respectively contains the vertex on the right horizontal, top vertical and bottom vertical axes. The opposite presentations were grouped into horizontal (H) and vertical (V). The hit rate for each visual field group and each eccentricity was calculated.

In addition to the eye movement experiment, a psychophysics experment was also done as a control. In this experiment the same target presentations were used except that the gaps of the target and decoy were closed after 500 msec to simulate a tachistoscopic condition. The subject was instructed to maintain his fixation at the central c throughout the trial. He indicated whether the target was to the left or to the right of the decoy by pressing one of two buttons. In all except one presentation, the target and the decoy had a clear left-right relationship. The only exception is in the opposite presentation when target and decoy appear on the vertical axis. In that case the subject was trained to press the left button when the target was at the top position. The hit rates were also calculated according to those visual field groups and different eccentricities.

7.3.2 Results

The average reaction times for eye movement response and button pressing response are shown in Table 7.1. The average reaction times for the eye movement response were about 350 msec to 450 msec longer than the average reaction time in response to a single dot stimulus, depending on subjects. Thus the time related to the acuity processing is about twice as long as the previous saccadic latency. The variations in the processing time of acuity information may obscure various timing phenomena for the saccadic programming system.

The main results of this experiment are the percentage of correct responses for different size of gap, different eccentricities, and different visual fields. However, an additional factor, which was not expected when the experiment was designed, was found to affect the

Table 7.1

Average Reaction Times for Eye Movement Response in msec

Size of Gap	Subject RW	Subject MB
2 min of arc	655 ± 122	499 ± 106
4 min of arc	668 ± 96	554 ± 105
6 min of arc	637 ± 101	573 ± 102
Average Reaction Times for Psychophysics Response		
4 min of arc	1362 ± 447	987 ± 499
6 min of arc	1455 ± 601	1039 ± 456

percentage of correct responses. During the experiment, the subjects reported that the task seemed to be more difficult when the orientations of the gaps for the target and decoy were parallel to each other than when they were perpendicular to each other. Therefore, this additional factor was included when calculating the percentage of correct responses. The following symbols are used to indicate these two conditions: || for the two orientations in parallel and ⊥ for the two orientations perpendicular to each other.

The probability of correct responses for different conditions are summarized in Fig. 7.2 for subject RW and in Fig. 7.3 for subject MB. For 6 min of arc of gap size, smaller eccentricities were used on the vertical meridian to obtain the data points around the acuity threshold. The acuity threshold was set to 75 percent of correct response. This

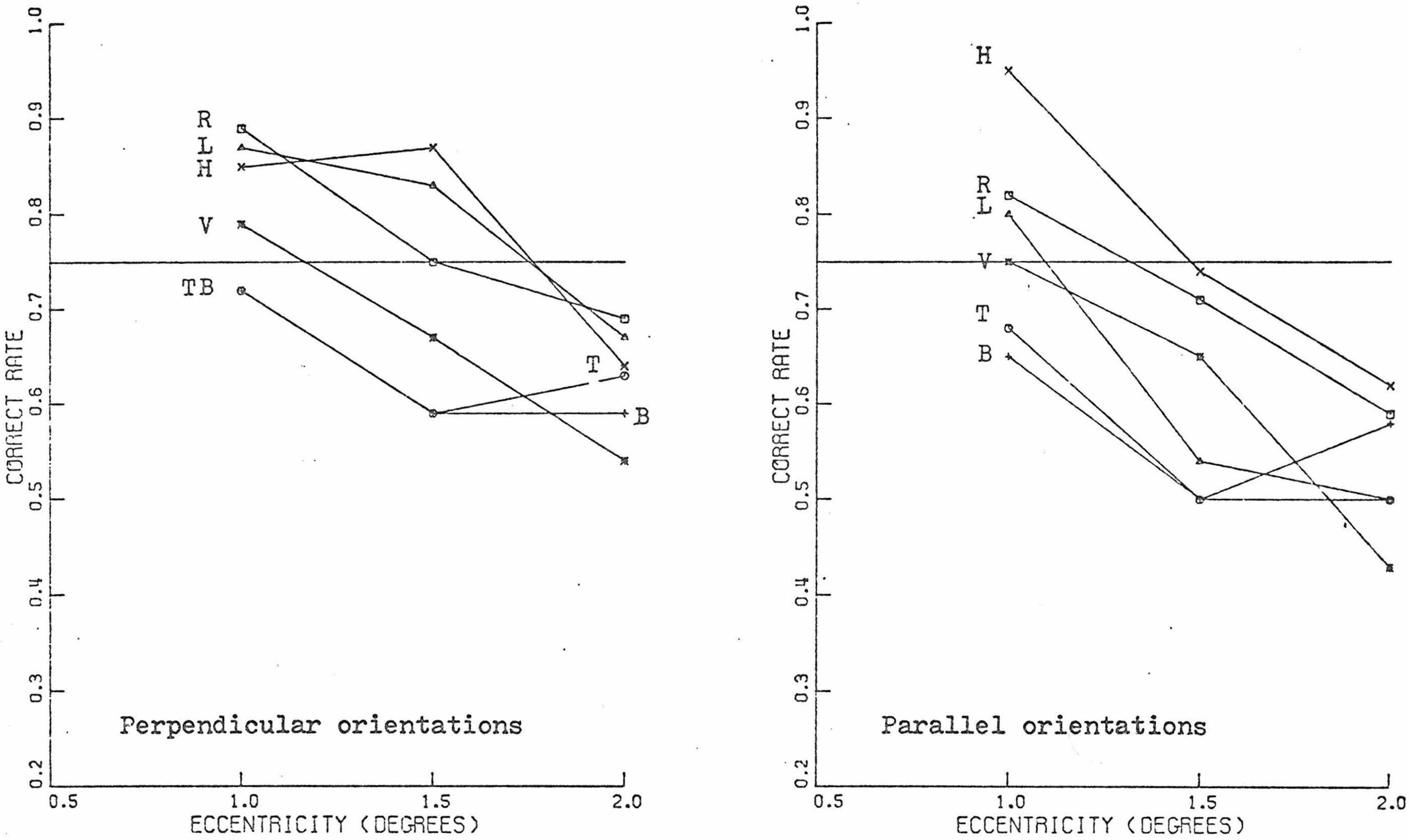


Fig. 7.2a Eye movement experiment. Gap size: 2 min. of arc. Subject RW.

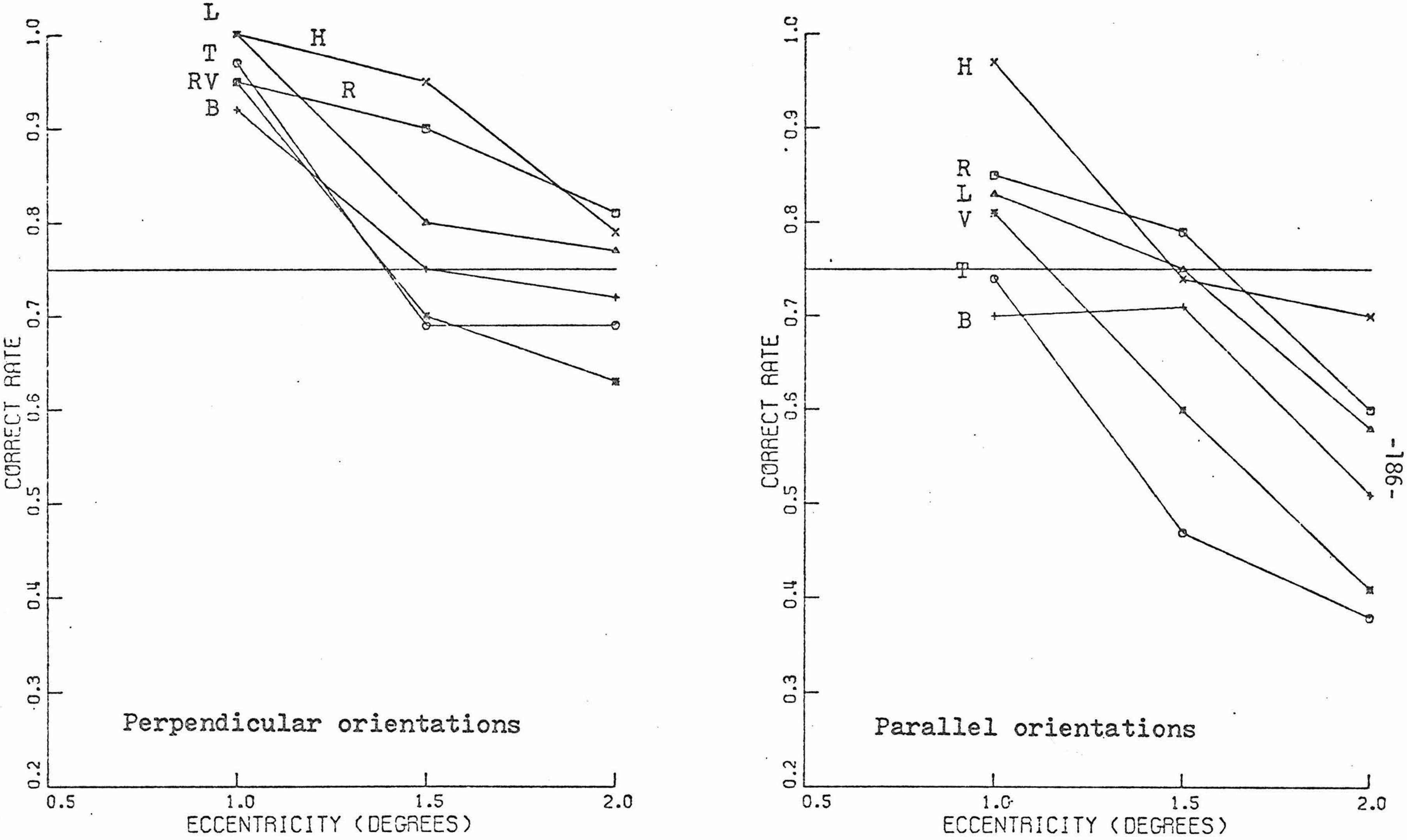


Fig. 7.2b Psychophysics experiment. Gap size: 2 min. of arc. Subject RW.

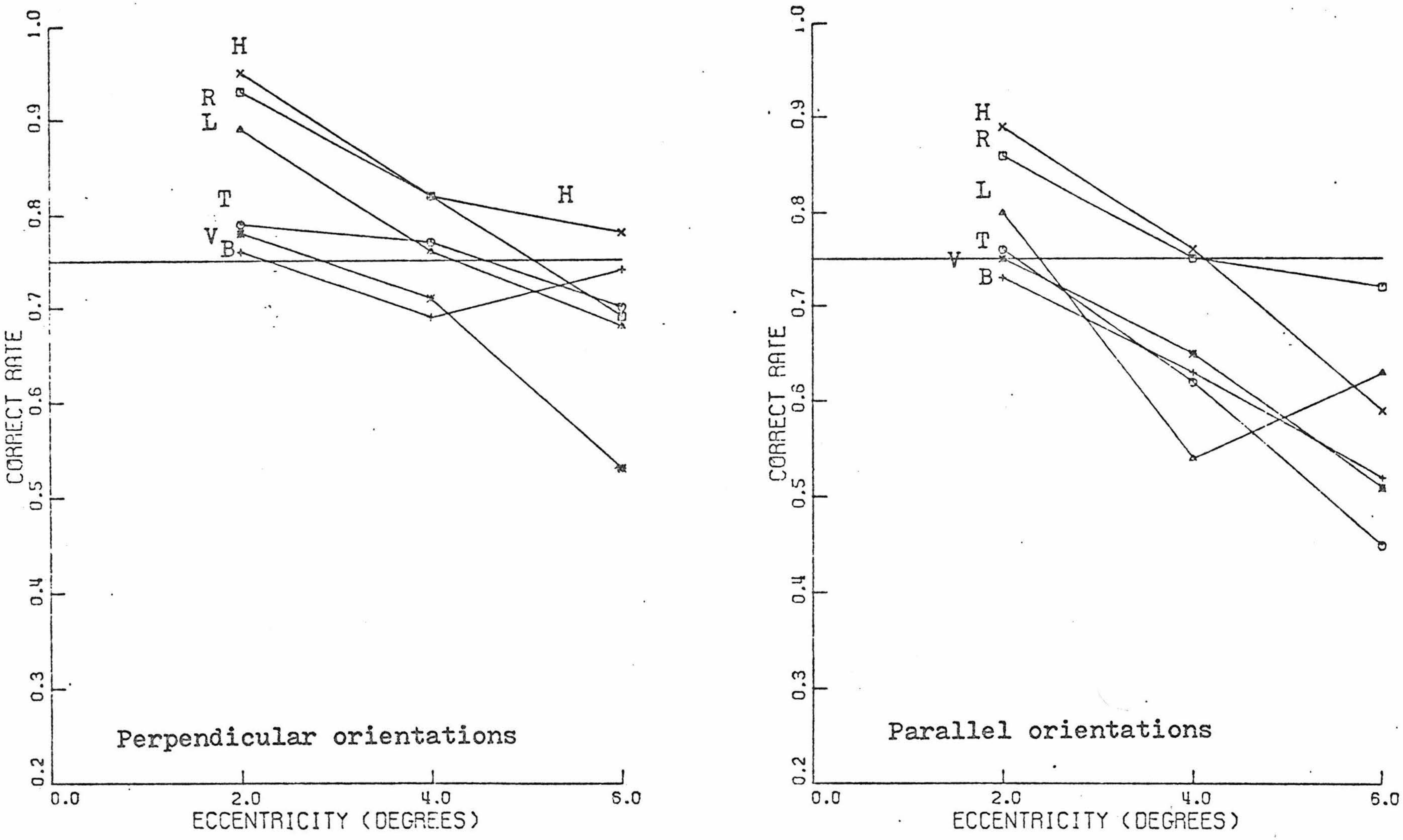


Fig. 7.2c Eye movement experiment. Gap size: 4 min. of arc. Subject RW.

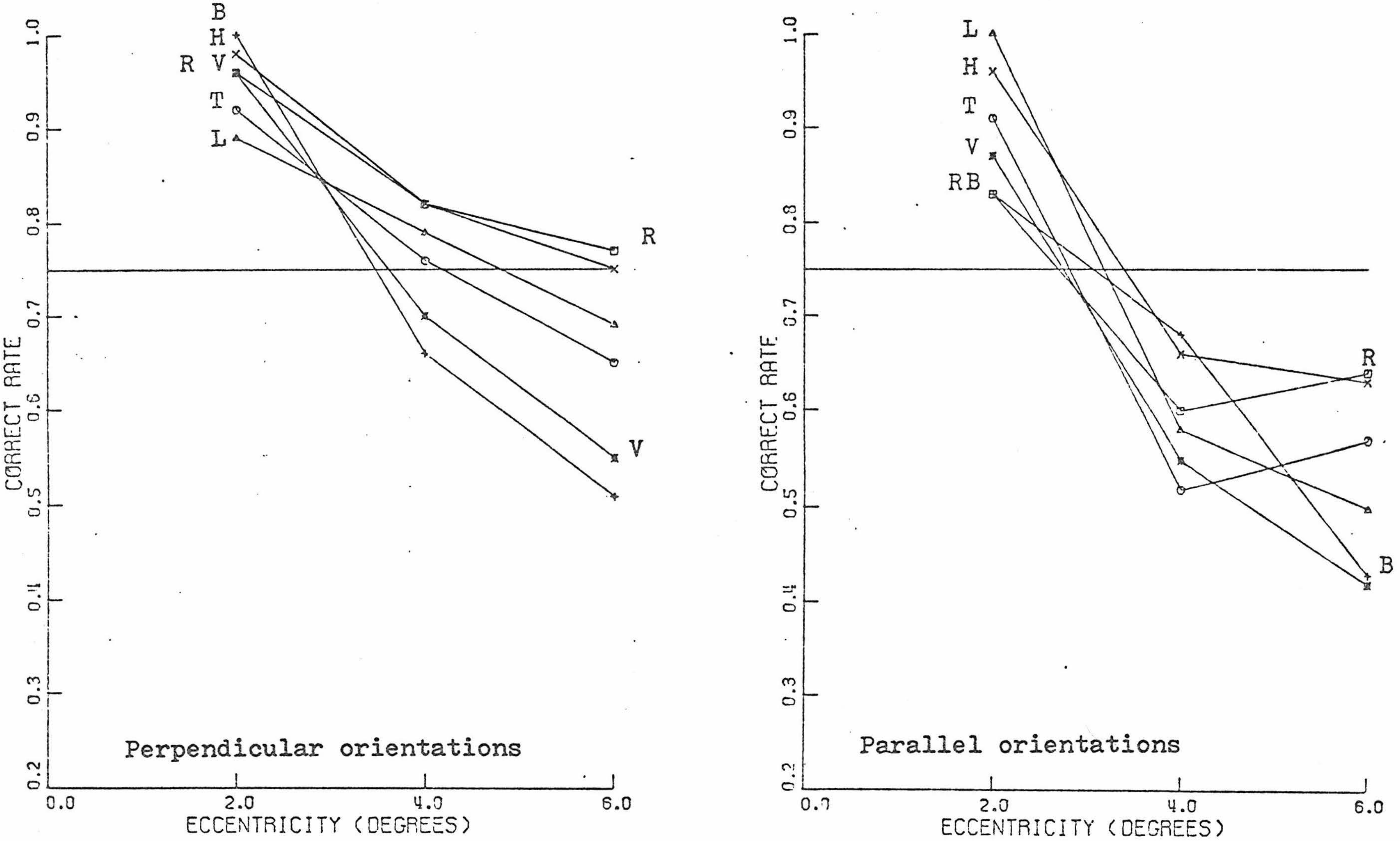
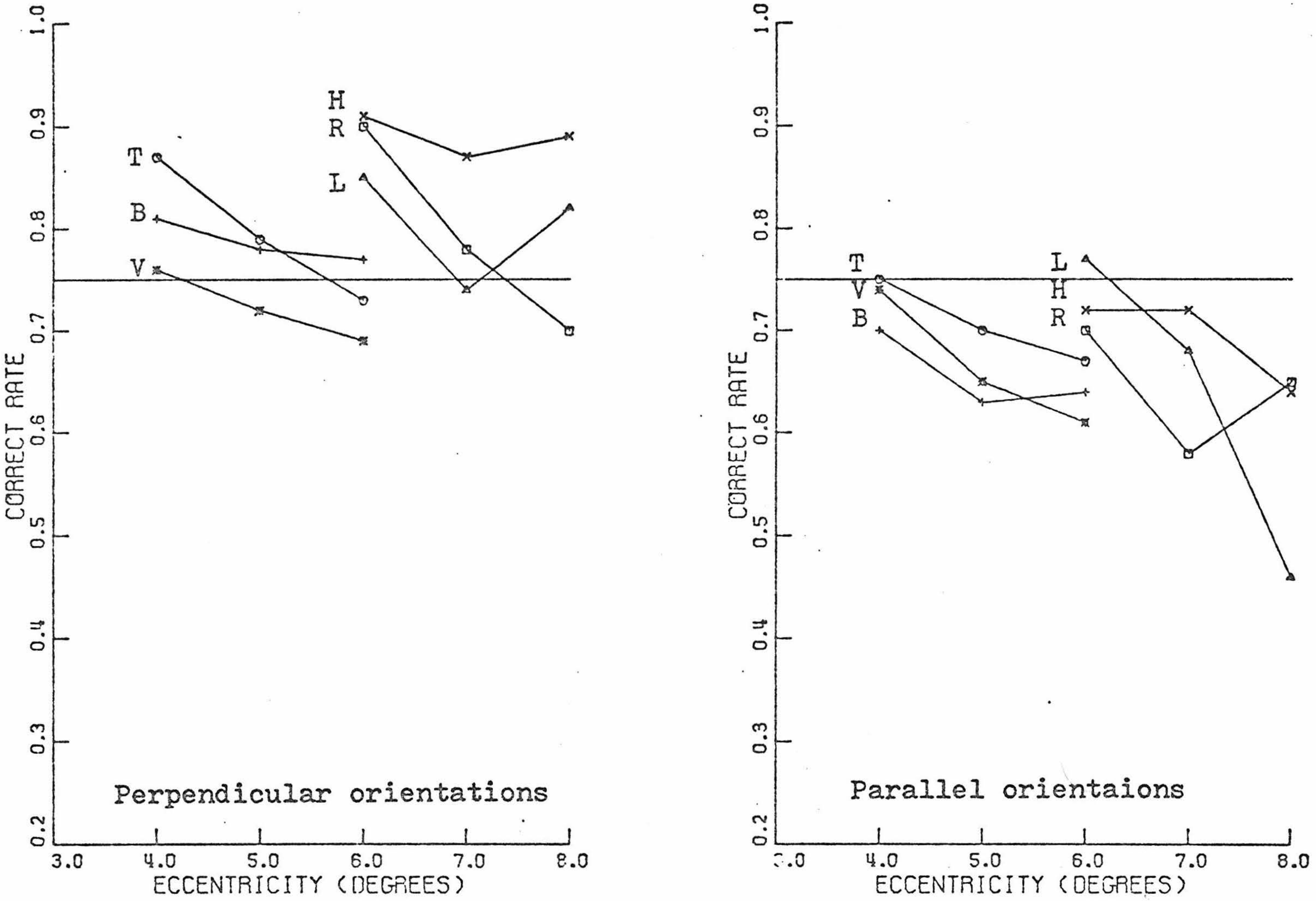


Fig. 7.2d Psychophysics experiment. Gap size: 4 min. of arc. Subject RW.


Perpendicular orientations

Parallel orientaions

Fig. 7.2e Eye movement experiment. Gap size: 6 min. of arc. Subject RW.

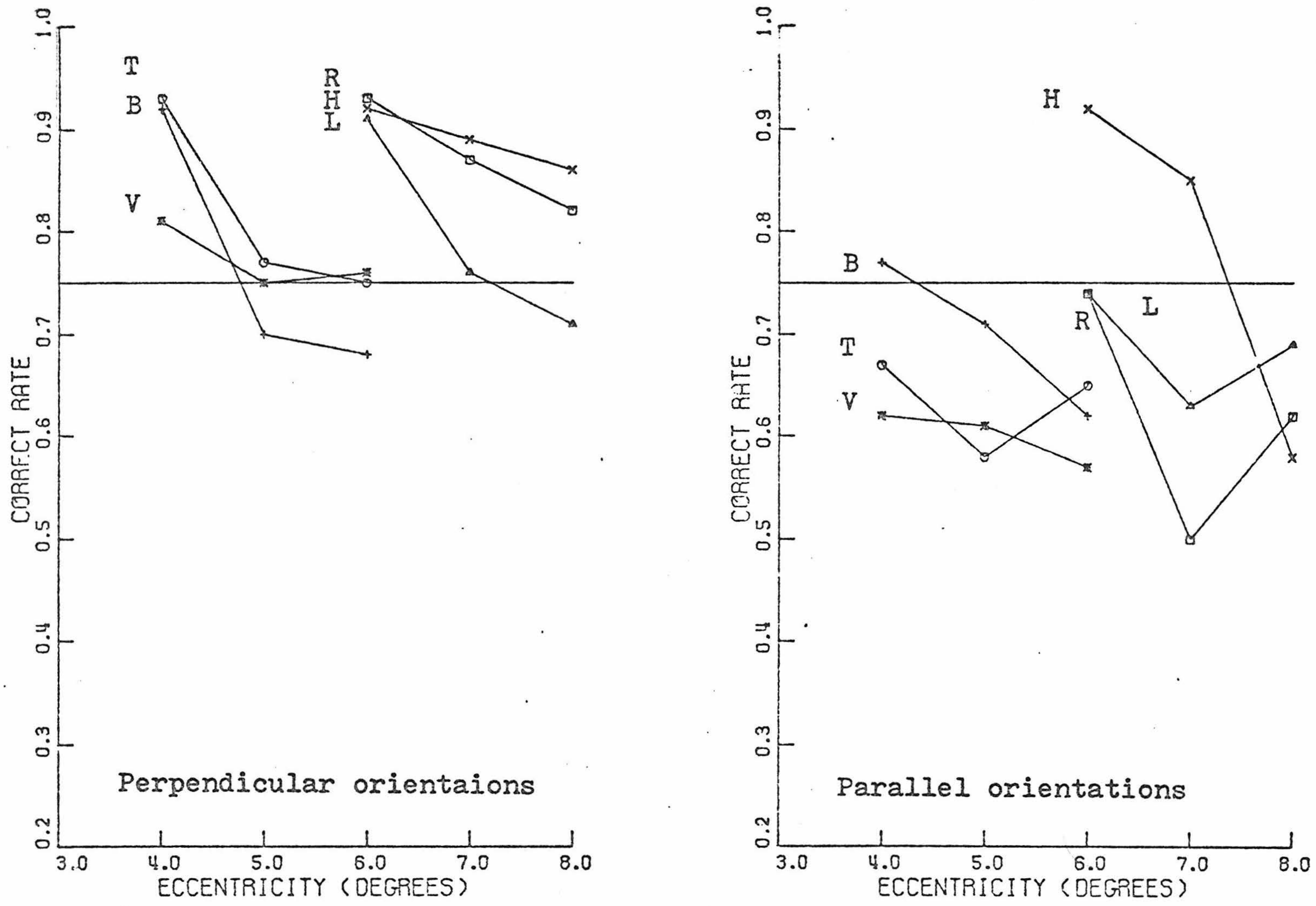


Fig. 7.2f Psychophysics experiment. Gap size: 6 min. of arc. Subject RW.

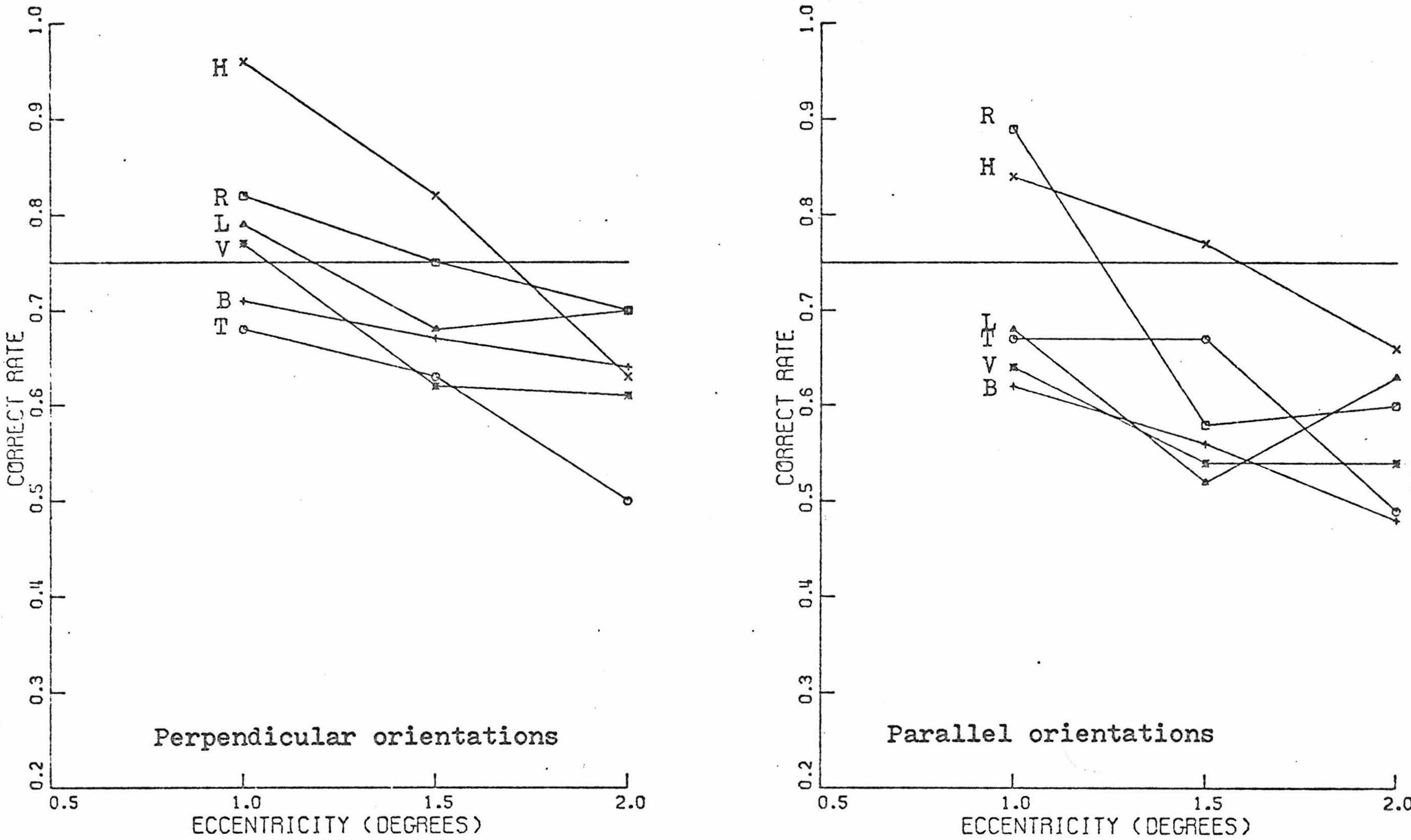


Fig. 7.3a Eye movement experient. Gap size: 2 min. of arc. Subject MB.

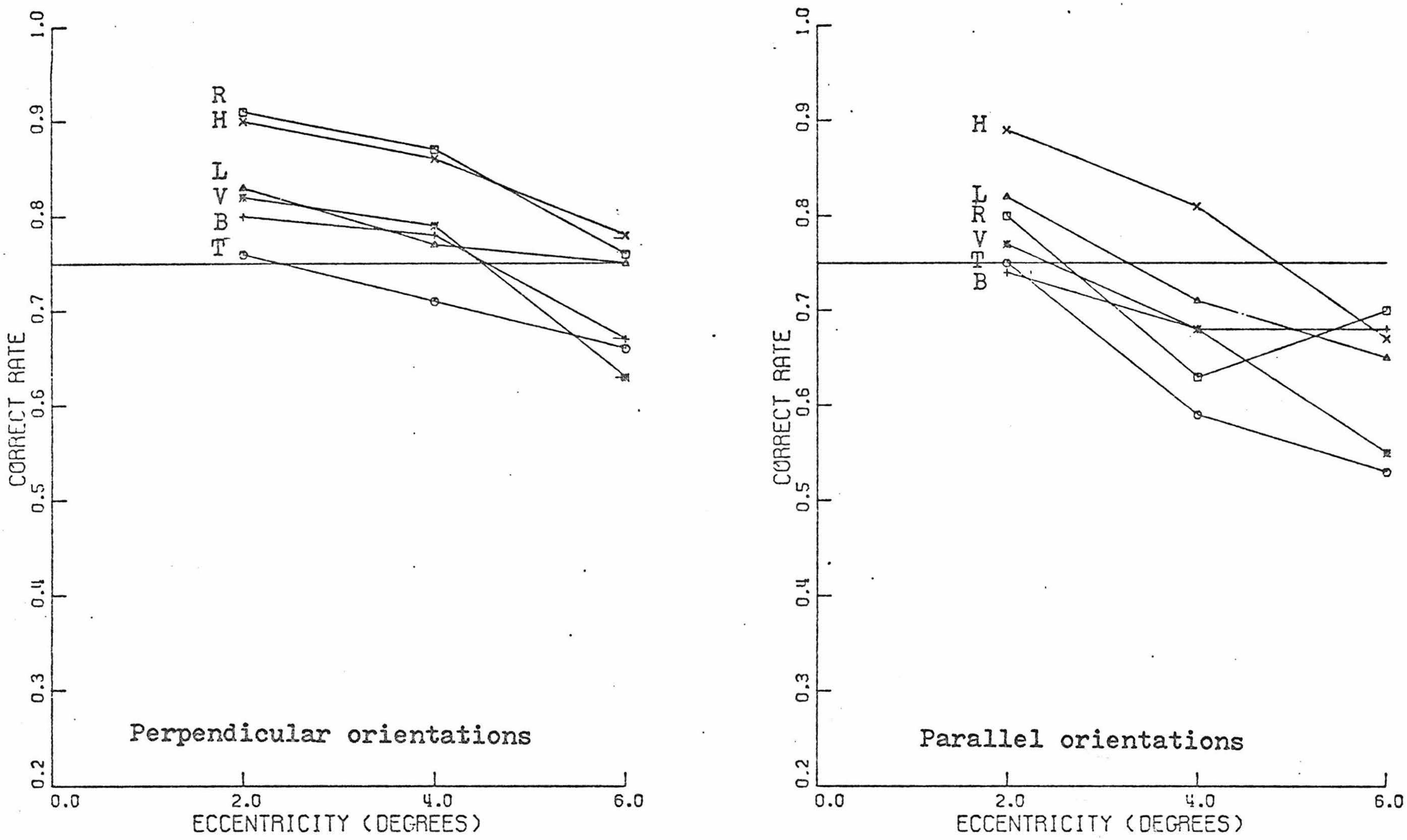


Fig. 7.3b Eye movement experiment. Gap size: 4 min. of arc. Subject MB.

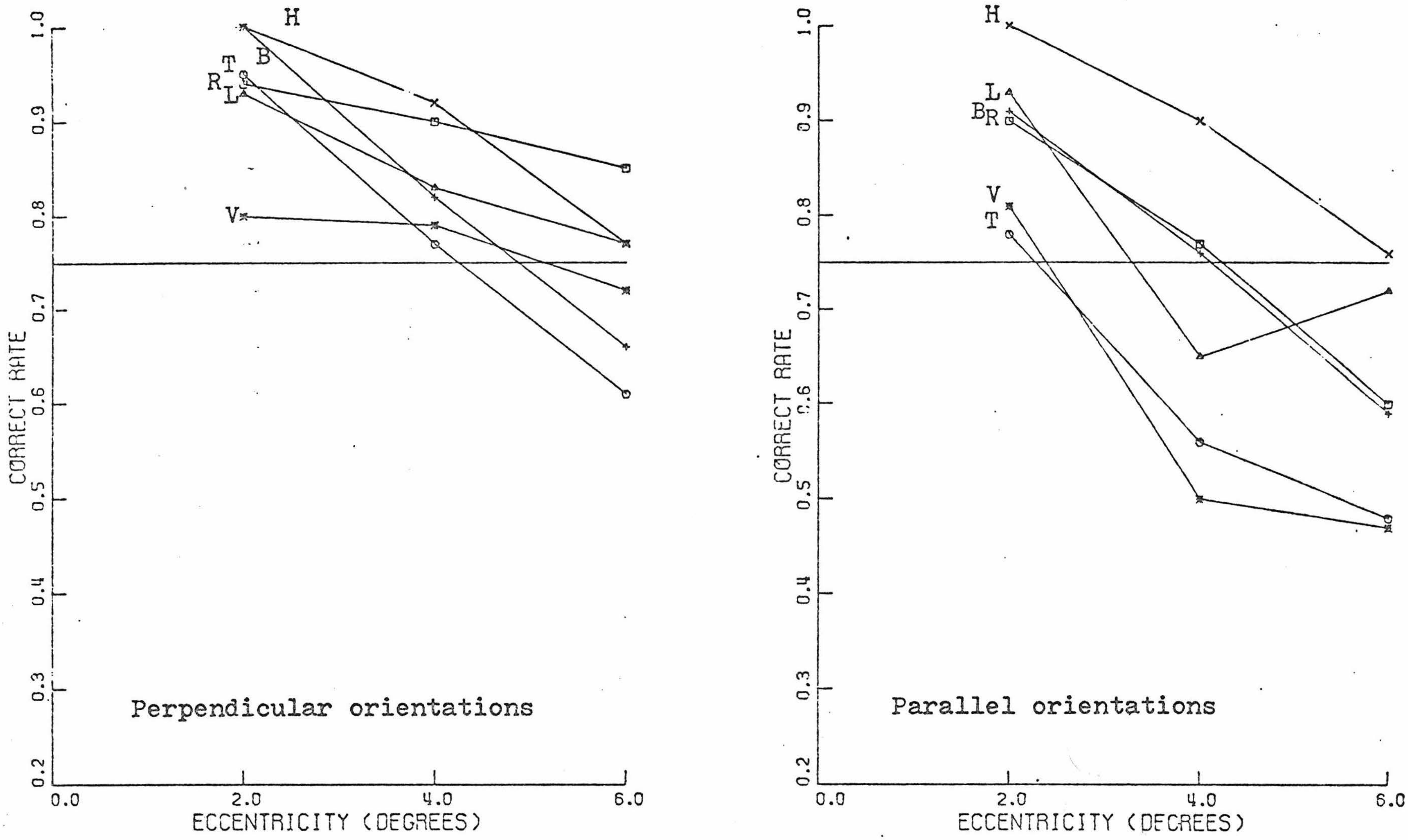


Fig. 7.3c Psychophysics experiment. Gap size: 4 min. of arc. Subject MB.

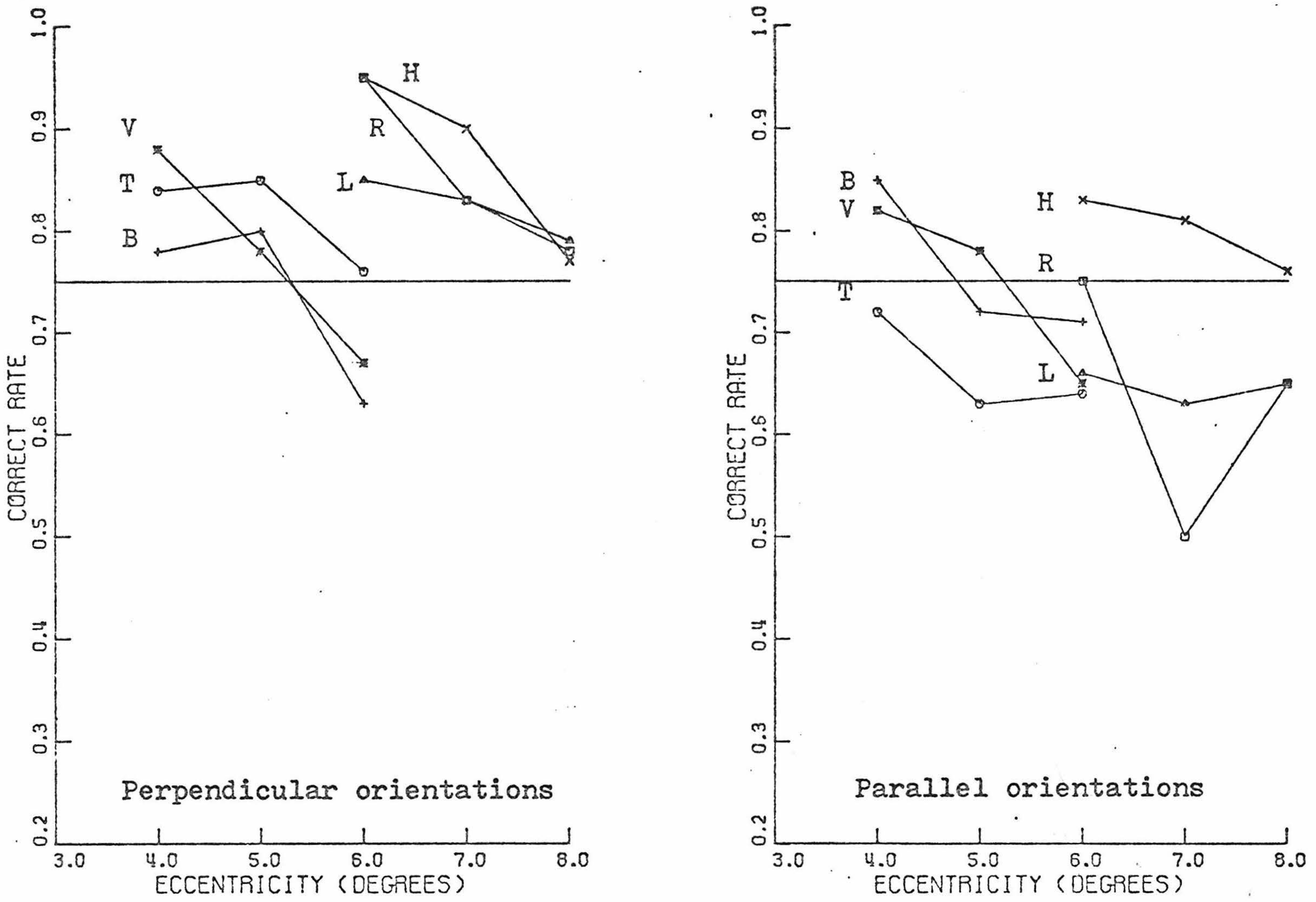


Fig. 7.3d Eye movement experiment. Gap size: 6 min. of arc. Subject MB.

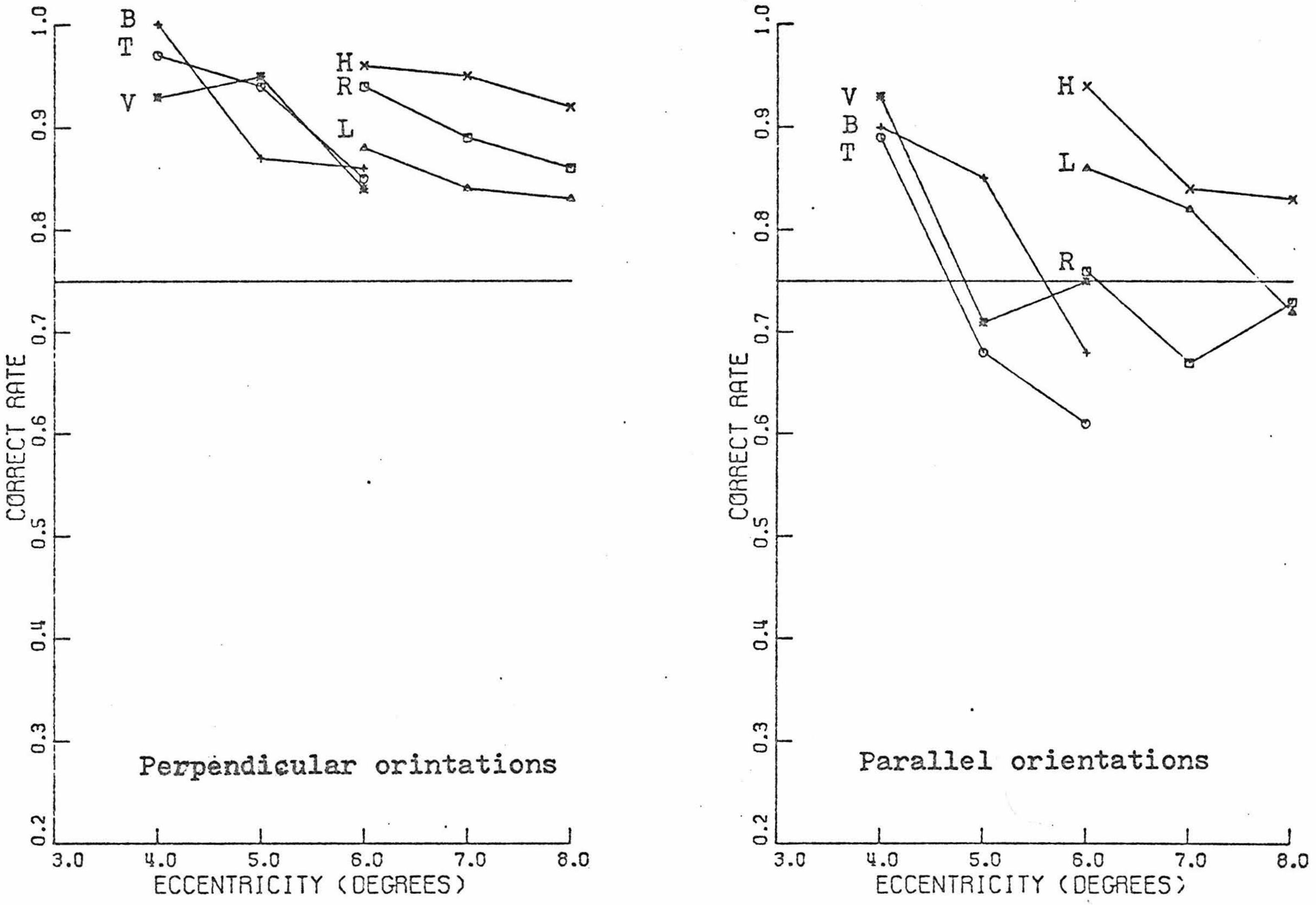


Fig. 7.3e Psychophysics experiment. Gap size: 6 min. of arc. Subject MB.

test is like a force-choice test and the noise level is 50 percent correct response.

In general, the correct rate in both experiments decreases as eccentricity increases. However, the detailed examination of these figures reveals large variations. Despite the variations, both eye movement response and psychophysical response exhibit some of the established characteristics of peripheral acuity. For example, the correct responses drop as eccentricity increases. The eye movement responses are more accurate when the test stimuli appear in the left or right visual field, or on the horizontal meridian, than when they appear in the top or bottom visual field or the vertical meridian. In other words, the contour which represents the eccentricity threshold over the whole retina for a constant gap size has oval shape.

The eccentricity threshold is defined as the eccentricity corresponding to 75 percent of correct responses. This threshold was estimated by eye and the results are shown in Figs. 7.4 and 7.5 for two subjects. In these two figures the eccentricity thresholds are plotted as a function of gap size. In each plot the four eccentricity thresholds correspond to the four combinations of eye movement and psychophysics experiments with parallel and perpendicular orientations. Each plot is for one visual field group defined above.

The eccentricity threshold is generally longer for the psychophysical results than for the eye movement results. Therefore, the percentage of correct response in the psychophysics experiment is better, or at least not worse, than the eye movement response. This does

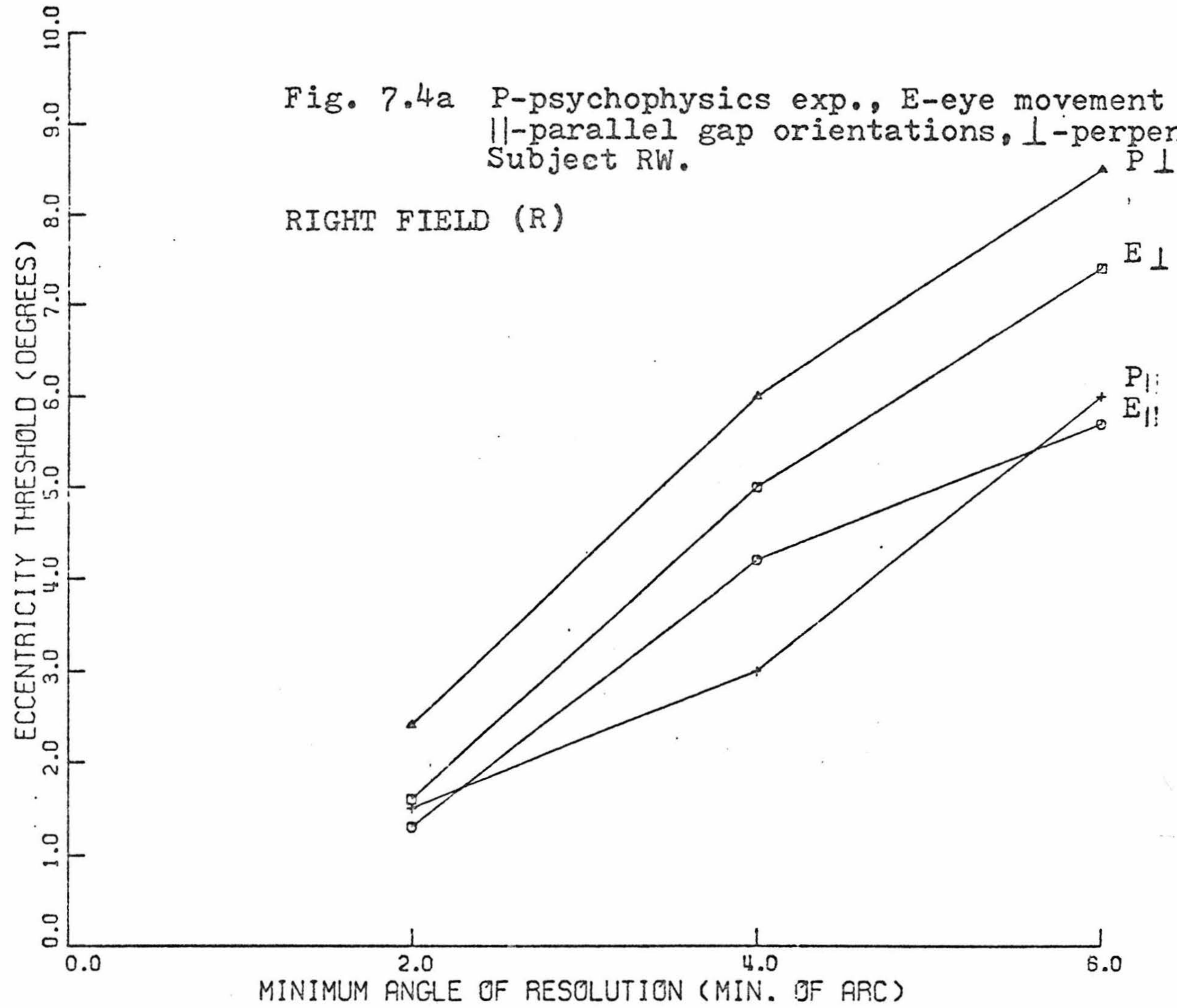
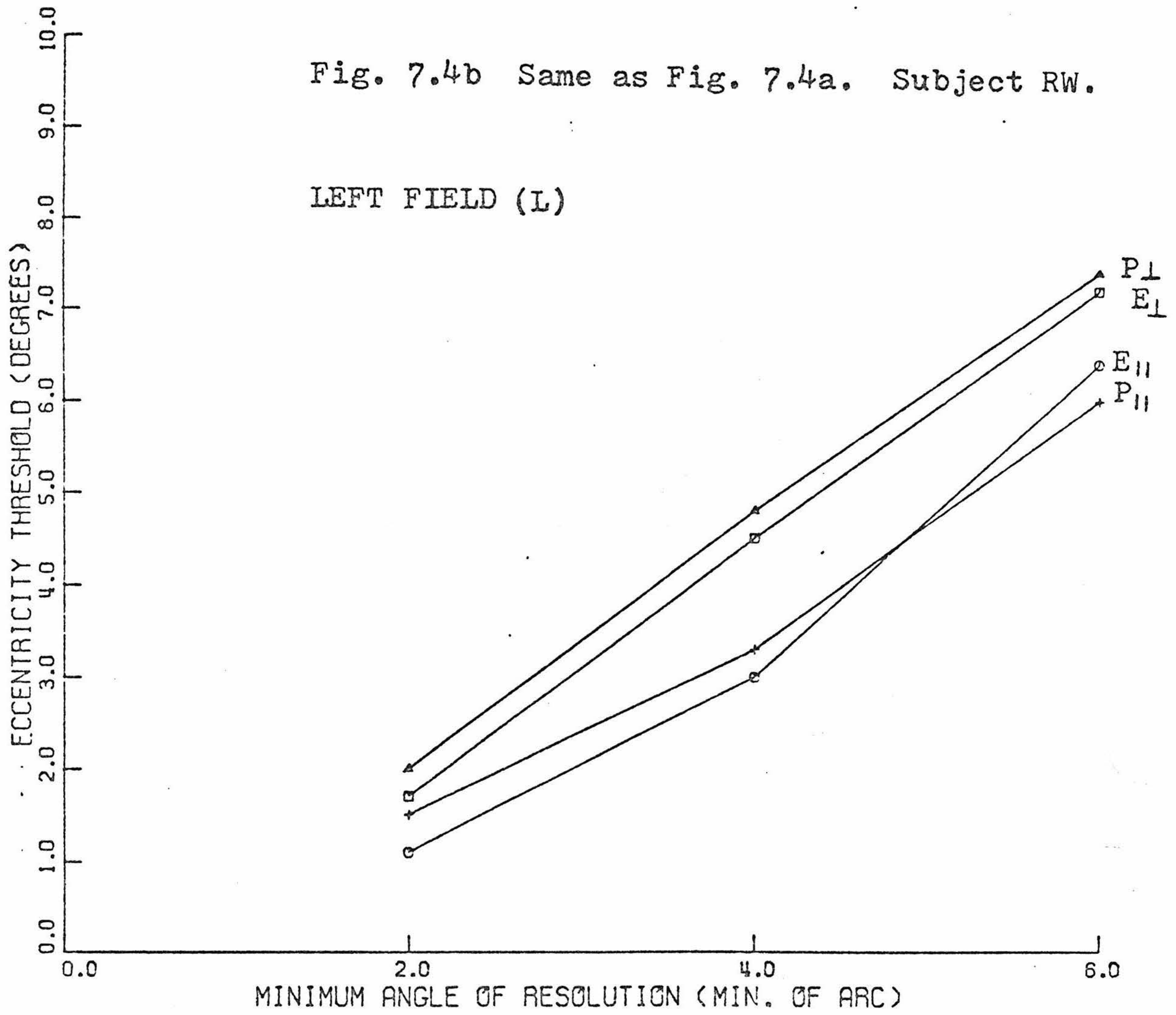


Fig. 7.4a P-psychophysics exp., E-eye movement exp.
||-parallel gap orientations, ⊥-perpendicular gap orientations
Subject RW.

Fig. 7.4b Same as Fig. 7.4a. Subject RW.



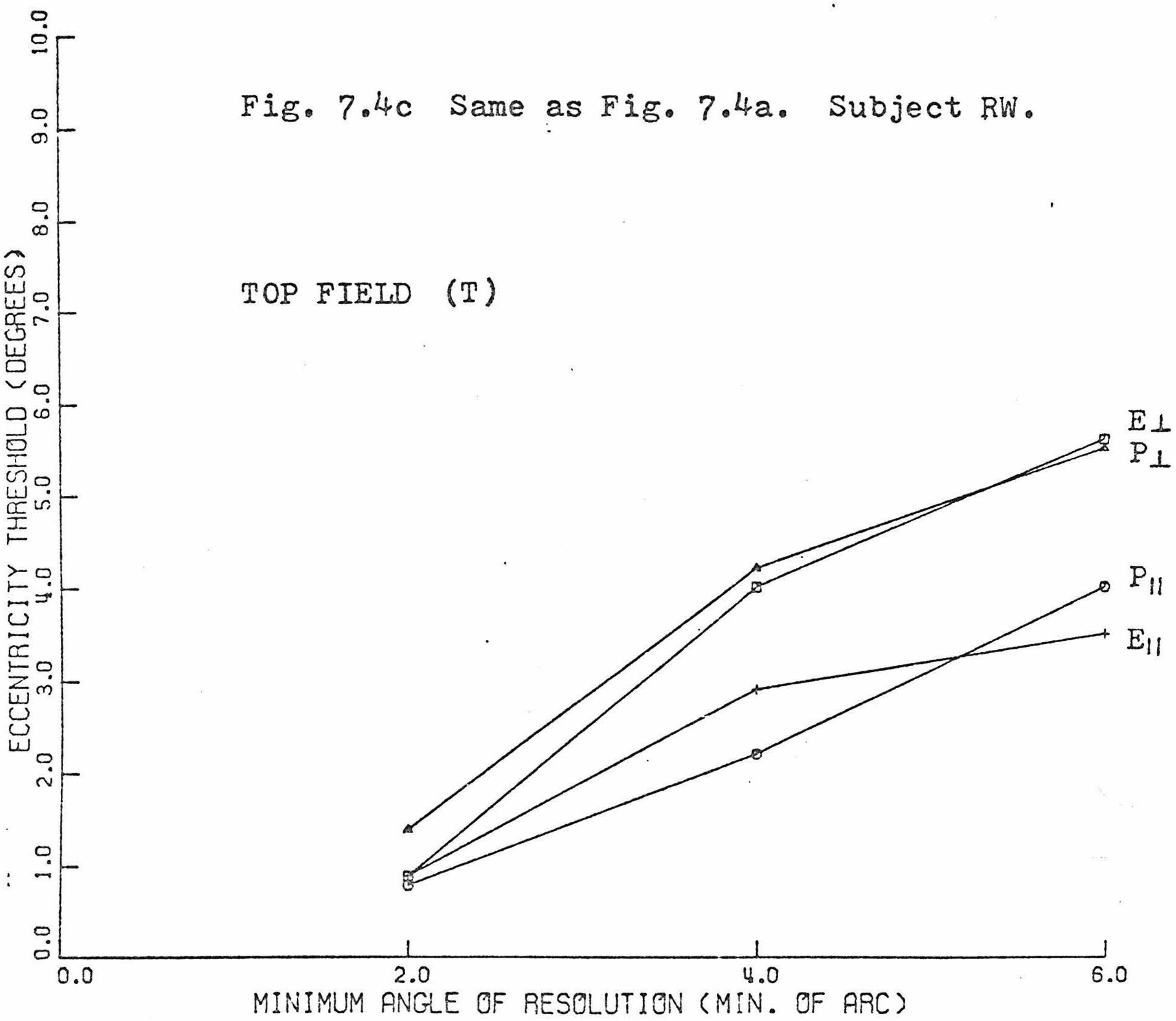


Fig. 7.4c Same as Fig. 7.4a. Subject RW.

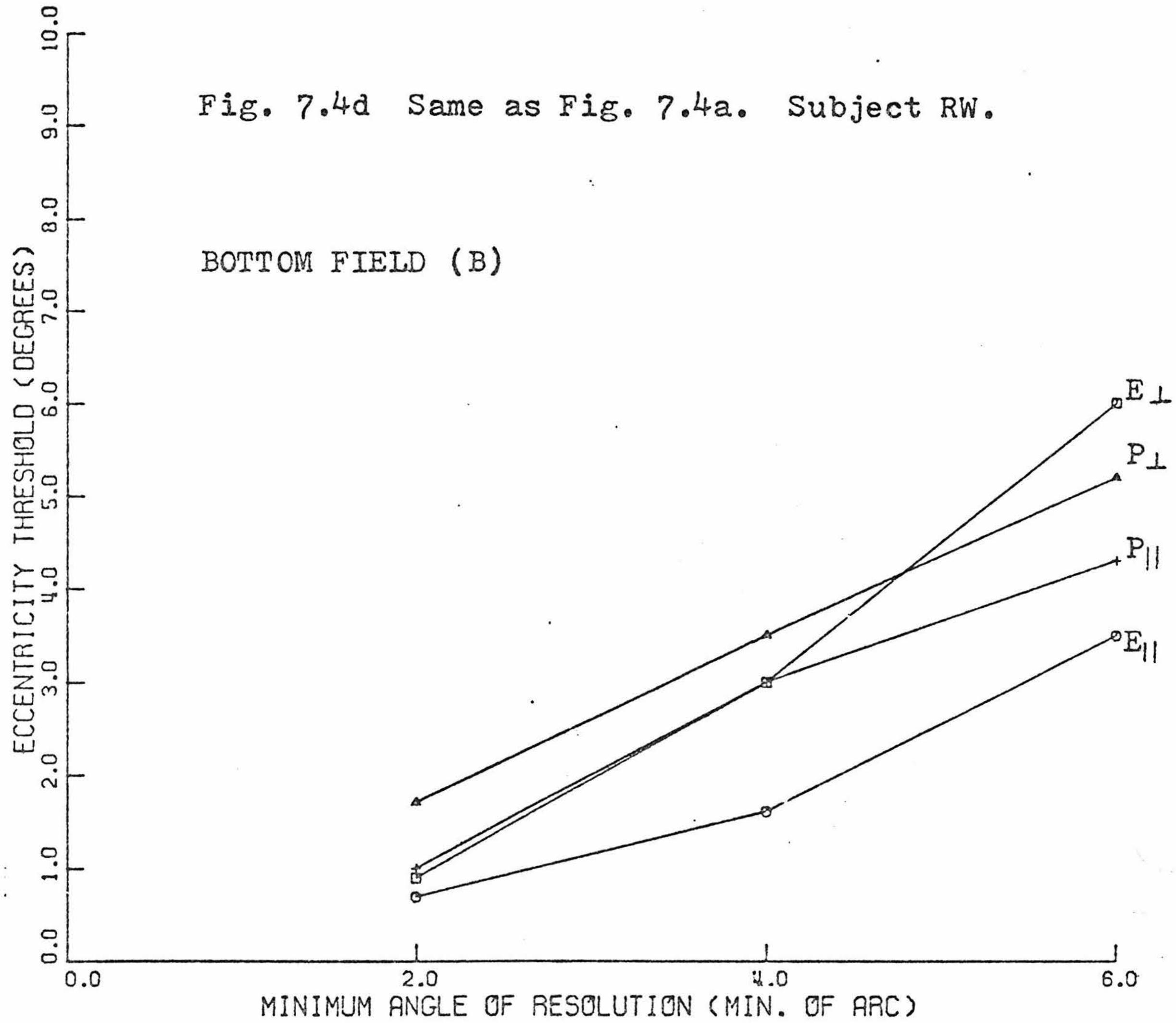


Fig. 7.4d Same as Fig. 7.4a. Subject RW.

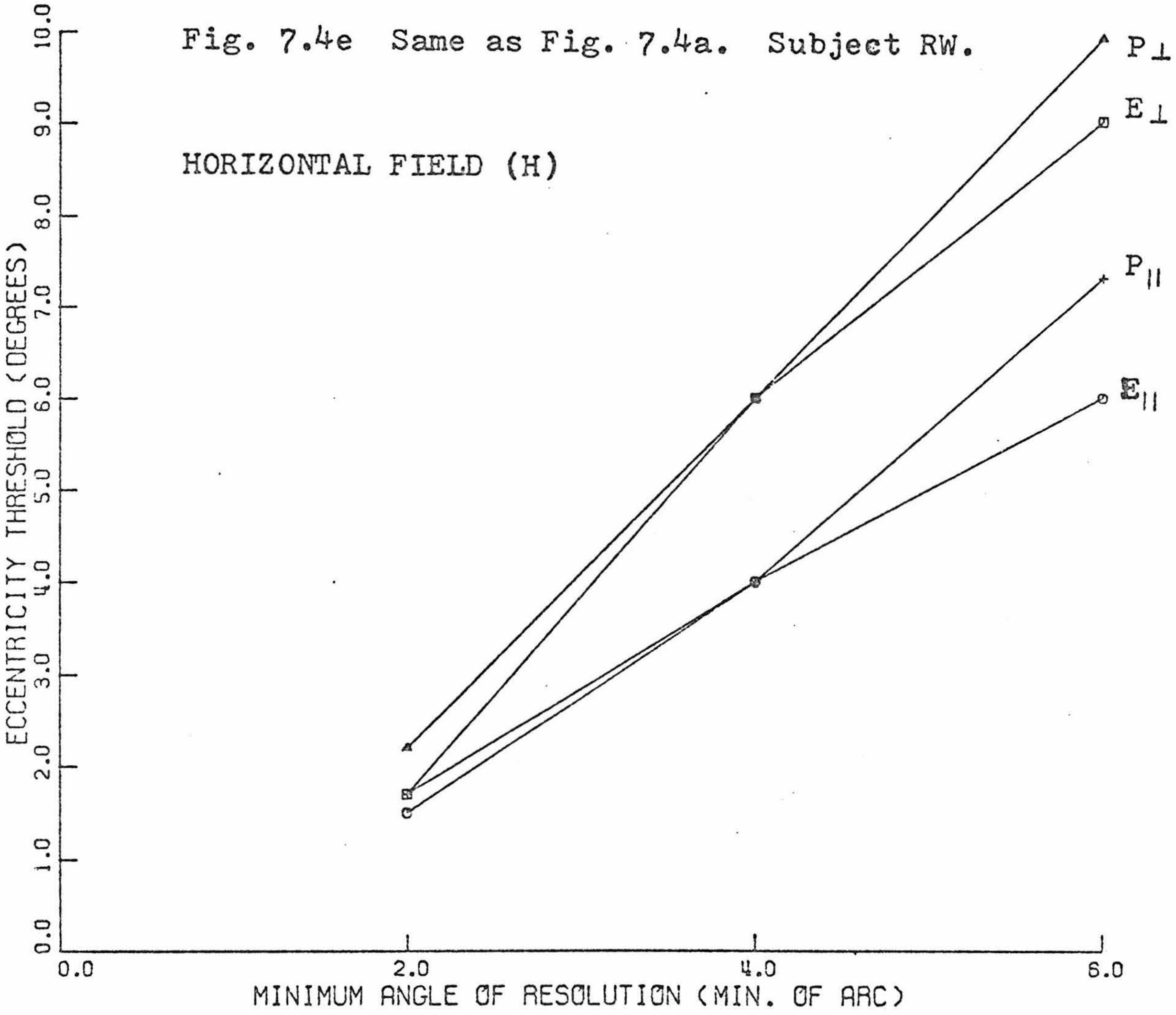


Fig. 7.4e Same as Fig. 7.4a. Subject RW.

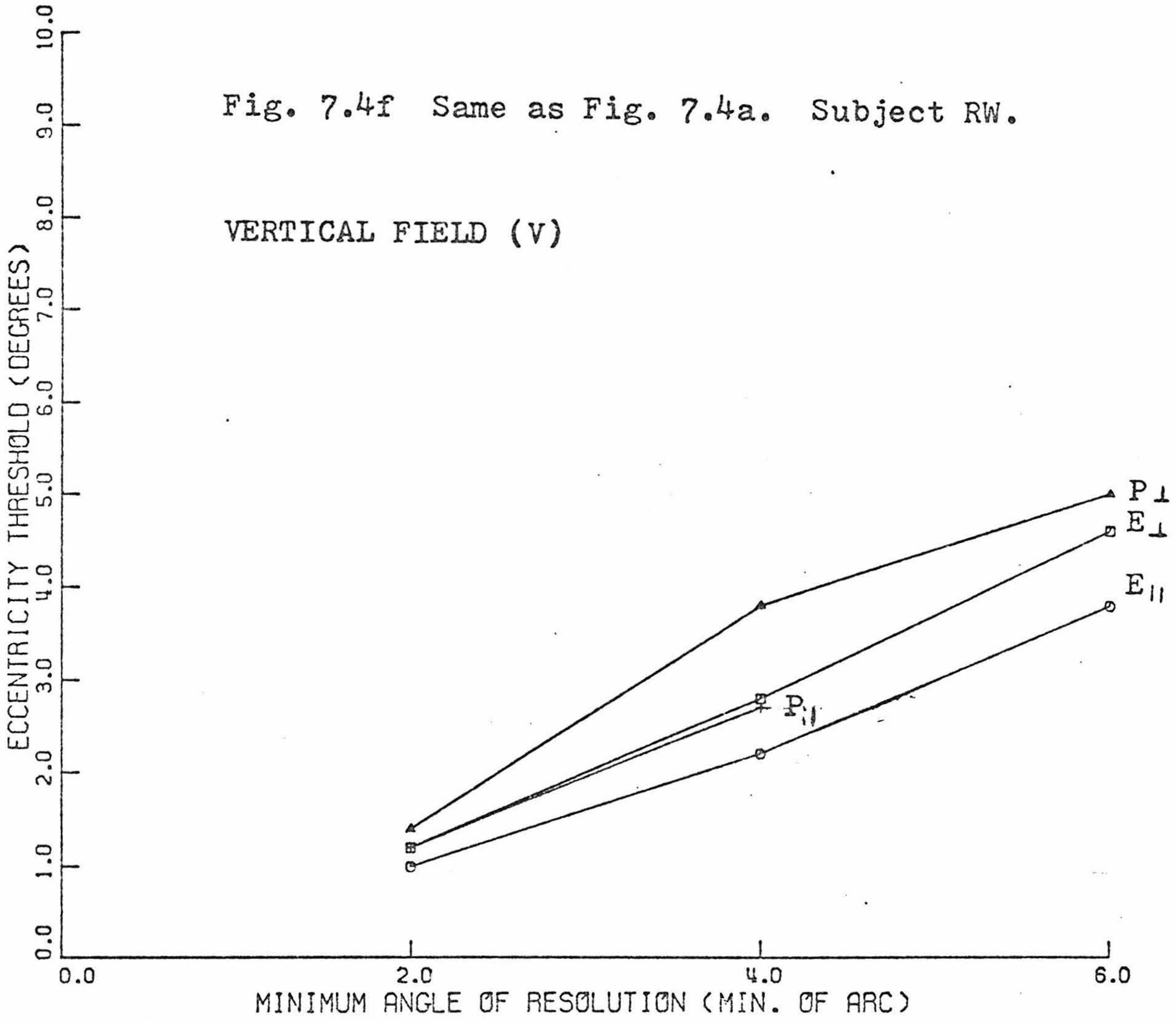


Fig. 7.4f Same as Fig. 7.4a. Subject RW.

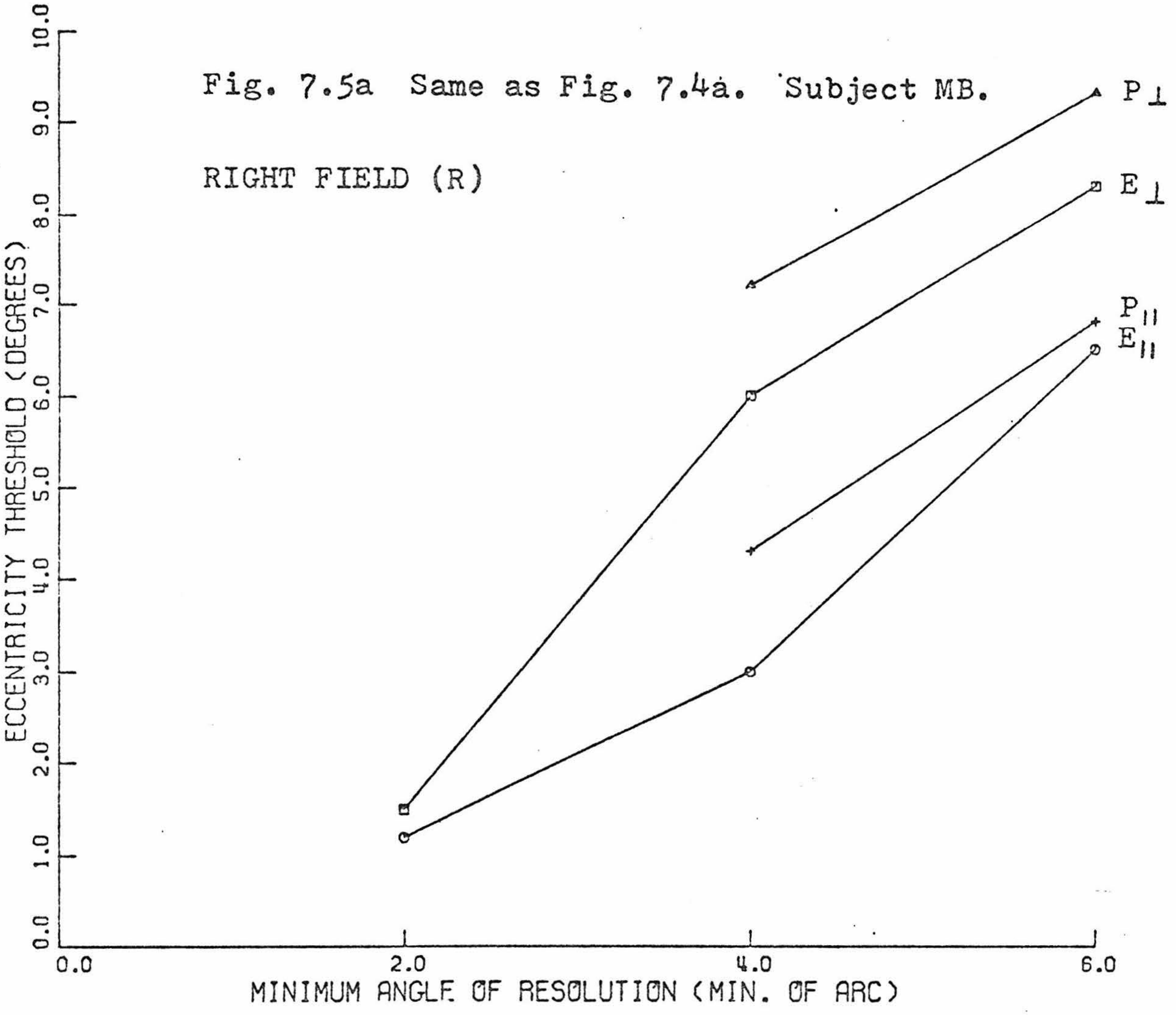


Fig. 7.5a Same as Fig. 7.4a. Subject MB.

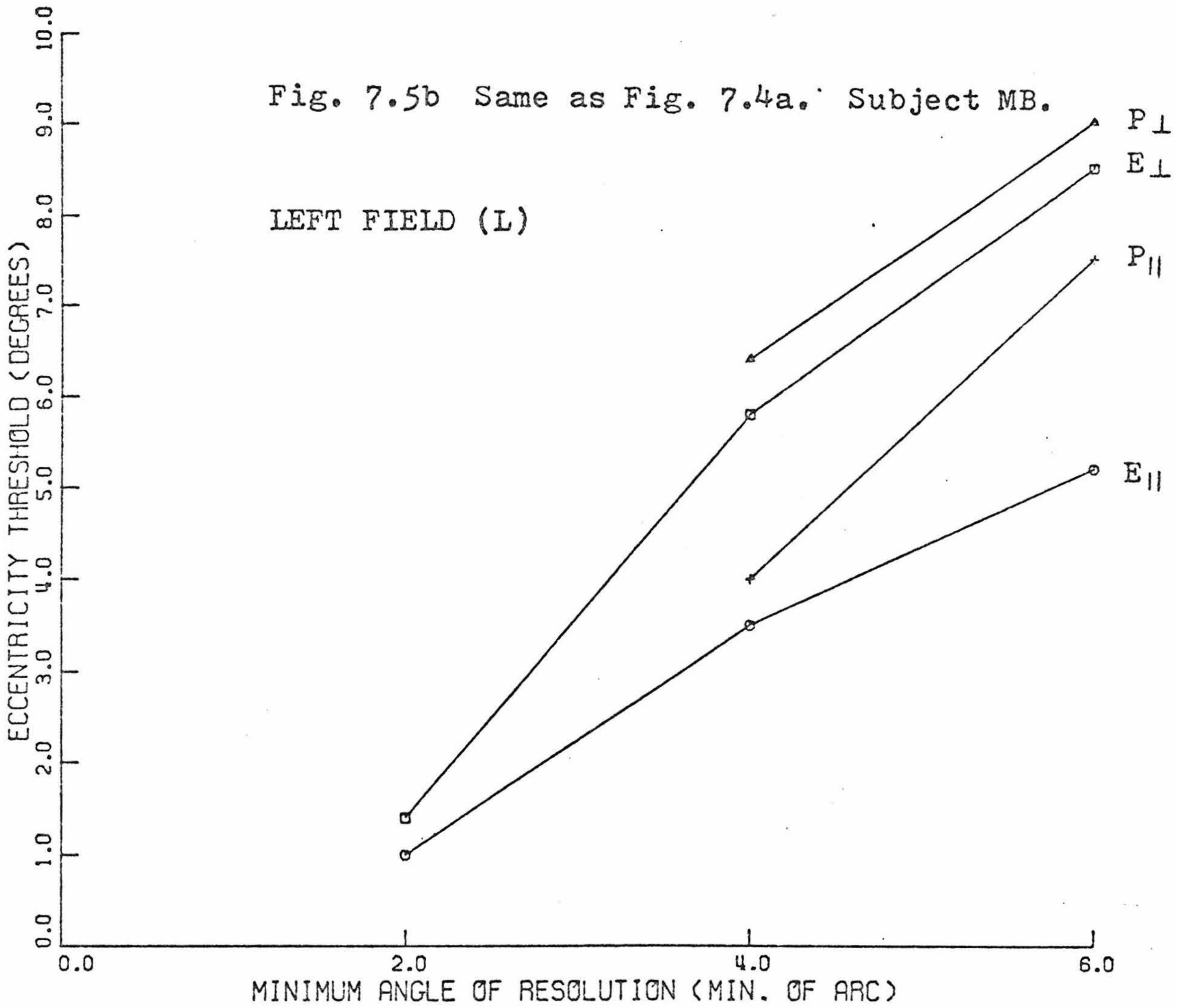
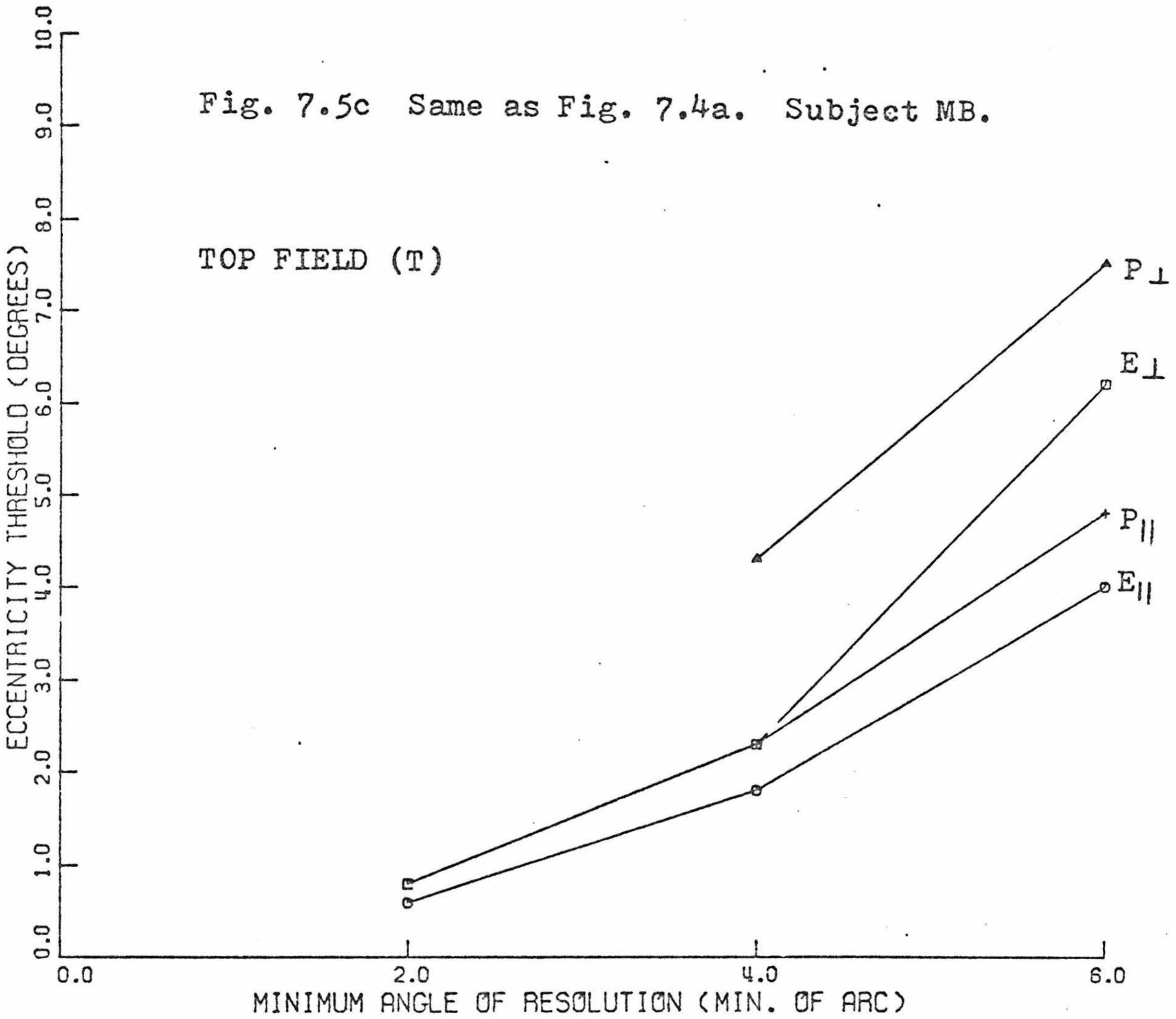


Fig. 7.5b Same as Fig. 7.4a. Subject MB.

Fig. 7.5c Same as Fig. 7.4a. Subject MB.



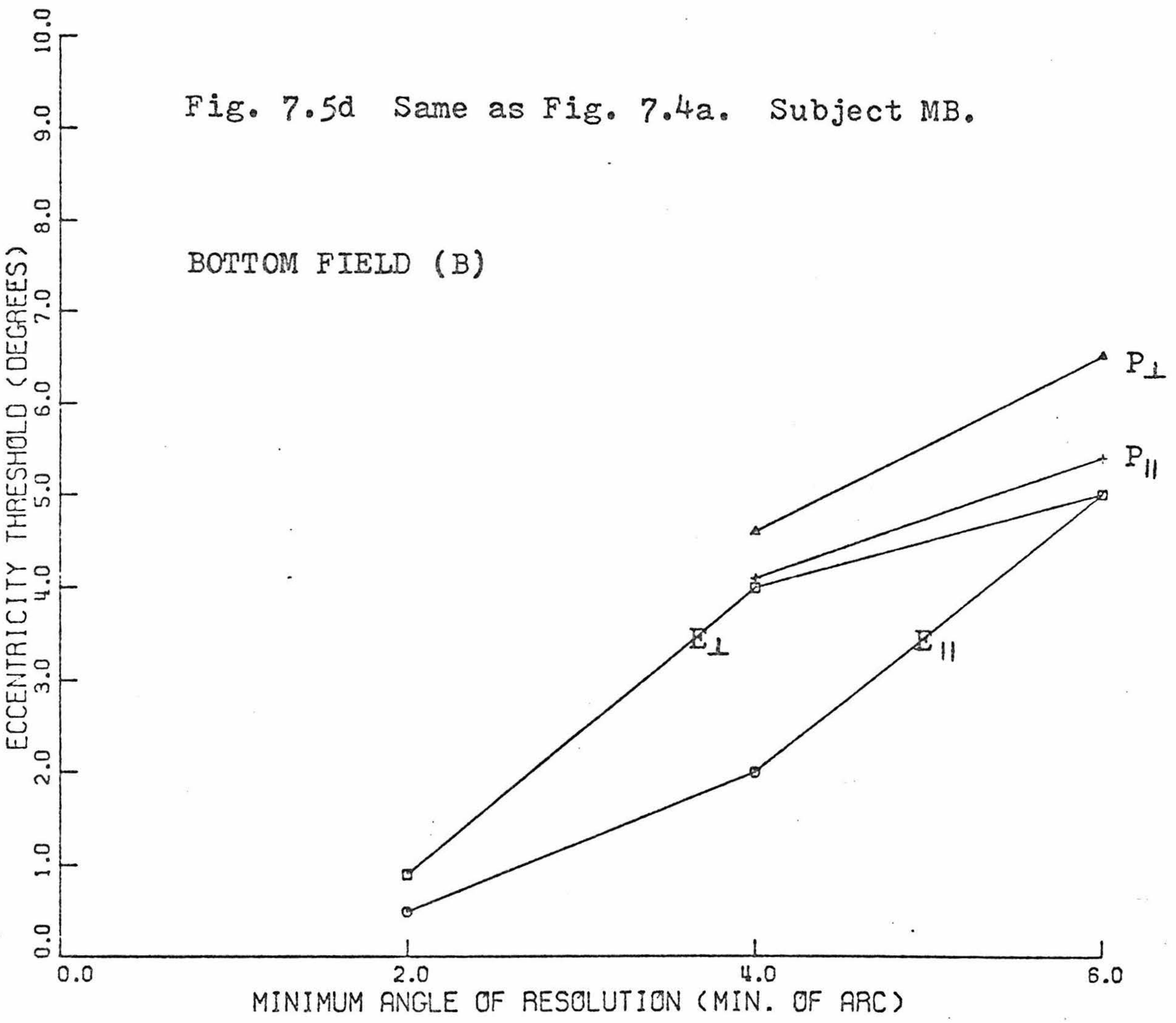


Fig. 7.5d Same as Fig. 7.4a. Subject MB.

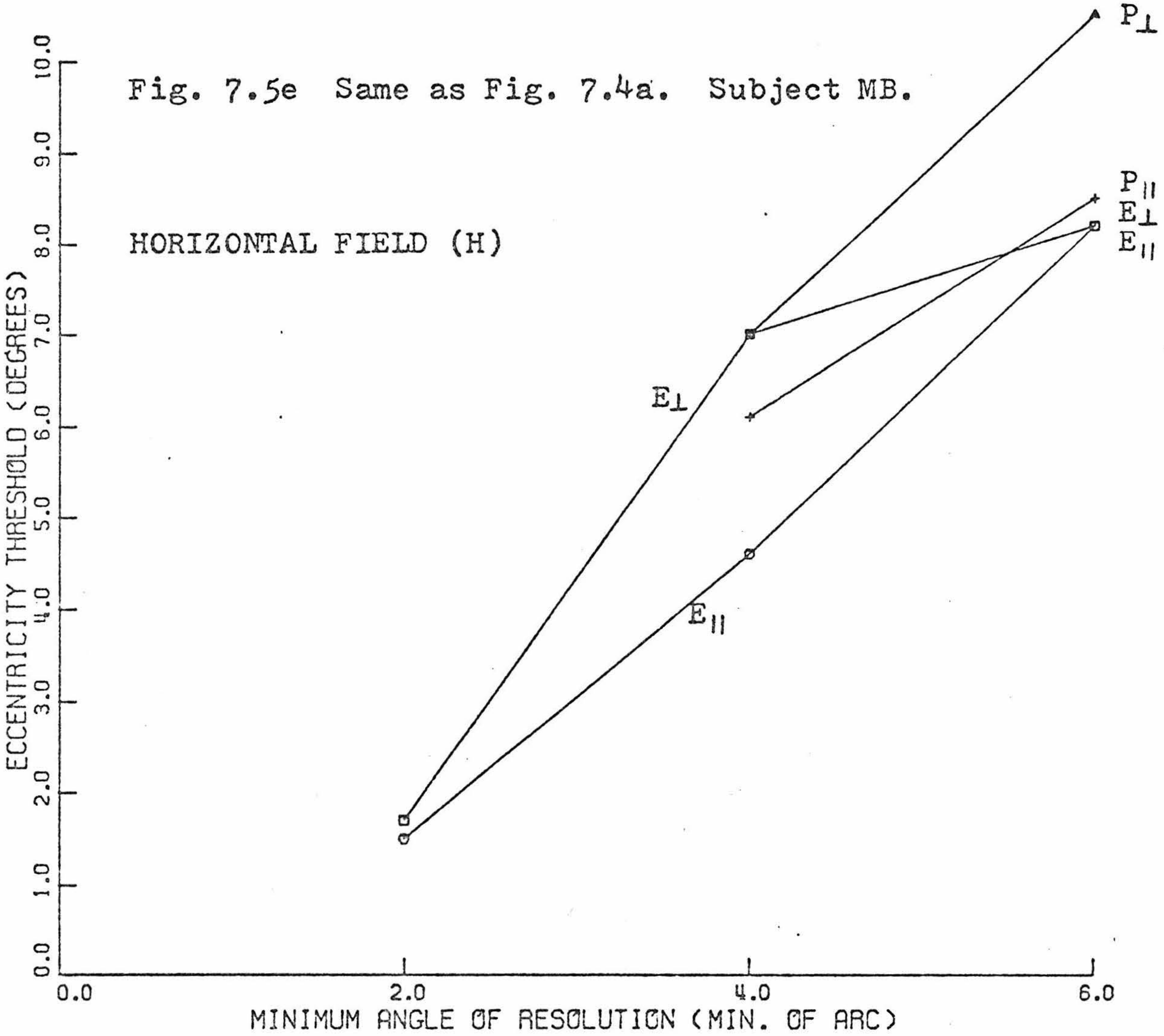


Fig. 7.5e Same as Fig. 7.4a. Subject MB.

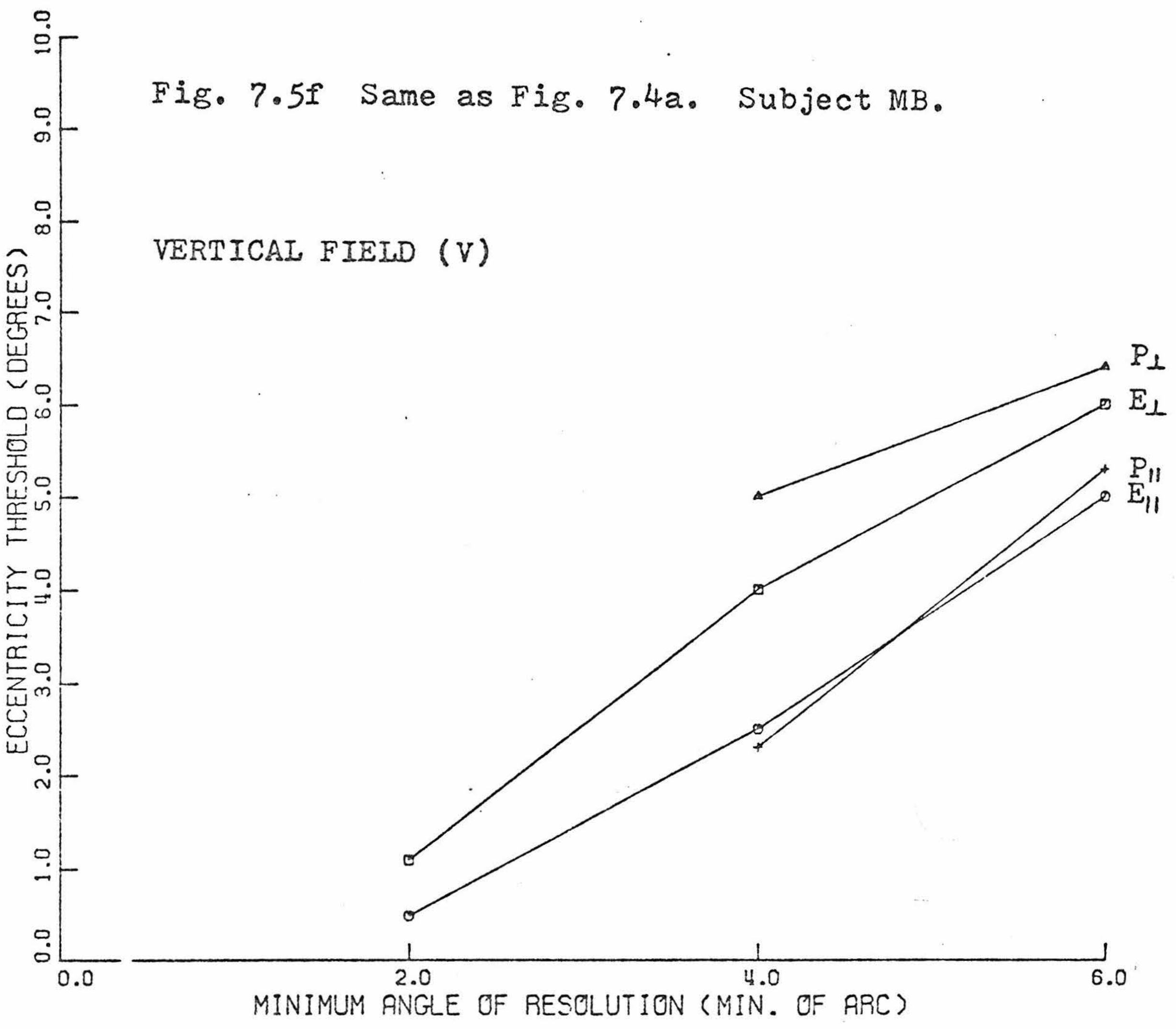


Fig. 7.5f Same as Fig. 7.4a. Subject MB.

VERTICAL FIELD (V)

not support the theory that the oculomotor system receives privileged acuity inputs.

The results do show consistently better response for those presentations which have perpendicular gap orientations than for those which have parallel gap orientations. This phenomenon appears in both eye movement and psychophysics experiments. This, I believe, is caused by the stimulus pattern used. As shown in Fig. 7.1, this c pattern is a simulation of the curved Landolt c. It consists of horizontal, vertical and oblique bars. A c pattern with its gap pointing to either left or right has two horizontal bars and one vertical bar. Similarly, a c pattern with its gap pointing either up or down has two vertical bars and one horizontal bar. Therefore, one pattern has more horizontal structures and the other has more vertical structures. This difference in the horizontal and vertical structures can be easily demonstrated with their two-dimensional Fourier transforms (Fig. 7.6). When the gap orientations of target and decoy are perpendicular to each other, they can be distinguished by their general horizontal and vertical structures. But when their gap orientations are parallel to each other, they have the same general structure. To distinguish the target from the decoy, the position of the gap has to be detected, which is more difficult.

Since the eye movement response to an acuity stimulus shares the same characteristics as the response to the psychophysical acuity experiment, it is likely that they share a common acuity discrimination system.

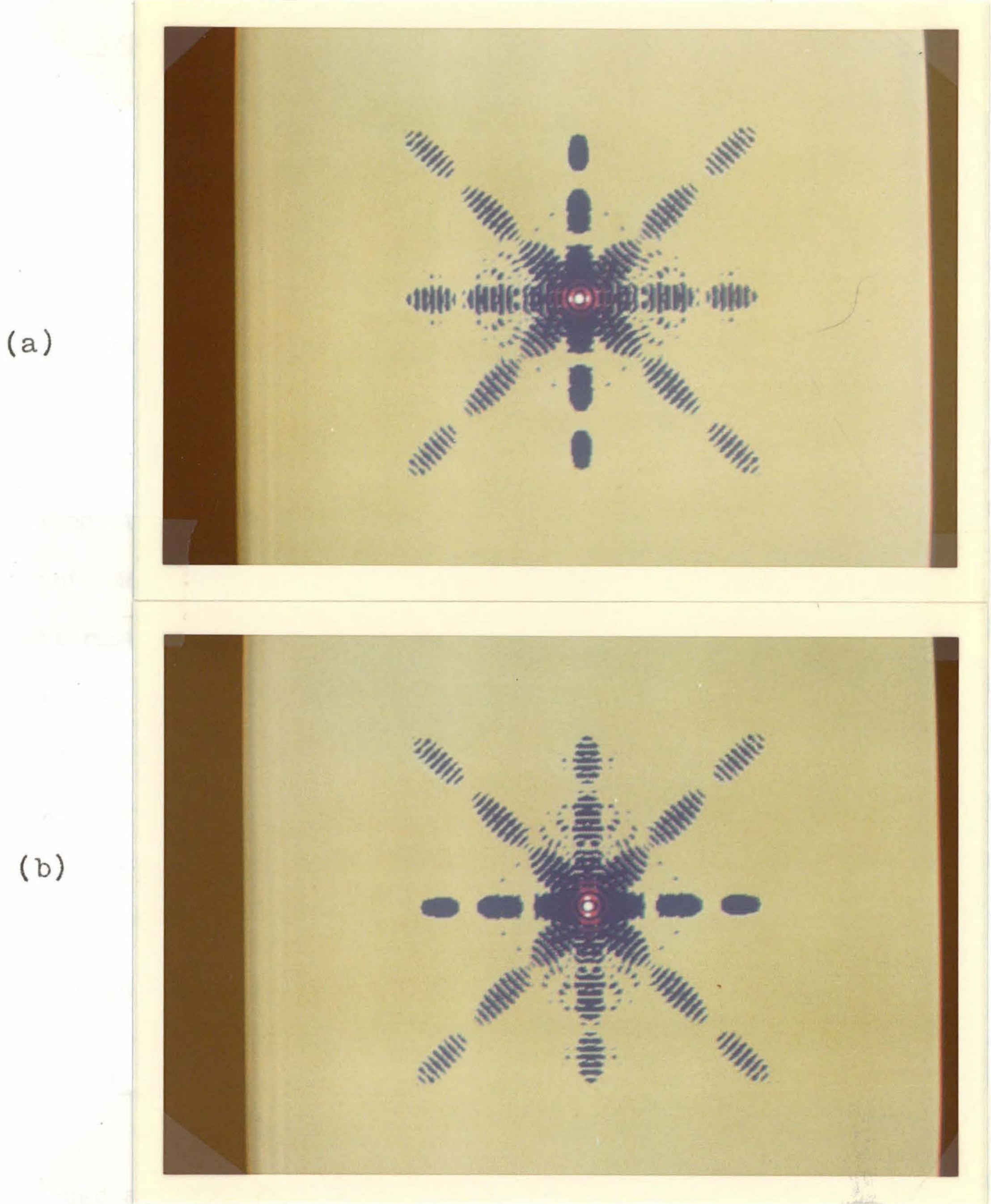


Fig. 7.6 The amplitude of the two-dimensional Fourier Transform of a single Landolt-c like stimulus. Color code: intensity level 0--background color, intensity levels 1-31--colors change from bright blue into bright red, intensity levels above 31--white.
(a) gap points to the right. (b) gap points up.

7.4 Experiment II

The results of Experiment I suggested that the oculomotor system shares the same acuity discrimination system as the psychophysical acuity response system. But how does this acuity discrimination system interface with the saccadic programming system? This is a very difficult question because of the complexity of the discrimination process. However, I believe that some information about this system can be obtained if we employ an experimental technique similar to the double-step stimulation used in Chapter IV. If we provide the system new information about the target before its processing is done, how will it respond to this new information? The answer to this question certainly tells us something about the processing capability of the system. To apply this approach to Experiment I, one may switch target and decoy at various times. That is, before the subject responds to the correct target, the target will become the decoy and the decoy will become the target. This experiment uses this scheme to study the subjects' response strategy.

7.4.1 Method

In this experiment the c pattern described in Experiment I was used again. The size of the gap was 4 min of arc, and only one eccentricity was used, that is, 3° from the fovea, in order to avoid large variations of acuity between the horizontal meridian and the vertical meridian. The vertices at the top and bottom of the octagon described in Experiment I were excluded, thus there were only six possible locations where the target and decoy could appear. The target/decoy pair could appear either in adjacent locations (adjacent presentation) or in the two horizontal locations (opposite presentation). Also, the orientation of the decoy c was always perpendicular to the orientation of the target c. This was to avoid the variations caused by gap orientation effects discussed in Experiment I. These conditions were chosen so that the subject should have more than 80 percent correct responses.

At the beginning of each trial, a center fixation c was displayed and the subject was instructed to fixate it and to note its gap orientation. When the computer program determined that the subject was looking at the fixation c, the target and decoy were displayed in two of the six positions described above. The subject was instructed to move his gaze to the target accurately and as soon as he could.

At various times after the target and decoy were displayed, the gaps in the two c-patterns were filled in with dots and then reestablished so that either the target and decoy exchanged places or retained their original positions. It was found that the change of gap orientation caused a fairly strong sensation, as a group of target dots flashed on and off. This could give the subjects a clue that the target and decoy had switched. To avoid this, a ring of dots was also added to the inside next to the dots of the pattern. Those additional dots were displayed for 20 msec, then the gap reappeared and the inside ring of dots disappeared. These additional dots flashed on for 20 msec even when there was no switching between target and decoy; this masked out the clue that target and decoy had switched. The time intervals between the first display of the target/decoy pair and the reopening of the gaps were 100, 200, 300, 400 and 500 msec. I will use ISI to represent this time interval. The saccadic eye movement responses to the trials in which the target and decoy switched were the data of interest for this experiment. Those trials in which the target and decoy did not switch served as a control experiment. If the subject made a wrong saccade in these control trials, a visual feedback was displayed on the screen to help the subject control his error rate.

The eye movements recording and processing were the same as those described in Experiment I.

7.4.2 Results

In this experiment there were undoubtedly some wrong responses in which the subject responded to the decoy from the beginning. Subject RH had 90 percent correct responses, and subject RW had 80 percent correct responses in the control experiment. RW had a faster reaction time, e.g., 458.6 msec, compared with RH's 650 msec. There might be some speed-accuracy trade-off involved. However, this is not the topic of my study.

7.4.2.1 Classification of responses

The responses to the stimuli in which target and decoy switch their roles can be generally classified into two types of responses, depending on whether the initial target was responded to or not. If the initial target was ignored, the subject only responded with one saccade to the final target position after the switch. I will use the term "reprogrammed saccade" for this type of response, inherited from the double-target-step experiment of Chapter IV. If the first target position was responded to, and the target switched with the decoy, the subject would find that he ended up at the decoy and another saccade was necessary to correct his direction of gaze. This type of response will be referred to as a "two-saccade response." There was not a significant number of saccades with intermediate magnitude, therefore the intermediate two-saccade response defined in Chapter IV is omitted.

As mentioned above, there were wrong responses in which the subject moved to the decoy first. If target and decoy switched, his gaze ended up at the correct target. Fortunately, this type of response could usually be picked out if we use the reaction times in addition to the number of saccades to classify the responses. This wrong response normally has a short reaction time. For example, if ISI is 500 msec, a single saccade response to the final target position with a reaction time of about 500 msec is clearly an error. The errors picked up in this way were discarded. Therefore the classification of responses is done by two criteria: (1) whether the first target position is ignored; (2) whether the reaction time is within a reasonable limit.

7.4.2.2. Percentage of reprogrammed saccade responses

The existence of reprogrammed saccades suggests that if the new acuity information arrives in time it can be used to reprogram the response. But what time is "in time"? Is there a statistically distributed critical time before which the new information can affect the responses and after which it cannot? To answer these questions let us examine the probability of reprogrammed saccades shown in Fig. 7.7a.

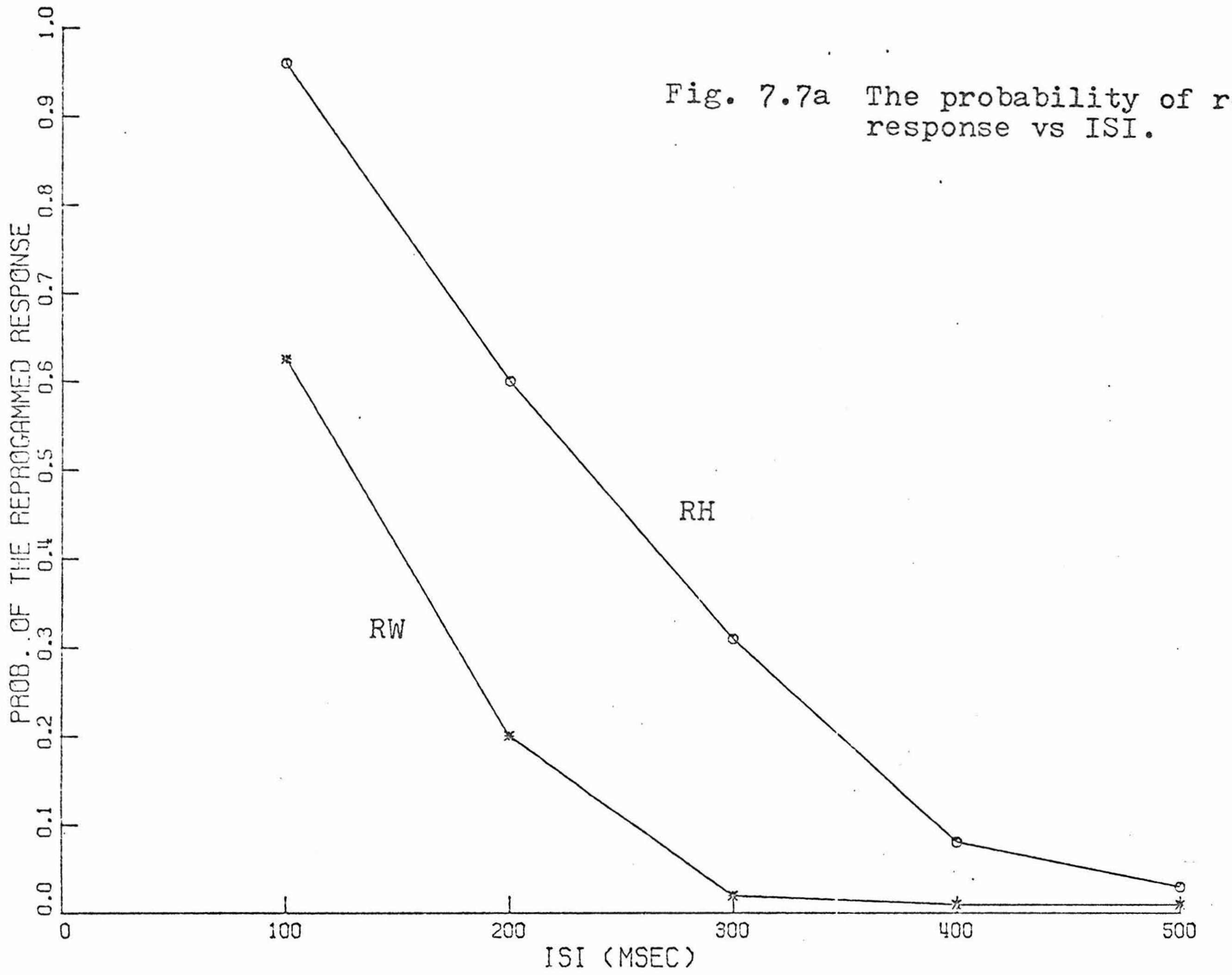


Fig. 7.7a The probability of reprogrammed response vs ISI.

In this figure, the percentages are plotted against ISI for two subjects. These two subjects showed dramatic differences in the probability of reprogramming a saccade. But RW has much shorter reaction time (458.6 msec vs 650 msec). When target and decoy switch at some ISI value, two subjects may be at the different stages of processing, thus they have different percentages of reprogrammed response. To compare them, the data should be normalized by the average reaction times. As discussed in Chapter IV, a reasonable normalization factor is to divide the ISI by the subject's average reaction time. The percentages are replotted against ISI/ $\overline{RT}$ in Fig. 7.7b. In this figure RW still has lower percentage of the reprogrammed response, but the difference has been reduced. Although there are only two data points which are greater than zero for RW, two curves do show similar shape.

If new information arrives after 36 percent of RH's average processing time, there is only a .5 probability that this information will be utilized to modify the current processing. After 50 percent of processing time, the probability of a reprogrammed response is very slim. For RW, the new information has to come even earlier to have the same probability of a reprogrammed response.

It is assumed that the extra saccadic reaction time in this discrimination task is approximately the time spent by the discrimination process, which corresponds to about 50-70 percent of the total processing time. Since the discrimination process logically precedes the

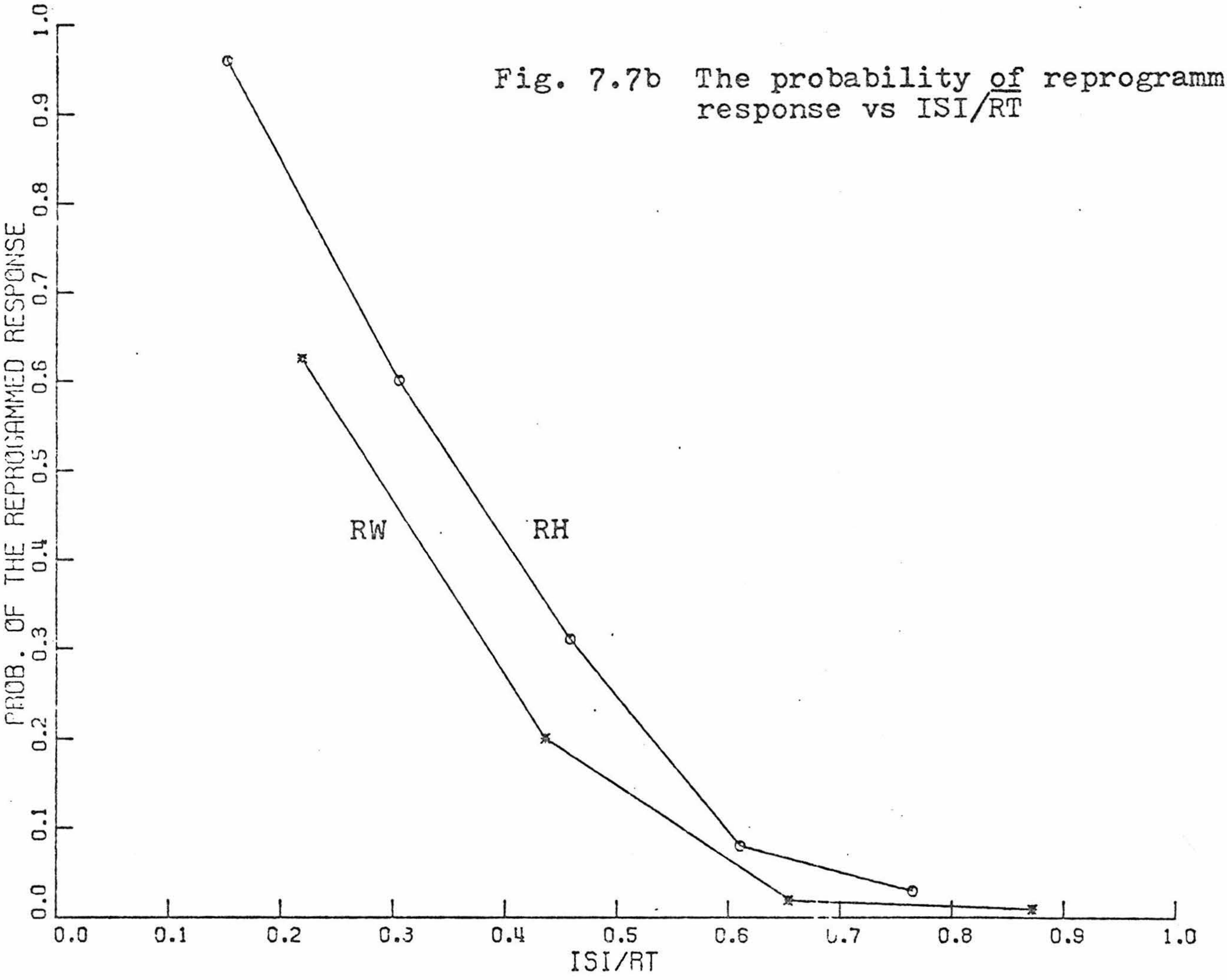


Fig. 7.7b The probability of reprogrammed response vs ISI/RT

direction and magnitude computation process of a saccade, the above data suggested that the new target information which is displayed after the previous target is discriminated is very unlikely to be used to reprogram the response. If there is a critical stage in the information processing, such that the new information which arrives after this stage cannot be used to reprogram the response, this stage seems to exist before the completion of the discrimination process.

Comparing with the results of the experiment using the single spot stimulus in Chapter IV, the probability of reprogramming a saccade is higher for the single spot stimulus than for the discrimination stimulus, if we compare them on the basis of ISI/ $\overline{RT}$. This is probably because the target cue is much weaker in the discrimination task.

7.4.2.3 Reaction times

The reaction times of the saccades in this discrimination task may tell us more about the discrimination process and the saccadic programming. The definitions of various reaction times are as follows:

RT is the reaction time of a correct saccade response to the target when there is no switch.

RT_r is the reaction time of the reprogrammed saccade to the target after the switch.

RT_1 is the reaction time of the initial saccade to the target before the switch in the two-saccade response.

RT_2 is the reaction time of the second saccade to the target after the switch in the two-saccade response.

RT, RT_r, RT_1 and RT_2 are all measured from the onset of the display of the first target/decoy pair. Figure 7.8a,b shows the $\overline{RT}$, $\overline{RT}_r$, $\overline{RT}_1$ and $\overline{RT}_2$ as functions of ISI.

$\overline{RT}_r$ for RH increases with ISI and the slope is close to one. In other words, when an old response is reprogrammed due to new information, it takes about the same time to generate a reprogrammed saccade, no matter when the new information arrives. For RW, $\overline{RT}_r$ also increases with ISI, but the slope is much less than one. Because there are only two reliable data points for him, it is difficult to estimate the slope. From the figure it is found that $\overline{RT}_r$-ISI is less than $\overline{RT}$ for all ISI's and it is true for both subjects. This means that the processing time for a reprogrammed saccade, measured from the time that target and decoy switch, is shorter than the average reaction time of the control task. This suggests that the reprogrammed response can use some processing results from the previous cancelled response. For the single spot simulus, the results of directional computation can be passed to the new saccadic response. In this task, since the locations of the target and decoy pair do not change, there is no need to redo this processing.

In two-saccade responses, the average reaction time of the first saccade seems to have a break-point in both subjects. Before the break-point $\overline{RT}_1$ is less than $\overline{RT}$, and after it $\overline{RT}_1$ is close to $\overline{RT}$. The break is between 300 and 400 msec for RH and between 100 and 200 for RW. Part of the reason is due to the bias in the statistical sampling, because the slower response is likely to be reprogrammed. This explanation is

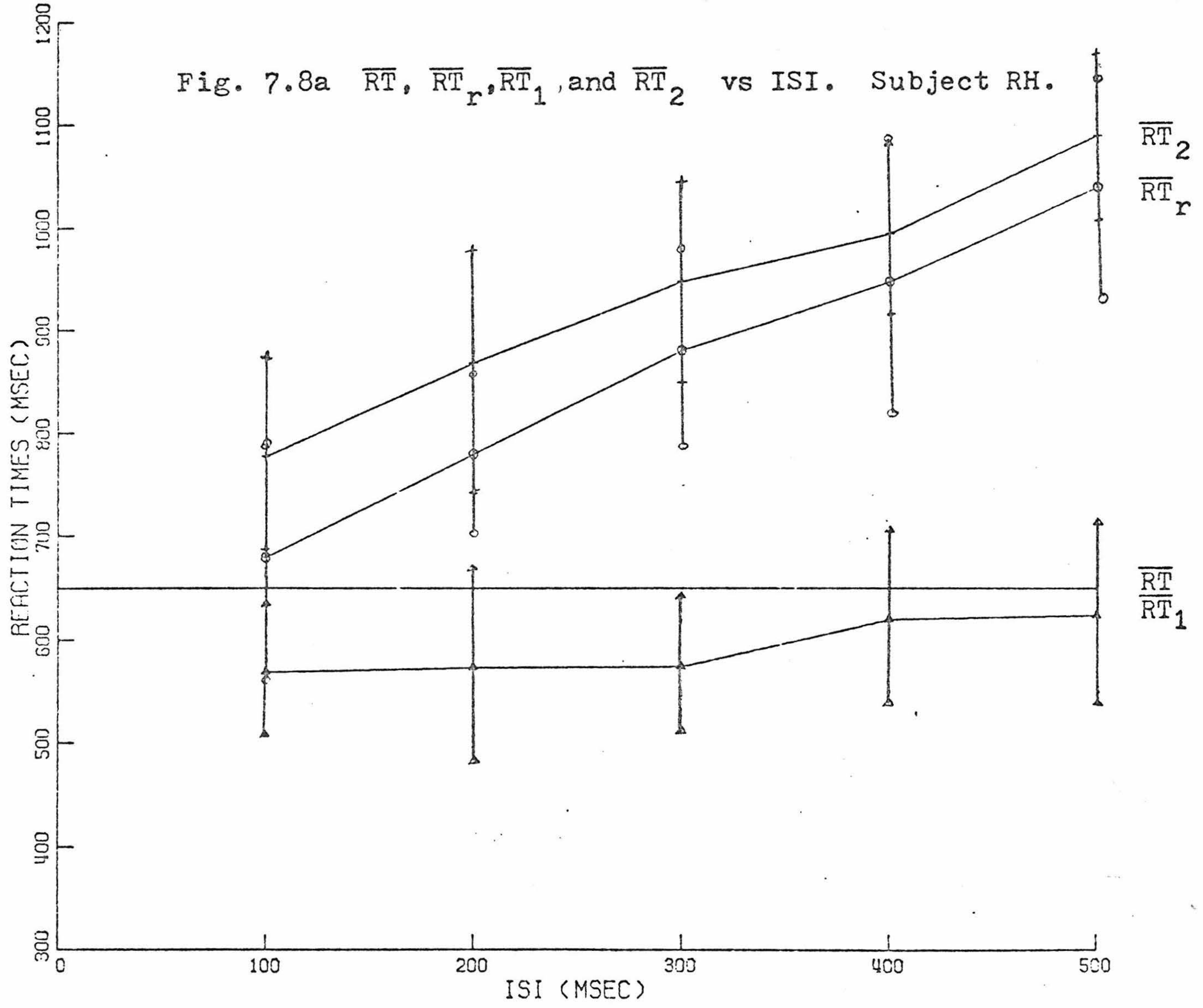
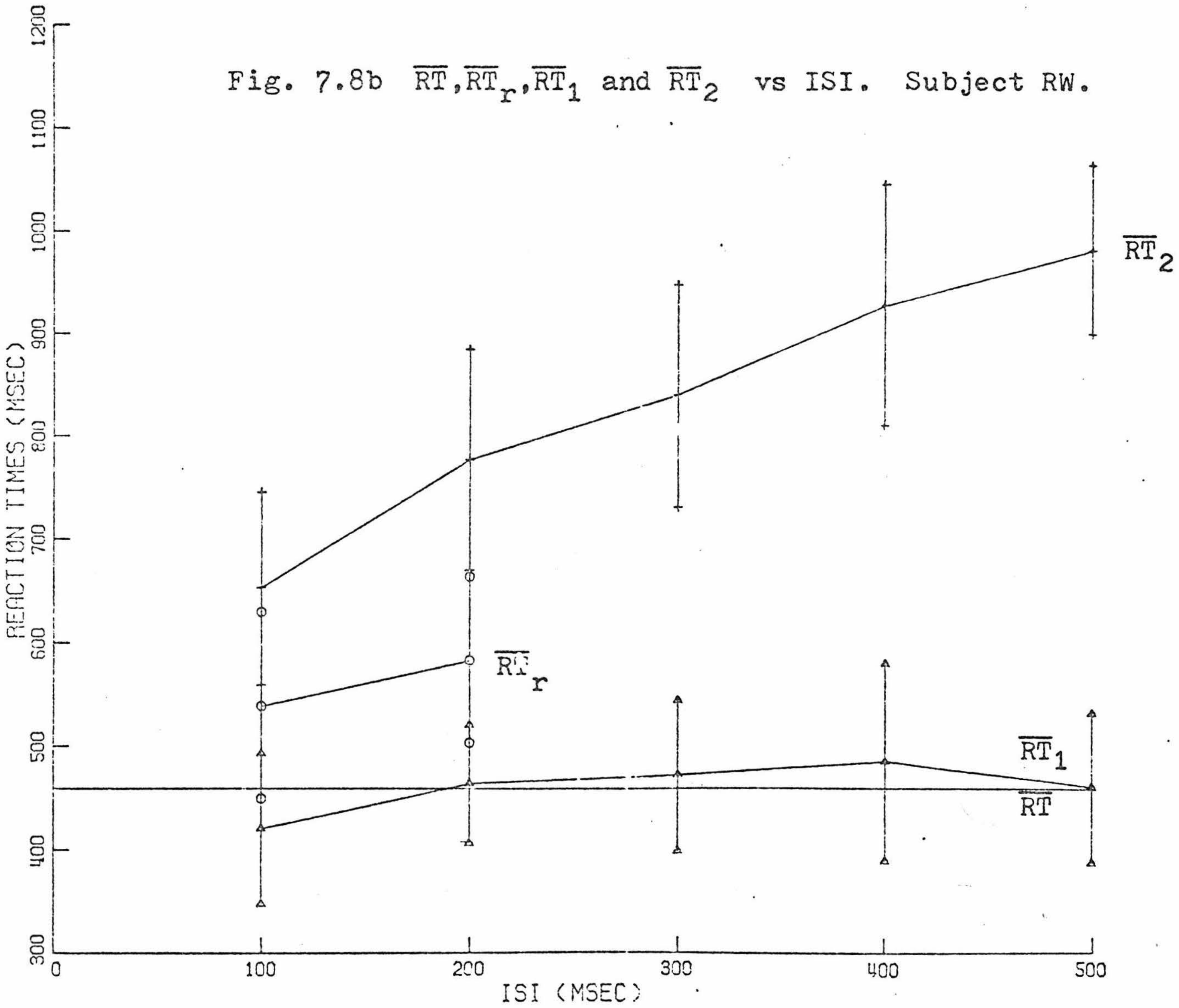


Fig. 7.8a $\overline{RT}$, $\overline{RT}_r$, $\overline{RT}_1$, and $\overline{RT}_2$ vs ISI. Subject RH.

Fig. 7.8b $\overline{RT}, \overline{RT}_r, \overline{RT}_1$ and $\overline{RT}_2$ vs ISI. Subject RW.



consistent with the data. RH has significant reprogrammed response when ISI is less than 300 msec, and for RW, ISI should be less than 200 msec. These are the ISI values where the break exists.

The average reaction time of the second saccade ($\overline{RT}_2$) showed a surprising rising function of ISI. The slope is close to one for both subjects. This means that the first and the second saccadic responses are processed simultaneously, at least when the ISI is equal to or greater than 100 msec. It is surprising because the cue for the discrimination is fairly subtle. When this cue is present, it is picked up immediately by the processing system and starts processing right away. $\overline{RT}_2$-ISI is close to $\overline{RT}$ for RH and about 100 msec more than $\overline{RT}$ for RW.

Conclusion

In this chapter two experiments were done, in which more complex information processing--that is, discrimination of the orientation of Landolt-c-like patterns, is required to make a saccadic eye movement. In this task the subject has to discriminate between target and decoy, then program his saccade to the target. The results of Experiment I showed that the correct rate of saccadic eye movement responses is slightly less than the correct rate of a control psychophysical experiment. Both of them have the same characteristics, such as variations over eccentricity, variations on different meridians, and the effect of orientation of the target and decoy. These suggest that saccadic eye movement systems use a common discrimination process shared by a psychophysical response system for acuity discrimination. When the task requires discrimination, a central control mechanism will connect this discrimination system to the saccadic programming system.

In Experiment II, target and decoy switched at various times during brain processing. It is found that the new target and decoy information is picked up almost immediately after its presentation. This argument is supported by the result that $\overline{RT}_2$-ISI was about the same as $\overline{RT}$ for different switching times (ISI). This new information may be used to modify the current processing, but the new information has to arrive early enough. It has to be in the first 30 percent of the processing time of the previous response in order to have about 50 percent chance of reprogramming. At this time, the system is believed to be still in the discrimination stage. If the previous response cannot be reprogrammed, the new target information is processed simultaneously with the previous response. There was no refractory period even if the two processings were 100 msec apart.

These experiments would seem to show that although the brain has sophisticated capability for acuity discrimination, this information does not have any important role in directing our every-day eye movements. The large variation in the correct rate of saccadic responses may be an indication that this discrimination processing is not generally utilized by the saccadic eye movement system. This is a reasonable speculation because I believe that there is no need to move our gaze to a pattern whose detail can already be discriminated by peripheral acuity; the saccadic eye movement system should always search for unknown features with high information content.

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Appendix: SIMULATION PROCEDURE FOR THE DOUBLE TARGET-STEP EXPERIMENT

This simulation program is designed to find a set of processing times for those saccadic programming processes that fit the experimental results best. In Section 6.4 four time variables were defined: Tdet, Tdir, ΔT, Tex. They are assumed to be independent gaussian distributions. The mean values of these distributions are the parameters to be optimized. The standard deviation of the gaussian distribution is assumed to be one-third of its mean value in order to reduce the number of parameters to be optimized. The mean value of Tex is assumed to be a known value, 20 msec, in the simulation. The constraint is that $\overline{Tdet} + \overline{Tdir} + \Delta\overline{T} + \overline{Tex} = \overline{RT}$.

For a single simulation run, the random numbers $Tdet_1$, $Tdir_1$, ΔT_1 for the first target step, and $Tdet_2$ for the second target step are generated according to their distributions. The simulation program then decides what type of saccadic responses will be generated by this set of processing times. The decision rule is as follows:

(1) $Tdet_2 + ISI < Tdet_1$ or $Tdet_2 + ISI < Tdet_1 + Tdir_1$

will generate the reprogrammed saccade response.

(2) $Tdet_1 + Tdir_1 < Tdet_2 + ISI < Tdet_1 + Tdir_1 + \Delta T_1$

will generate the intermediate saccade response (partial reprogramming).

(3) $Tdet_1 + Tdir_1 + \Delta T_1 < Tdet_2 + ISI$

will generate the full two-saccade response.

This type of simulation run is repeated 1000 times and the percentages of three types of responses are obtained. These percentages are compared with the experimental results to judge the goodness of fit. The criterion for the goodness of fit is to minimize the error term defined as:

$$\text{Error} \equiv \sum_{\substack{i:\text{three}\\ \text{ISI}\\ \text{values}}} \; \sum_{\substack{j:\ \text{three types}\\ \text{of saccadic responses (reprogrammed saccade}\\ \text{response, intermediate saccade response, full}\\ \text{two-saccade response)}}} \frac{(Pij - Rij)^2}{Pij}$$

where Pij is the simulated percentage for the j type of saccadic response and i ISI value.

Rij is the experimental result for corresponding i,j value.

A standard minimization routine was used to change the parameters (the set of mean values of the normal distribution Tdet, Tdir, T) in the maximum gradient direction. Because of the small perturbations existing in the statistical simulated results, the optimization procedure converges extremely slowly if it ever does. Therefore, this minimization routine was used only to obtain a rough estimate of a set of mean values. The finer optimization was done by human control, that is, I adjusted the parameters, then did 1000 simulation runs and checked the error. The simulation was terminated when it did not seem to improve the error any more.