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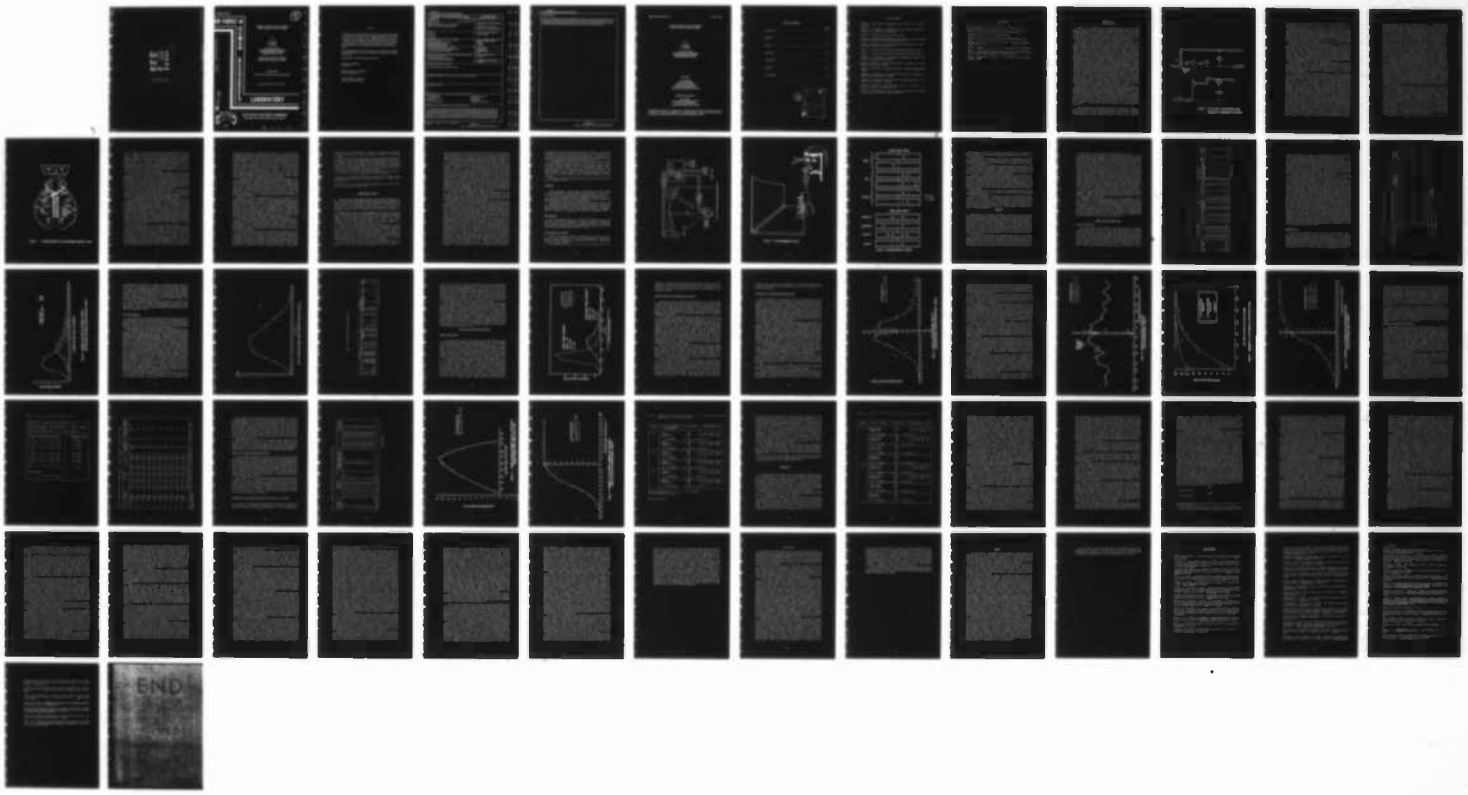

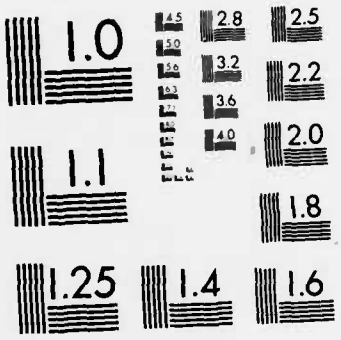

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TEMPORAL ASPECTS OF EYE MOVEMENT WHEN VIEWING MULTIPLE TARGETS

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A technique of eye position measurement and analysis was used to investigate the time necessary for processing visual information by comparing the mean response latency time of single targets to the response means of other novel stimuli. In all cases, stimuli were visual, context-free, point source targets, randomized for type, order of appearance, and time course. The separation of the visual fields is exploited to selectively present targets to either or both hemispheres. An asymmetry in single target left-right response latency time was observed in nearly all subjects. In all cases, there was a significant increase in response latency time when targets were presented to each hemisphere

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simultaneously. Delayed bihemispheric stimulation produced changes in response latency that were similar in both directions and the response latency increased still further when targets were presented sequentially. These studies helped to determine the timing of events prior to the execution of a saccade. The single and bihemispheric paradigms have also proven useful in studying the mechanisms and organization of visual information processing.

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INTRODUCTION

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

The type of eye movement elicited in response to movement of a visual target or scene depends, to a considerable extent, on the spatio-temporal characteristics of the stimulus. For instance, as a person reads, a pattern of eye movements is generated (Zuber & Wetzel, 1981). Following each fixation pause, the eye moves to the next fixation point by a rapid eye movement called a saccade. Similarly, when a person moves his or her eyes between two targets or during visual search and/or pattern recognition, one or more saccades may be executed. In these examples, the saccadic eye movement is under voluntary control and one is usually unable to make more than four or five saccades per second. Figure 1 illustrates a typical saccadic eye movement of 7 degrees. Following a delay of 200 to 250 msec, a rapid angular acceleration of the eyes of up to 40,000 deg/sec/sec with peak velocities of up to 1000 deg/sec may occur before midtrajectory. Subsequent deceleration and velocity braking towards the new fixation point often exhibits dynamic overshoot generated by the neurological control signal (Robinson, 1964; Bahill, Clark, & Stark, 1975). The saccadic duration is related to the target displacement angle and normally lasts between 20 and 50 msec (Robinson, 1964). If the target eccentricity -- the difference between the center of the fovea and the retinal target image -- exceeds about 0.3 degree, the angle subtended by the central fovea, an error-correcting saccade occurs. This secondary saccade, which further reduces the error, follows after a latency shorter than the regular saccadic refractory period .

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

A knowledge of the spatio-temporal stimulus pattern can reduce or eliminate the latency time through mediation of a predictor operator (Stark, Vossius, & Young, 1962; Saslow, 1967, Bahill; 1982). Hackman (1940) showed that, while individual subject results were not always

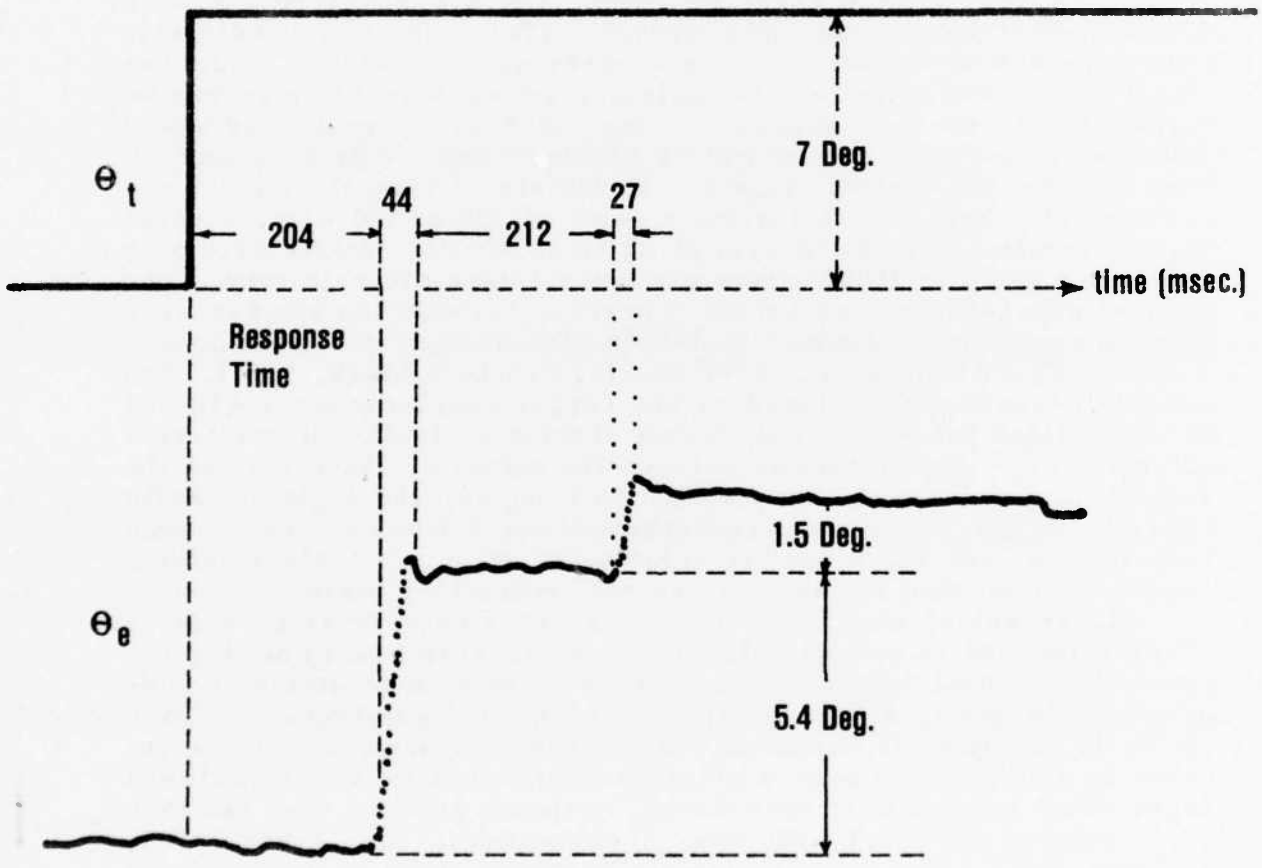

Figure 1 STEP TARGET DISPLACEMENT AND SACCADIC EYE MOVEMENT RESPONSE

consistent, his pooled results revealed a trend of decreasing latency attributable to the effects of practice and familiarity with the experimental conditions.

Bartz (1962) and White and associates (1962) demonstrated that response time increased with the number of possible targets. Hackman (1940) claimed latency would decrease with a knowledge of their location. In contrast, Saslow (1967) found that changing the size of the stimulus set had no significant influence on response latency and attributed the increase found by White (White, Eason & Bartlett, 1962) to the complex sequence of target stimuli and to the complicated instructions issued to their subjects.

The effect of target displacement amplitude and intensity has been shown to increase the saccadic response latency time (Bartz, 1962; Wheeless, Boynton & Cohen, 1966; Uneo, 1977; Uemura, Azrai & Shimayaki, 1980). Response latency was also found to increase slightly when visual target displacements were greater or less than 10 to 15 degrees (Frost & Poppel, 1976; Wetzel, Littlefield & Zeevi, 1982). Frost and Poppel hypothesized that the observed change in response latency as a function of target eccentricity was attributable to the functionally separate modes of information processing in the central and peripheral zones of the visual field.

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

To elucidate some of the timed mechanisms or processes necessary prior to a saccadic response, various stimulus profile combinations involving multiple step and pulse-step target displacements have been presented to subjects (Westheimer, 1954; Bartlett, Eason & White, 1961; White, et al., 1962; Wheeless, et al., 1966; Saslow, 1967; Becker & Fuchs, 1969; Levy-Schoen & Blanc-Garin, 1974; Carlow, Dell'osso, Troost, Daroff, & Birkett, 1975; Lisberger, Fuchs, King, & Evinger, 1975; Taumer, 1975; Frost and Poppel, 1976; Hallett and Lightstone, 1976 a,b; Hallett, 1978; Becker & Jurgens, 1979; Haywood & Churcher, 1979; Hallett & Adams, 1980). A fundamental finding of many of these studies has shown that contrary to earlier findings by Vossius (1960), Young (1962) and Robinson (1973), the saccadic system is not limited to only serial processing of visual information by restricting the number of saccades to only one response per reaction time but can respond in such a manner that suggests preprogrammed or parallel processing of visual information. With the appropriate stimulus profile the saccadic system can initiate a second response with a saccadic interval time shorter than a normal refractory period (Levy-Schoen & Blanc-Garin, 1974; Taumer, 1975; Carlow, et al., 1975). This response often occurs if a corrective secondary saccade is necessary when primary movements greater than 10 degrees are made (Becker, 1972; Hallett, 1978). Such responses imply that the secondary saccade was in preparation while the primary saccade was already

in progress and supports the hypothesis of either a packaged programmed response or of parallel processing of the visual information. As Becker and Jurgens (1979) have stated an important criterion regarding the existence of parallel processing of visual information is the critical amount of time available between the second stimulus step and the onset of the first response. Several studies using a double step paradigm have attempted to determine the allocated time prior to response that can still influence the saccade (Wheeless, et al., 1966; Lisberger, et al., 1975; Taumer, 1975; Becker & Jurgens, 1979). These studies indicate that a change in response direction can be made within 50 to 100 msec from the start of a stimulus, and changes in amplitude can be made up to 100 msec. Although the critical interval times for the decision making mechanisms have been determined with some degree of consistency among the investigators, the actual amount of time for decision making is not generally known. Furthermore, given that a change in target direction or position occurs within a critical period of time, the likelihood or probability that the change will influence the response has not been determined.

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

For most right-handed persons, spatial abilities are lateralized in the right hemisphere, while verbal skills and fine control of motor movement are lateralized in the left hemisphere (Sperry, 1974). The human nervous system is organized such that each hemisphere receives information primarily from the opposite side of the body. In the visual system the organization is somewhat different. Instead of the right eye being wholly mapped to the left hemisphere and the left eye being wholly mapped to the right hemisphere, the visual system is arranged so that the right visual field of each eye is mapped to the left hemisphere, while the left field of each eye is projected to the right hemisphere. Thus, while the eyes are fixating a central point, stimuli to the right of fixation are projected to the left hemisphere, while stimuli to the left of the fixated point are projected to the right hemisphere. A simplified diagram summarizing these specialized asymmetries between hemispheres is given in Figure 2.

The division of right eye visual field stimulation and registra-

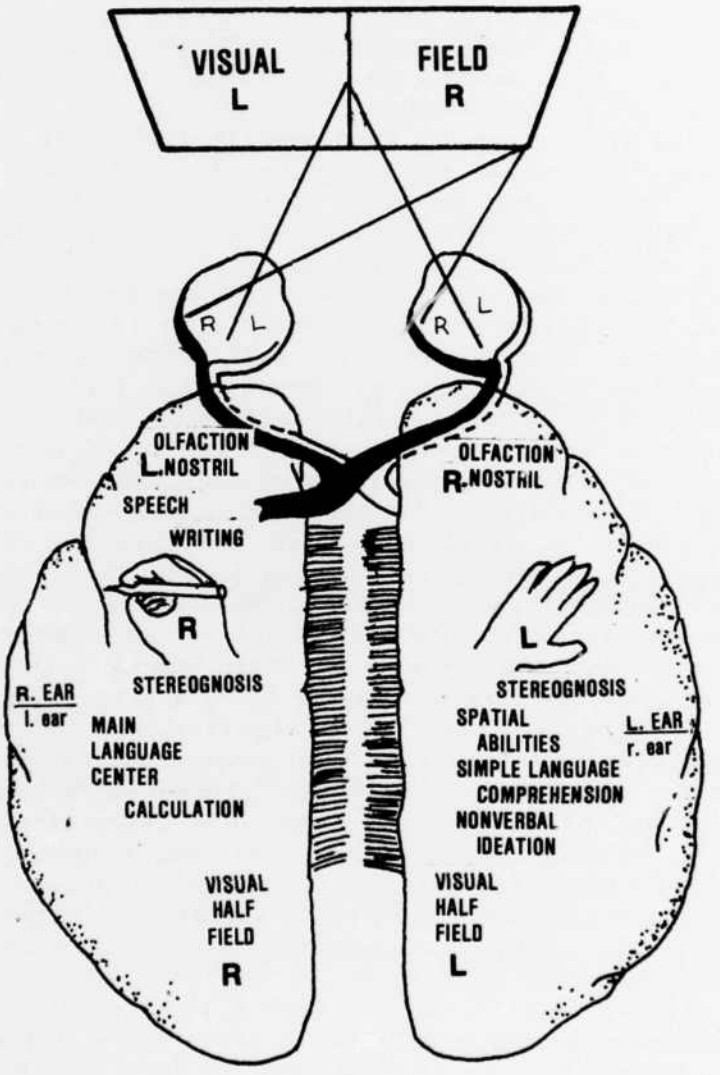

Figure 2 LATERALIZATION OF THE HEMISPHERES (SPERRY, 1974)

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

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

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

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

Because of the specificity of function and processing of certain kinds of information that are often located in one hemisphere or the other, cerebral dominance has been used to describe these functional differences. Differences between geographic and cultural backgrounds in reading between Israelis and Arabs who read from right to left, and Americans and Europeans who read from left to right are supposedly attributable to this hemispheric specialization (Albert, 1975). The left hemisphere is thought to be language dominant and is more skilled at sequential processing and analytical information than the right or spatially dominant hemisphere which is more skilled at synthesizing many different kinds of information. Therefore, when a person who

reads from right to left starts a new line or word, only the left hemisphere is initially activated and according to Kinsbourne (1972) the right hemisphere is inhibited whereas, those who read from left to right develop , with practice and time, an integrated response from both hemispheres. Thus, when a person who reads from right to left is told to look to the right or left, the command activates the left dominant verbal hemisphere, while the left or right spatial response activates the right spatial dominant hemisphere. The dissociation between concurrent verbal and spatial tasks was most clearly seen between left to right and right to left readers. The latter group showed a significantly greater number of initial directional errors and a higher frequency of slower responses than left to right readers. Albert (1975) attributed these differences to the ways in which information was activated and integrated in both hemisphere.

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

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

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

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

informational processing effects. The goal is therefore to determine if these differences can be measured through non-invasive eye movement analysis.

The experiments involved in this study are similar in certain respects to the pulse step and double step experiments of Wheeless et al. (1966) and Becker and Jurgens (1979), except that here the stimuli were double steps or anti-steps and, on many occasions, were presented with no interceding delay between them. These types of experiments should have important implications as to the processing mechanisms involved prior to saccadic eye movement response.

Utilizing a technique of eye position measurement, the objective of this research effort is divided into two major questions:

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

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

APPARATUS AND STIMULI

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

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

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

In all instances visual stimuli were randomized for type -- single or dual target stimuli, direction, displacement, and time course. Targets were binocularly observed in the dark while an

infrared reflectance technique was used to continuously measure horizontal movement of the left eye. To be assured that the eye movement records obtained from each subject were not contaminated with extraneous motion artifacts, several precautions were taken to reduce the effects of head and body movement during the experimental sessions.

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

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

Horizontal eye position was measured by a differential infrared reflectance technique. A DC-driven infrared light emitting diode (LED) light source at 940 nanometers (Texas Instruments TIL33) was used to illuminate the left eye. The infrared radiant output power from the LED was approximately 2.25 milliwatt/centimeter^2 when driven at the normal current of 50 milliamps. A pair of phototransistors (Texas Instruments LS-400) separated by 20 mm were mounted on each side of the infrared emitter and aimed slightly below and to opposite sides of the iris-sclera borders (the limbus) of the left eye. The distance between the photodetectors and eye varied between 10 and 15 mm depending on the length of the eyelashes. With this type of eye movement system, accurate positional measurements were limited to 15 degrees. The phototransistors are part of a balanced bridge circuit configuration. As the eye moves horizontally, photodetector signals proportional to the amount of infrared light reflectance from the eye are differentially summed and amplified to produce an analog voltage proportional to eye position. A first order low pass filter with a cutoff frequency of 1 KHz was placed at the output of the eye movement monitor. At nominal gain settings, typical system noise was less than 2 mV (RMS). Common mode noise rejection was adjustable to 90 dB down. Monitor gain was adjustable from less than one to 180; full scale output voltage was restricted to 1 volt. Horizontal linearity of the system was limited to approximately 15 degrees and was largely dependent on the placement of the infrared emitter and photo-

transistors but could be minimized during a three- or five-point calibration procedure. Horizontal sensitivity was typically 67 mV. per degree. Vertical sensitivity was negligible. Instrumentation parameters over which the experimenter had control were the output gain, phototransistor bridge balance and DC-level output.

Incorporated into the eye movement monitor was a stimulus marker circuit. When desired, this circuit could summate a 5 or 15 msec (switch selectable) saturated pulse with the movement output whenever a stimulus occurred. Under certain circumstances the marker circuit could provide information on direction and type of stimulus. The analog output of the eye movement monitor was sampled by the laboratory peripheral system (LPS), a 12 bit analog-to-digital converter, at rates not less than 100 pts/sec and stored on disk for later analysis.

A diagram showing the experimental setup for the WFD setup is given in Figures 3 and 4.

Procedure

Fifteen subjects, mostly students, participated in various phases of these experiments; at least three of these subjects have participated in nearly all of the experiments spanning almost two years.

Prior to the experimental run, subjects were seated and comfortably positioned directly in front of the display's center target, the EMM was adjusted, and the room lights darkened.

Subjects were instructed to respond to the different target types in a rapid and spontaneous manner. Each subject over the course of the experimental sessions was presented with a minimum of 100 stimuli. Sessions lasted less than 1 hour, and attempts were made to schedule a subject's sessions at the same hour of the day on subsequent visits.

Data Analysis

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

Classification of Stimuli

Visual stimuli were classified according to their initial projection of visual information to one or both hemispheres. Stimuli consisted of single hemispheric or bihemispheric stimuli, examples of which are shown in Figure 5.

Single-target stimuli were used to assess any significant left-

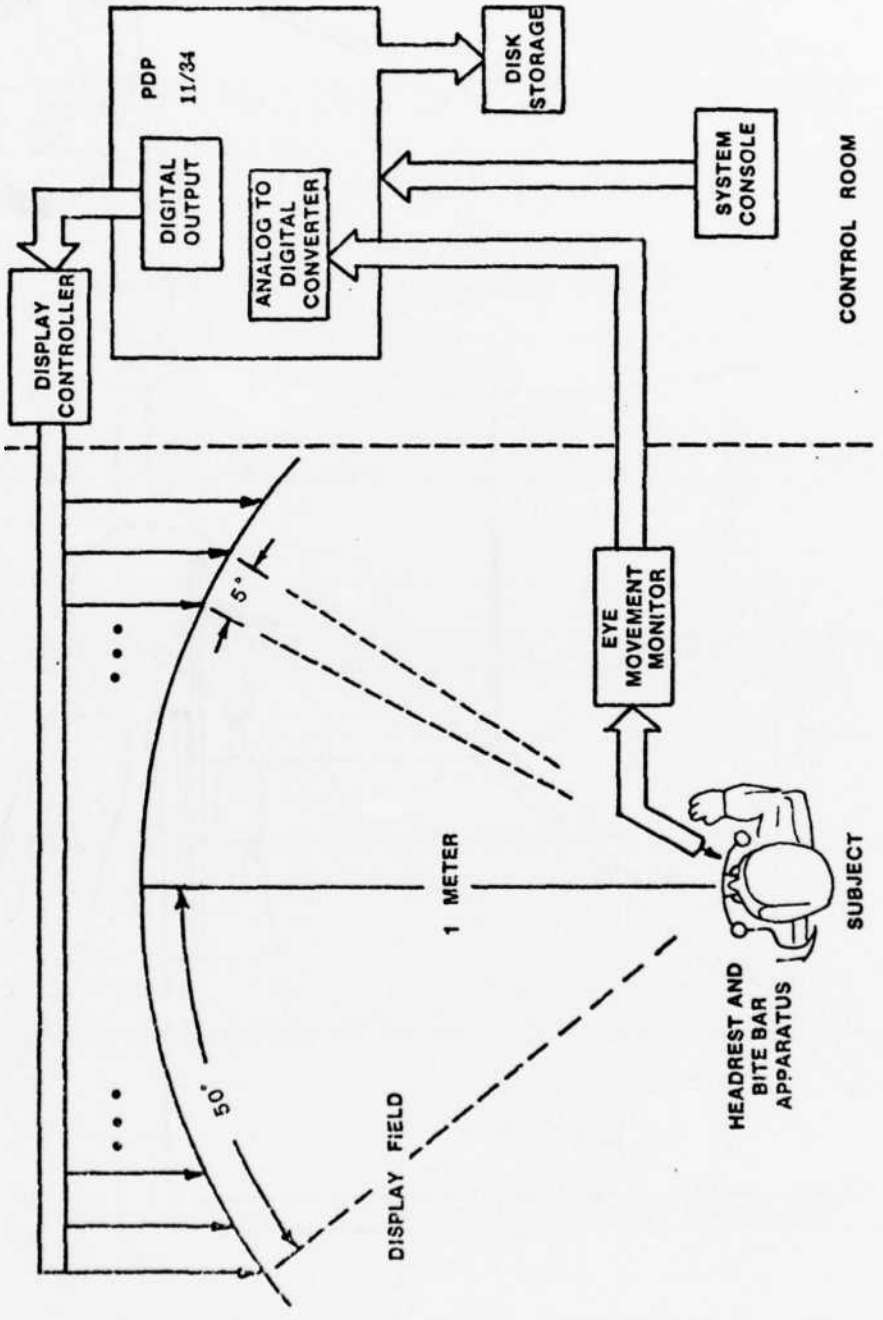

Figure 3 DIAGRAM OF THE EXPERIMENTAL SETUP

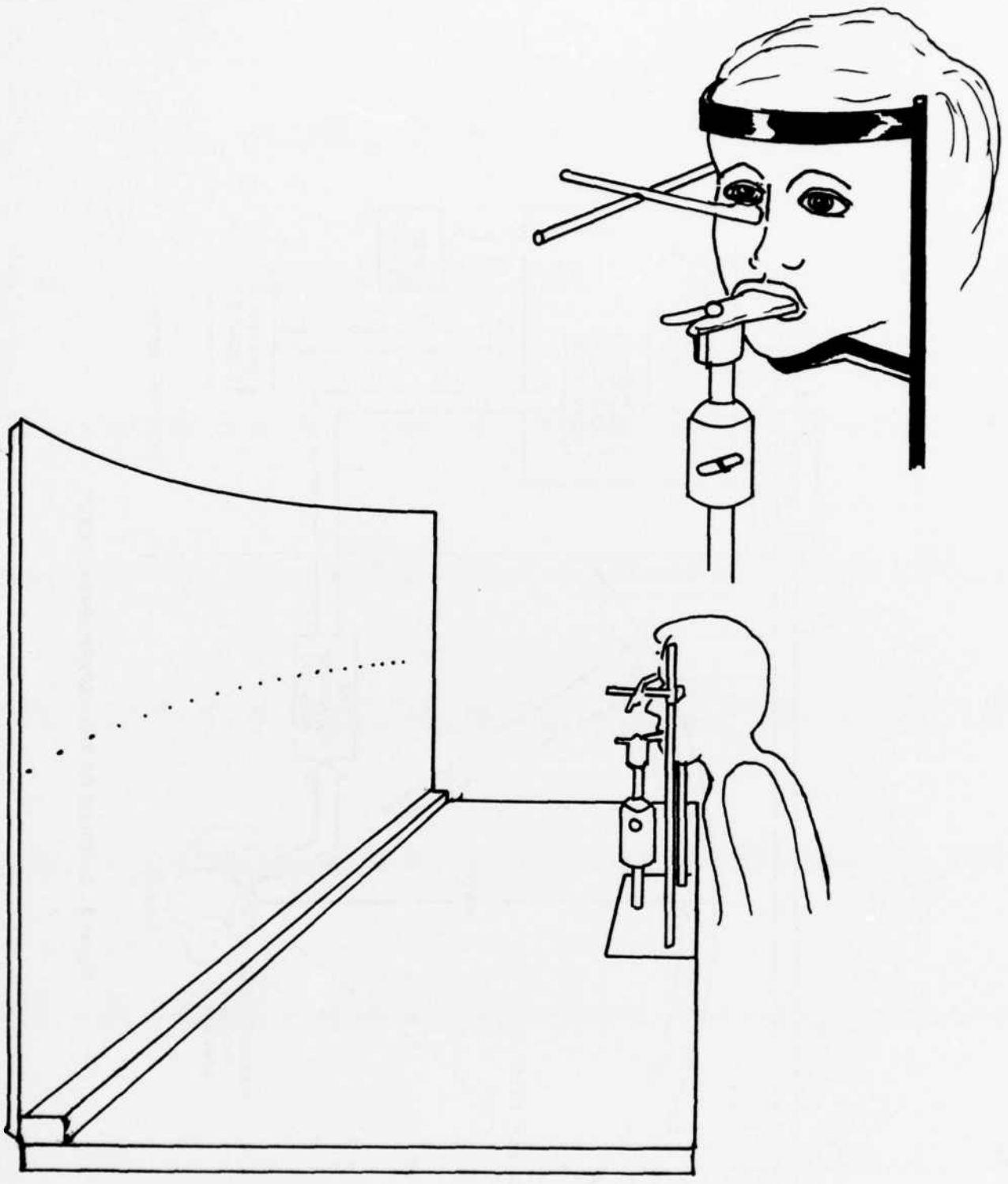

Figure 4 THE EXPERIMENTAL SETUP

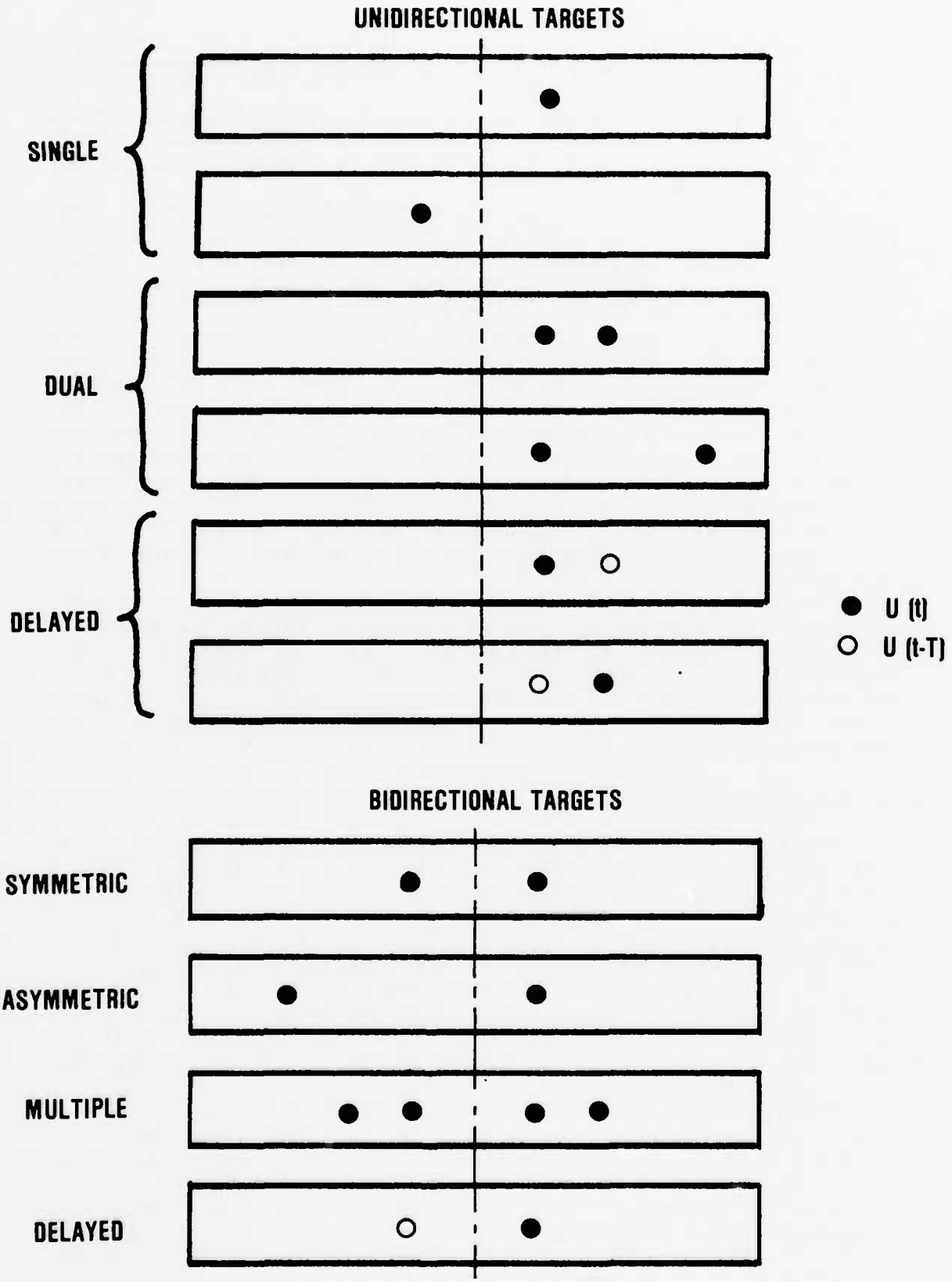

Figure 5 CLASSIFICATION OF STIMULI

right response differences or response time dependency on eccentricity and to serve as a comparative reference for the other types of stimulus response.

Bifurcating dual target stimuli involved either bidirectional (bihemispheric) or unidirectional situations. Bidirectional stimuli were either symmetric, equal displacements, or asymmetric unequal but opposite displacements.

The final class of targets were delayed bifurcation (double step) representations of unidirectional and bidirectional stimuli where one of the two targets was delayed. Targets were delayed in either direction by 10 msec intervals up to 120 msec and 20 msec intervals from 140 to 220 msec. The greatest delay was 250 msec.

The type of stimuli that could be presented on each display was dependent on the sophistication of the display controller. Because the NFD controller was manually controlled by switches, stimuli were limited to symmetrical bifurcations and single target stimuli. The digitally designed display controller, on the other hand, presented none of these limitations and, as a consequence, could present any stimulus pattern desired including highly repeatable inter-target delay intervals.

The response data for each subject were analyzed with the aid of a computer graphics display terminal in conjunction with the SPARTA data analysis program.

For each response at least two pieces of information were recorded: the saccadic eye movement response latency time and the direction of movement. When appropriate, the amplitude of the response was also measured. If the movement was unique or novel indicating false alarms, blinks due to the stimuli, or smooth movements, these occurrences were noted and their location recorded in the file for later examination.

RESULTS

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

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

information concerning asymmetries and directional biases.

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

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

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

Single Target Response Time

Narrow Field Display

The single-target mean response time obtained from 10 subjects (representing a total of 518 left and right displacements on the NFD at 3, 5 and 7 degrees) was 254 ($\pm$76) msec. The mean was calculated without regard to the possible existence of left and right directional differences within subjects and between the left-right sample population means. The single target response mean times varied widely among the 10 subjects who participated in the NFD experiments and were somewhat longer than those reported by other investigators. Subject means ranged from 200 to 300 msec (Table 1). The superposition of such a range of subject-specific response times gave rise to the wide-

Table 1: Summary of narrow field display response data

SINGLE TARGET RESPONSE									BIFURCATION RESPONSE						
SUBJECT	HANDEDNESS	LEFT		RIGHT		DIFFERENCE		COMPUTED t	LEVEL OF ATTAINED SIGNIFICANCE	MEAN ± SD	DIFFERENCE	COMPUTED t	LEVEL OF SIGNIFICANCE	PERCENT INCREASE OVER SINGLE TARGET RESPONSE	RESPONSES LEFT	RESPONSES RIGHT	% PREFERRED RESPONSE
1 BA	R	305	N = 23 ± 38	273	N = 19 ± 83	32	NS	1.465	0.1433	565 ± 759	255	6.106	0.0006	87	11	15	54
2	R	233	N = 27 ± 38	226	N = 26 ± 62	7	NS	0.636	0.5276	330 ± 59	101	10.899	0.0000	66	22	6	79
5	R	242	N = 12 ± 57	216	N = 26 ± 29	16	NS	1.1907	0.2369	299 ± 52	65	4.865	0.0000	28	18	2	90
6	L	244	N = 26 ± 36	118	N = 25 ± 26	26	SIG	3.0790	0.0035	563 ± 96	112	5.079	0.0035	69	16	11	59
5	R	320	N = 25 ± 50	295	N = 29 ± 78	25	NS	1.3420	0.1866	600 ± 106	93	6.160	0.0002	30	5	22	81
6	R	323	N = 27 ± 19	267	N = 26 ± 38	56	NS	1.6691	0.1650	605 ± 202	111	2.509	0.0196	37	19	8	69
7	R	265	N = 26 ± 61	226	N = 27 ± 30	18	NS	1.8028	0.0781	522 ± 51	87	7.997	0.0000	57	2	26	93
8 MB	R	504	N = 28 ± 76	261	N = 26 ± 61	65	SIG	2.6399	0.1190	655 ± 215	172	2.639	0.0117	61	6	15	81
9	R	230	N = 27 ± 66	218	N = 30 ± 77	12	NS	0.8655	0.5216	582 ± 130	159	6.220	0.0000	71	0	29	100
10	R	233	N = 30 ± 36	206	N = 19 ± 41	27	SIG	2.7574	0.0079	506 ± 68	86	2.760	0.0079	38	1	29	97
SAMPLE POPULATION		267	N = 261 ± 85	260	N = 257 ± 58	27	SIG	4.2605	0.0000	579 ± 190	125	12.09	0.0000	49	99	171	80

ALL RESPONSE TIMES ARE GIVEN IN MILLISECONDS

lobed distribution of Figure 6. Thus intersubject variability poses a problem in pooling the data and requires the application of normalization and nondimensionalization, as will be introduced later.

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

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

Further analysis revealed that the differences between left and right response times were significant in only three of these subjects. If the response variances of several subjects had been less, more subjects might have shown significant differences between left and right response time. Of the three subjects whose results were significant, two exhibited differences of less than 27 msec, while the third subject showed a left and right response time difference of 43 msec. Similar findings were obtained when the differences between left-right response direction of three groups formed from the 10 subjects were examined. The first group consisted of the three subjects who showed significant left-right response direction differences. The second group consisted of the remaining seven subjects who individually showed no significant left-right response differences. The third group was a collection of all 10 subjects. In each of the three groups, the differences between left-right response direction were highly significant (Table 2). Response was always faster to the right than to the left. Not surprisingly, the greatest difference between response direction occurred in group one, which was composed of those subjects who individually showed significant differences. When the results of group two were considered collectively they showed a significant difference of 25 msec between left-right response. When the responses of both groups were lumped together, the difference between left-right response assumed an intermediate value between the two groups, of 27 msec.

Normalization

To overcome the difficulties arising from intersubject variability, the individual response latency times of each subject throughout this study were normalized with respect to that subject's single target mean response times. The normalization of subject data permitted the comparison of results between displays and, when appropriate, could eliminate the individual differences between subjects' response time. For its intended purpose, the normalization of individual data incurrred no loss of sensitivity regarding the analysis or

Table 2: Narrow field display left-right response difference

NUMBER OF SUBJECTS	DIRECTION	RESPONSE MEAN ± S.D.	LEFT-RIGHT DIFFERENCE	t	ρ	DIFF. SIG/NS
10	LEFT	$\bar{x}$ = 267 ± 85 ms N = 261	27 ms	4.2603	0.000	SIG
	RIGHT	$\bar{x}$ = 240 ± 58 ms N = 257				
7	LEFT	$\bar{x}$ = 271 ± 95 ms N = 177	26 ms	2.9283	0.004	SIG
	RIGHT	$\bar{x}$ = 245 ± 63 ms N = 177				
3	LEFT	$\bar{x}$ = 260 ± 60 ms N = 84	32 ms	3.9853	0.000	SIG
	RIGHT	$\bar{x}$ = 228 ± 44 ms N = 80				

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

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

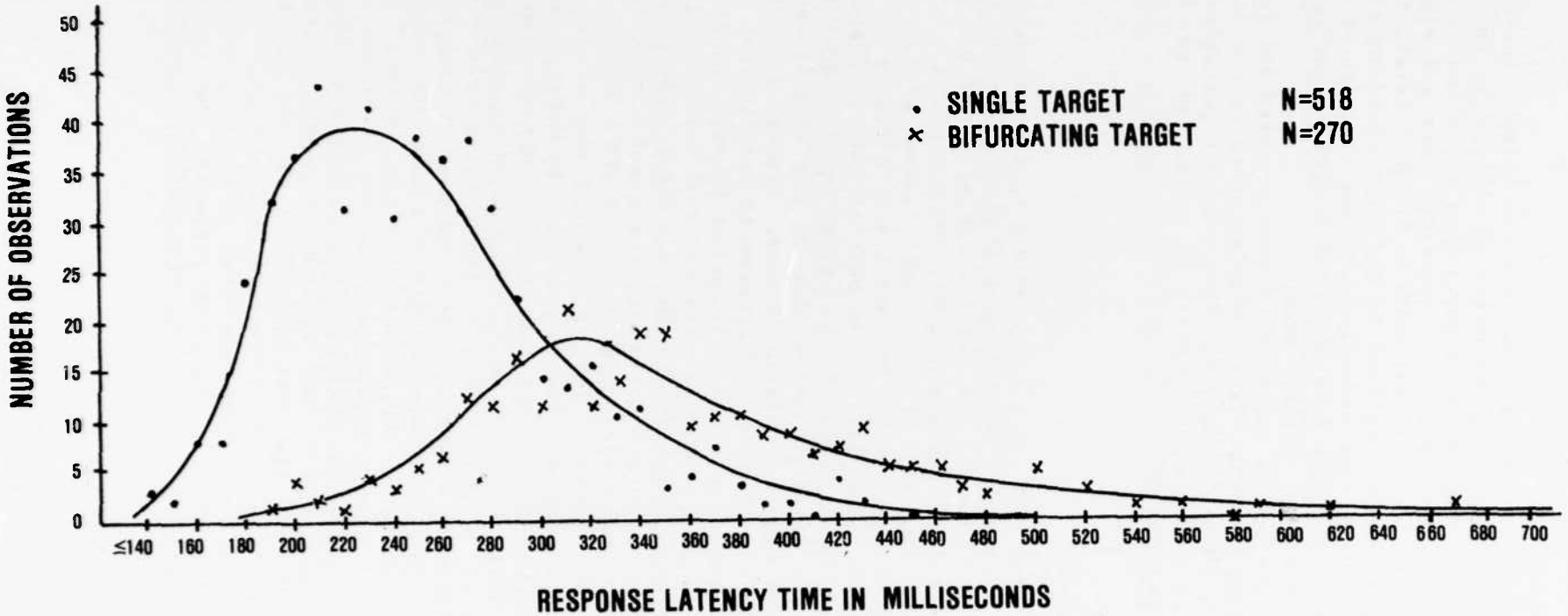

Figure 6 NARROW FIELD DISPLAY RESPONSE LATENCY DISTRIBUTIONS FOR SINGLE AND BIFURCATING TARGETS

interpretation of the results, because the primary interest here was the change in response time relative to the single target response mean, as it occurred when the complexity of the stimulus was changed.

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

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

Wide Field Display

The combined left and right single target mean response time was 211 (±39) msec, some 43 msec faster than for the NFD experimental group and 20 msec faster for the two subjects who had participated before. The frequency histogram distribution of the single target response times for all five subjects resembles the distribution results obtained from the NFD and are given in Figure 7.

The response time differences between the two displays (as shall be later established) were likely caused by distinguishing factors between the two displays rather than by any significant differences between the two sample population groups. Support for this conclusion was offered by the observed differences in results that were obtained from the two subjects who participated in experiments using both displays. One contributing factor may have been that the increased response time associated with the NFD was due to the extra accommodative or vergence control necessary for clear single target vision because of the shorter viewing distance. Another factor involved here may also be the effect of target eccentricity on response latency time. In preliminary experiments performed by Wetzel, Littlefield and Zeevi (1982), an attempt was made to quantify the change in single target response latency time with increasing target eccentricity from 5 to 50 degrees. In that study, the results from three subjects showed that response time varied as a function of target eccentricity, and, furthermore, the response rate of change was dependent on the magnitude of the target displacement angle. From 15 to 50 degrees response latency time increased at the rate of approximately 1 msec per degree of target displacement. A slight decrease in response latency time was observed when target displacement increased from 5 to 15 degrees. Finally, the most significant factor may have been the effect of target luminance on response latency time.

The individual mean response times of the five subjects from the WFD are given in Table 3. Subjects' response latencies extended from 182 to 239 msec and the standard deviations were, in each case, less

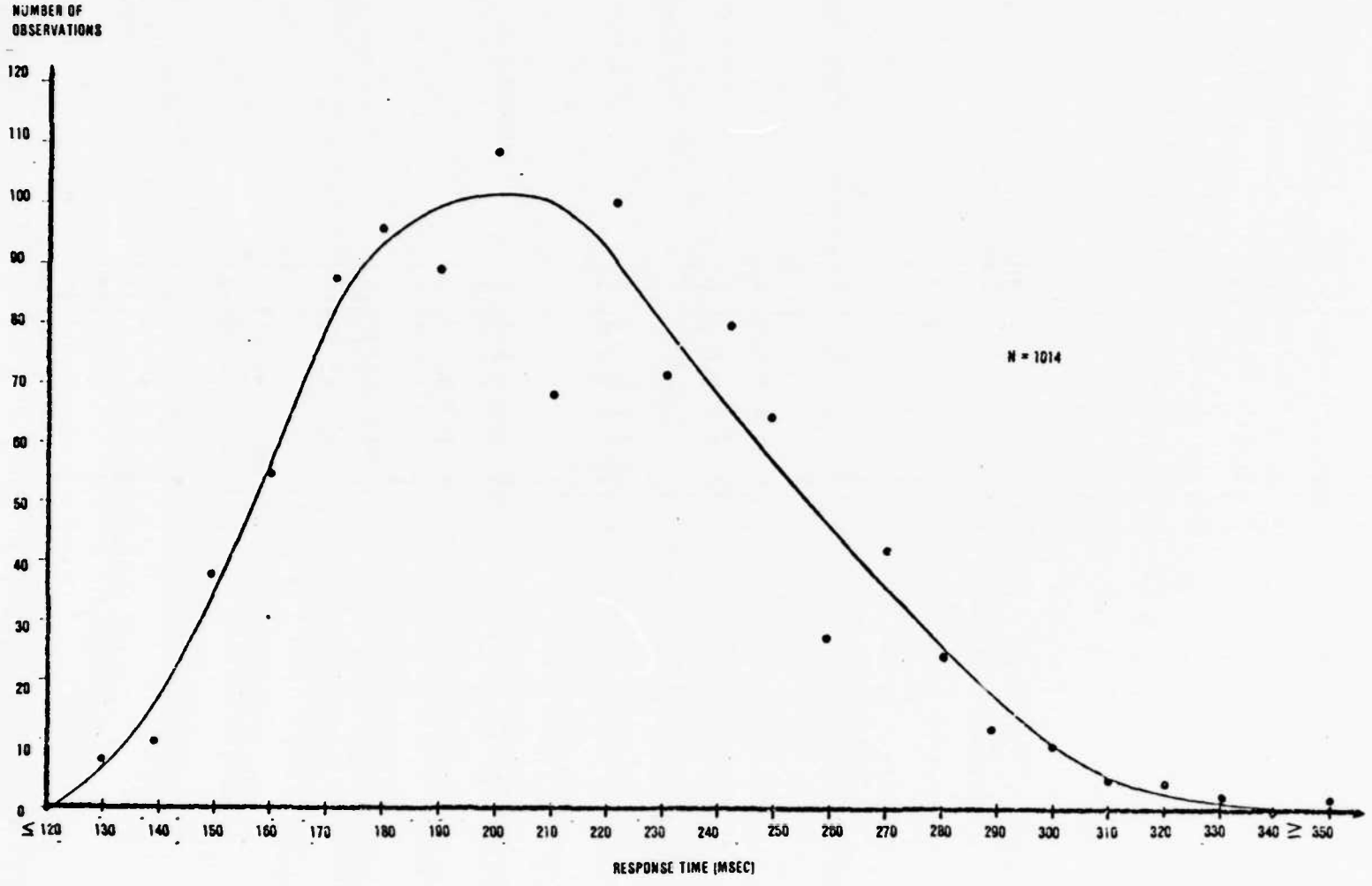

Figure 7 DISTRIBUTION OF SINGLE TARGET RESPONSE DATA FOR WIDE FIELD DISPLAY

Table 3. Wide field display response data

SINGLE TARGET RESPONSE								BIFURCATION RESPONSE						
SUBJECT	HANDEDNESS	LEFT	RIGHT	DIFFERENCE		COMPUTED t	LEVEL OF ATTAINED SIGNIFICANCE	MEAN ± SD	DIFFERENCE	COMPUTED t	LEVEL OF SIGNIFICANCE	PERCENT INCREASE OVER SINGLE TARGET RESPONSE	RESPONSES LEFT	RESPONSES RIGHT	% PREFERRED RESPONSE
		n = 105	n = 105												
11 GC	R	227 ± 55	239 ± 55	12	SIG	2.6410	0.0088	281 ± 41	48	5.999	0.0021	11	10	1	82
		n = 100	n = 105												
12 EM	R	201 ± 34	205 ± 31	4	NS	0.8972	0.5706	227 ± 96	25	0.898	0.3884	11	11	1	92
		n = 99	n = 98												
13 BL	R	195 ± 26	185 ± 36	10	SIG	2.2957	0.0251	220 ± 38	52	2.755	0.0194	17	9	2	82
		n = 98	n = 100												
14 MB	R	224 ± 51	235 ± 52	9	SIG	2.8195	0.0448	271 ± 66	45	2.115	0.0501	17	2	9	82
		n = 98	n = 100												
15 JM	R	198 ± 48	216 ± 42	19	SIG	2.9044	0.0041	251 ± 49	44	5.008	0.0109	21	12	0	100
SAMPLE POPULATION		n = 507	n = 507												
		208 ± 50	215 ± 41	7	SIG	2.8750	0.0042	250 ± 51	59	5.594	0.0000	18	44	14	88

ALL RESPONSE TIMES ARE GIVEN IN MILLISECONDS

than 35 msec, a value considerably smaller than the preceding NFD results. The significant differences that were observed between left-right response in the NFD experiments also existed in four of the five subjects in the WFD experiments. Surprisingly, however, the direction associated with faster mean response was opposite to the previous results. Of the two subjects who participated in both experiments, only BL showed faster response to the right, a finding consistent with the NFD experimental results. With the other subject, MB, differences in response direction were always significant on both experiments; however, response became faster to the left with the WFD.

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

Response to Bidirectional Stimuli

Narrow Field Display

A significant difference of 125 msec was measured between the single and bifurcating target sample population means. Mean response time increased from the single target response time of 254 ($\pm$ 79) msec to the bifurcation response time of 379 ($\pm$ 160) msec, a change equivalent to a 49 percent increase over the single target mean response. The extent of the bifurcation response time increase varied widely among the 10 subjects and ranged from 304 to 544 msec corresponding to increases in response from 38 to 87 percent over the single target response means. In each case, the increase in response time caused by the bifurcating stimulus was highly significant (Table 1).

The population frequency distribution of the normalized response data collected from the 10 subjects is shown for single and bifurcating target response in Figure 8. Comparing the two distributions, the bifurcation response exhibits much more extensive variability due to the larger response variance. The probability of a prolonged response latency was far greater when the stimulus involved a mapping onto both hemispheres rather than a single or unidirectional bifurcation. In no case was there ever a response to a bifurcation that was faster than the fastest single target response. Similarly, there was never a single target response longer than the longest bifurcation

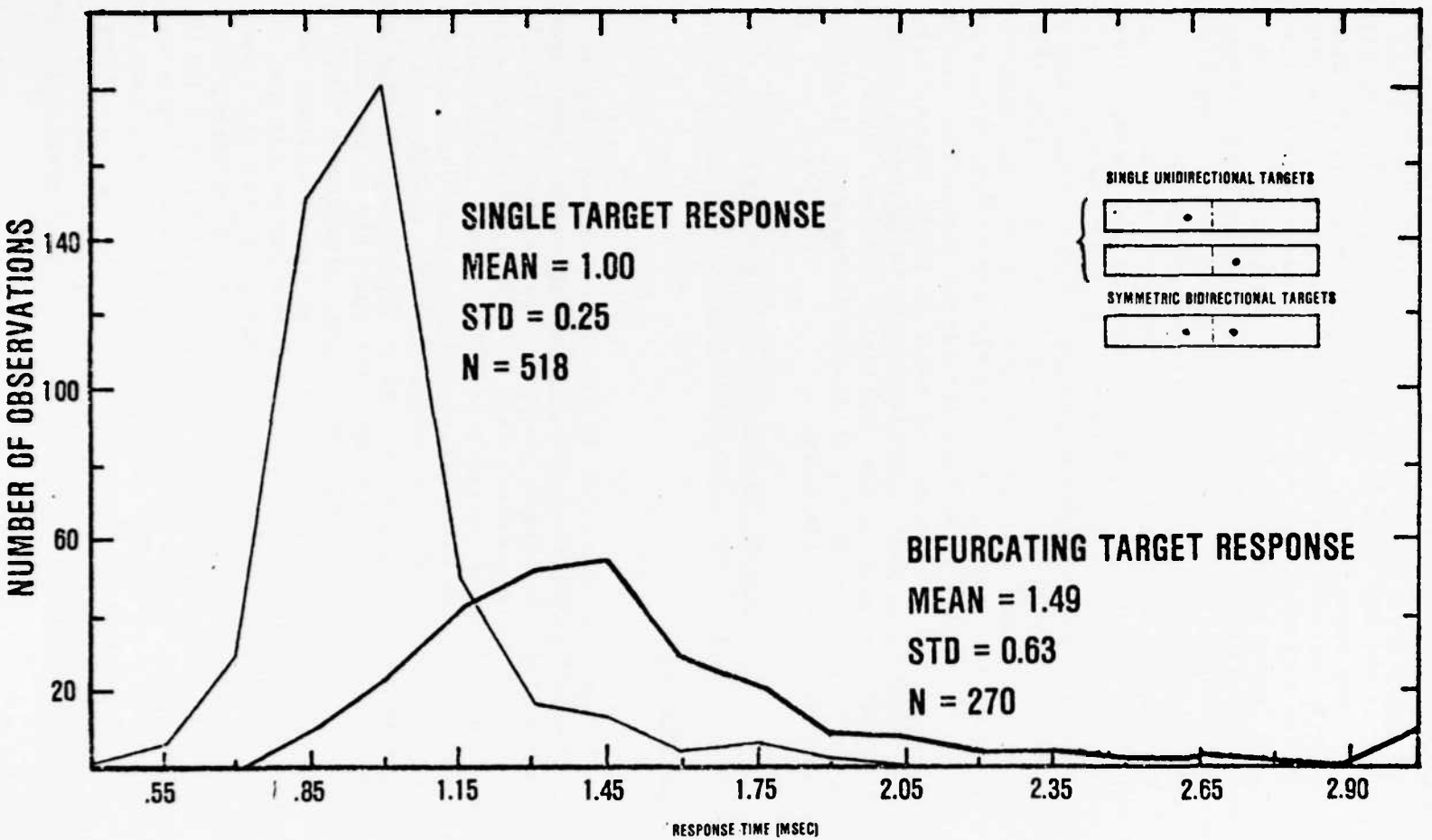

Figure 8 DISTRIBUTIONS OF NORMALIZED RESPONSE DATA (NFD) FOR SINGLE AND BIFURCATING TARGETS

response. The differences between bifurcation and single target response were significant at each displacement angle, implying that the differences were not attributable to effects of eccentricity but, instead, to direction processing necessitated by the difference between the stimuli.

Response Direction to Bidirectional Stimuli

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

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

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

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

shortest single-target mean response time. In this case, response was shorter to the right with the NFD but just the opposite when later tested on the WFD.

Responses to Delayed Bidirectional Stimuli

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

In addition to the delayed stimuli presented to each subject, a certain number of single and non-delayed bifurcating targets were also included as part of the stimuli sequences. The purpose of these non-delayed stimuli was twofold. First, the preferred response direction needed to be established for each of the five subjects, and second, their bifurcation response times needed to be determined. The single-target mean response times were used to normalize the response latencies and eliminate the single target response time differences between subjects. The sample population results and the individual subject response means are all given in Table 3. These results, as well as the percentage of responses in each direction to the bifurcating target, were already given in some detail in the previous sections.

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

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

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

The response time due to a bifurcating stimulus was nearly 40 msec greater than the single target mean response time (Figure 9). The increase in response time from 212 ($\pm$ 39) msec was statistically significant; however, the 18 percent increase was less than the amount

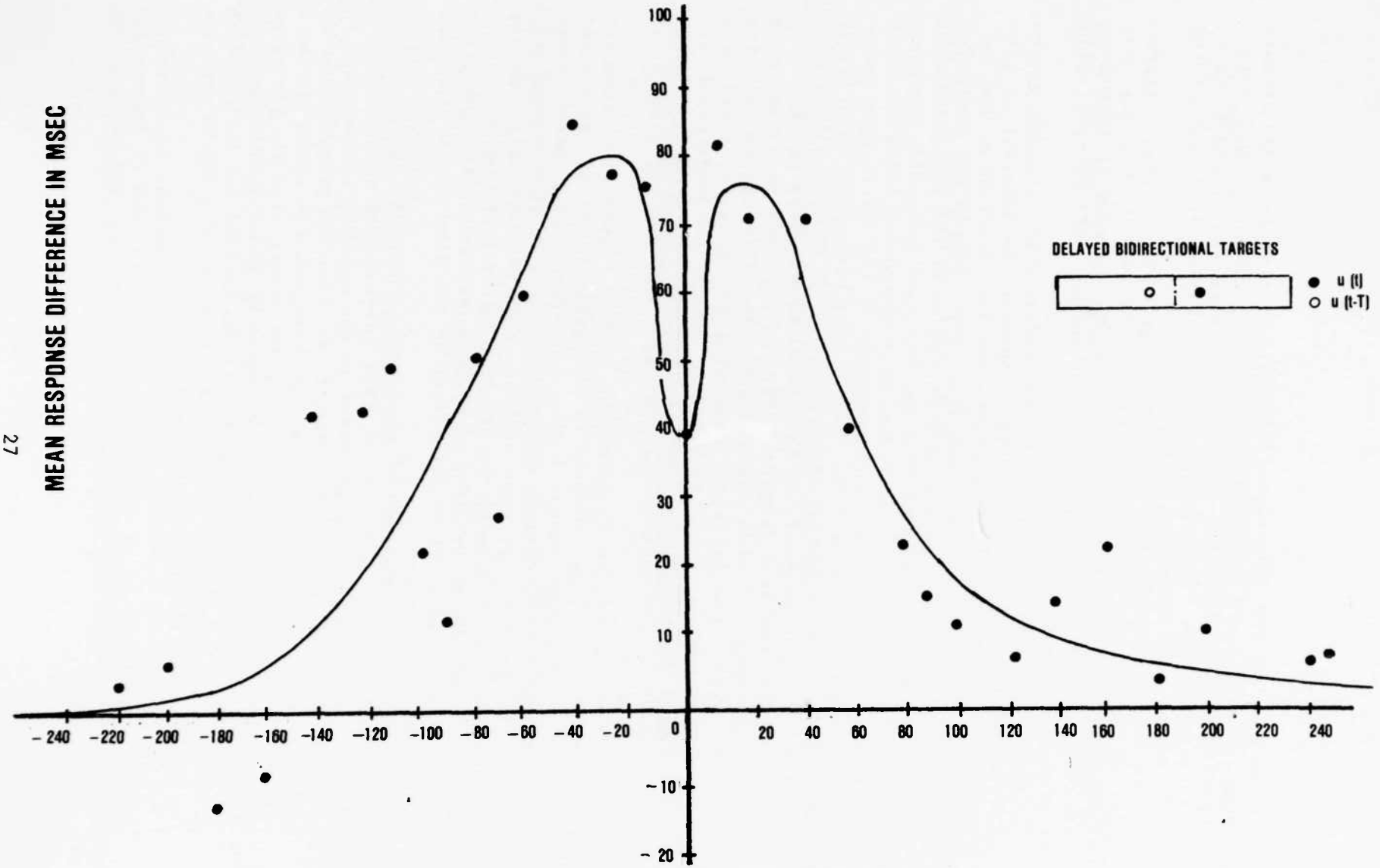

Figure 9 CHANGE IN MEAN RESPONSE TIME AS A FUNCTION OF DELAY BETWEEN BIDIRECTIONAL TARGETS

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

In both directions the greatest change in normalized response occurred within the period of 90 msec. The amount of change was similar in both directions and the differences between identical interval times were less than 8 percent and were not significantly different, as shown in Figure 10.

The probability of response in the preferred or reluctant direction was dependent on the relationship between the interval of time between the appearance of both targets and the direction of the initial target displacement (Figure 11). Response in the preferred direction was more likely when the direction of the initial target displacement and the preferred response direction coincided. Response in the preferred direction continued even though the initial target displacement was in the reluctant direction if the intertarget interval time was less than 80 msec. Beyond this range, the majority of response was in the reluctant direction.

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

The data for Figure 11 were replotted in Figure 12 to show the asymmetry of directional response to bidirectional stimuli as a function of the intertarget interval time. The region of greatest change in the probability of response in the preferred direction occured when the intertarget interval time was less than 80 to 90 msec. Beyond this interval, which included the critical interval of time for directional decision, the probability of response asymptotically approached the limits of probability as determined by the direction of the initial target displacement.

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

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

The procedure was similar to those of previous experiments. Targets were displaced to the left or right 5, 10, and 15 degrees and were either single, bifurcating, or delayed bifurcating stimuli. To

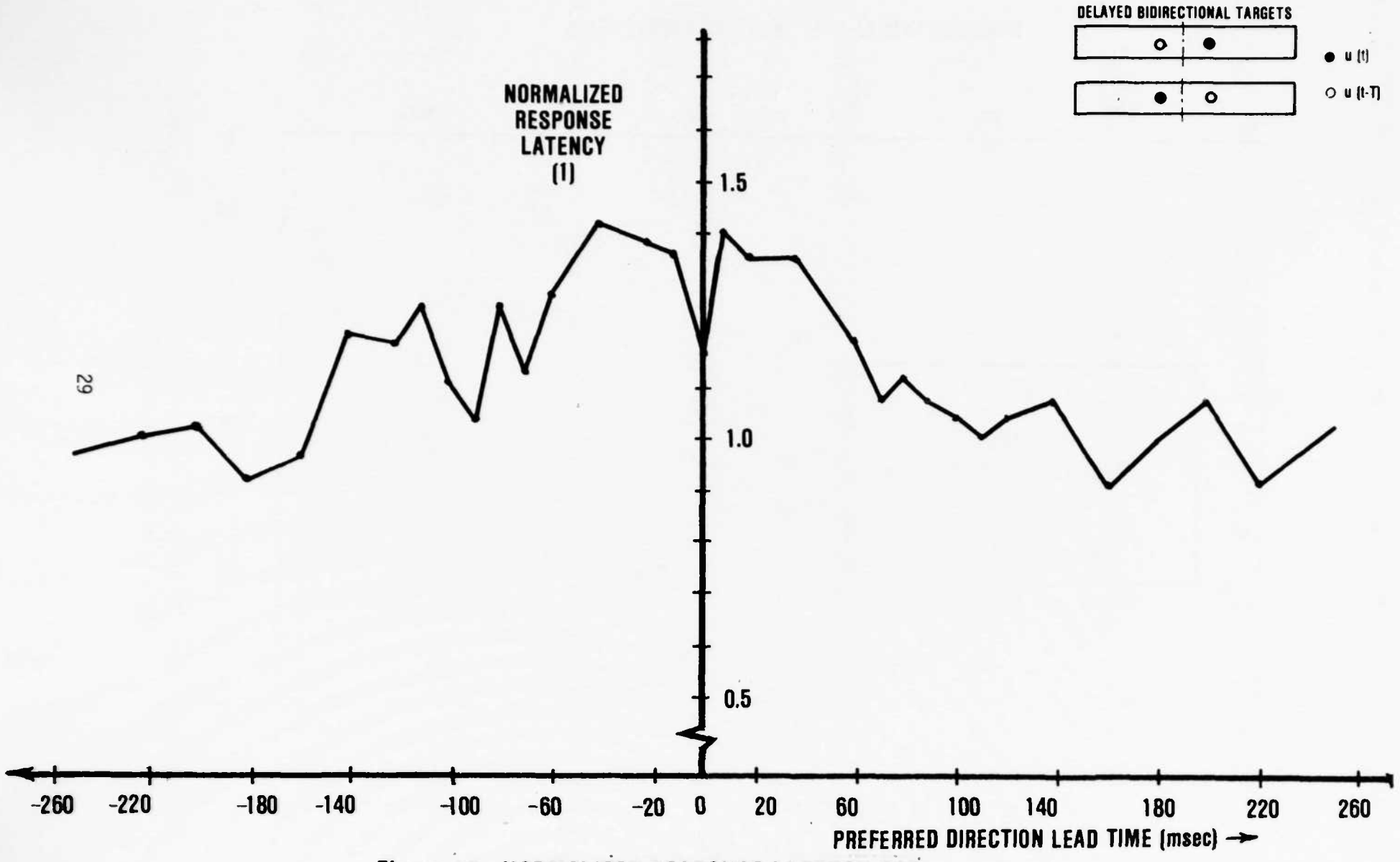

Figure 10 NORMALIZED RESPONSE LATENCY FOR DELAYED BIDIRECTIONAL TARGETS

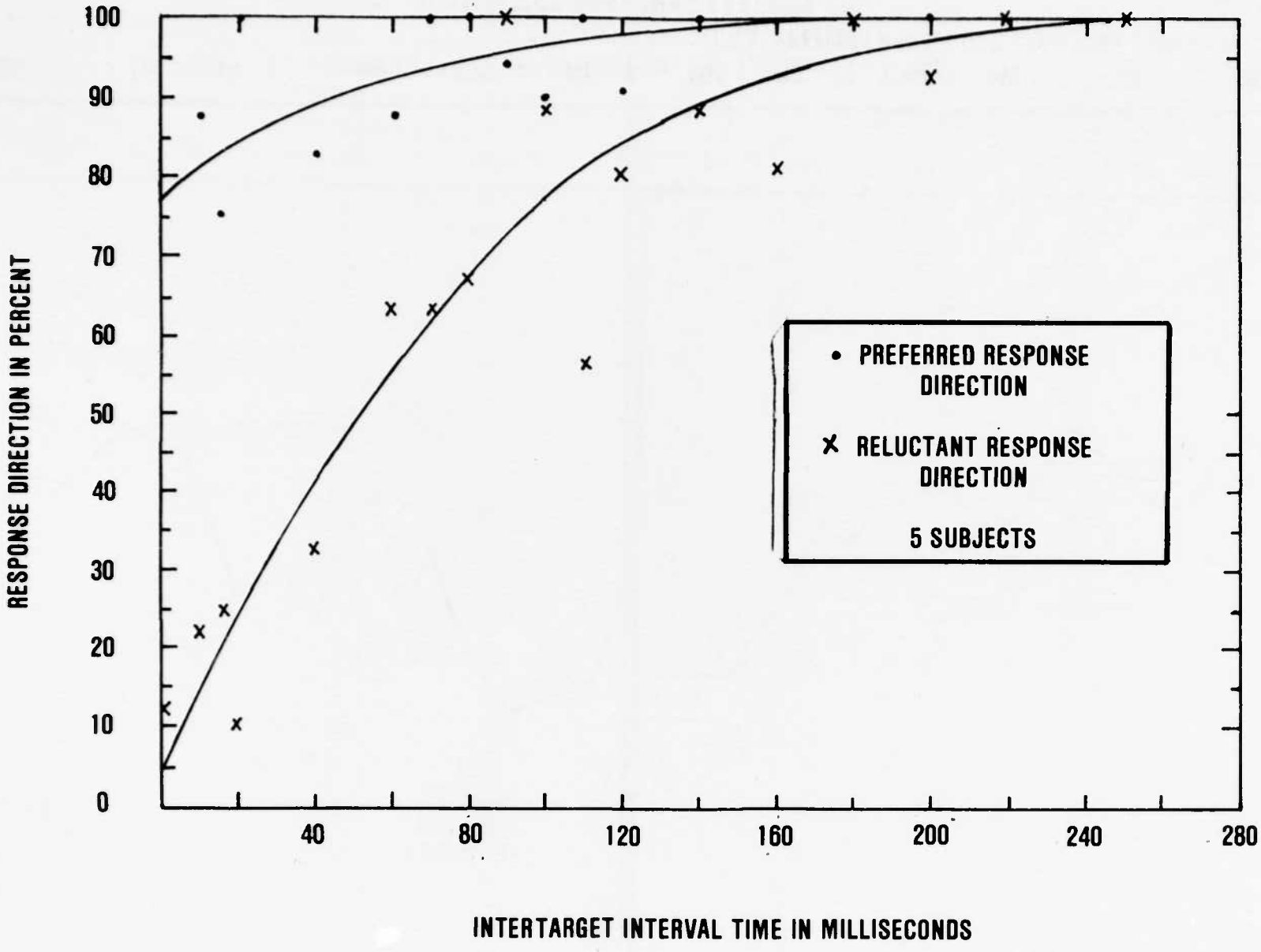

Figure 11 PROBABILITY OF RESPONSE AS A FUNCTION OF DELAY

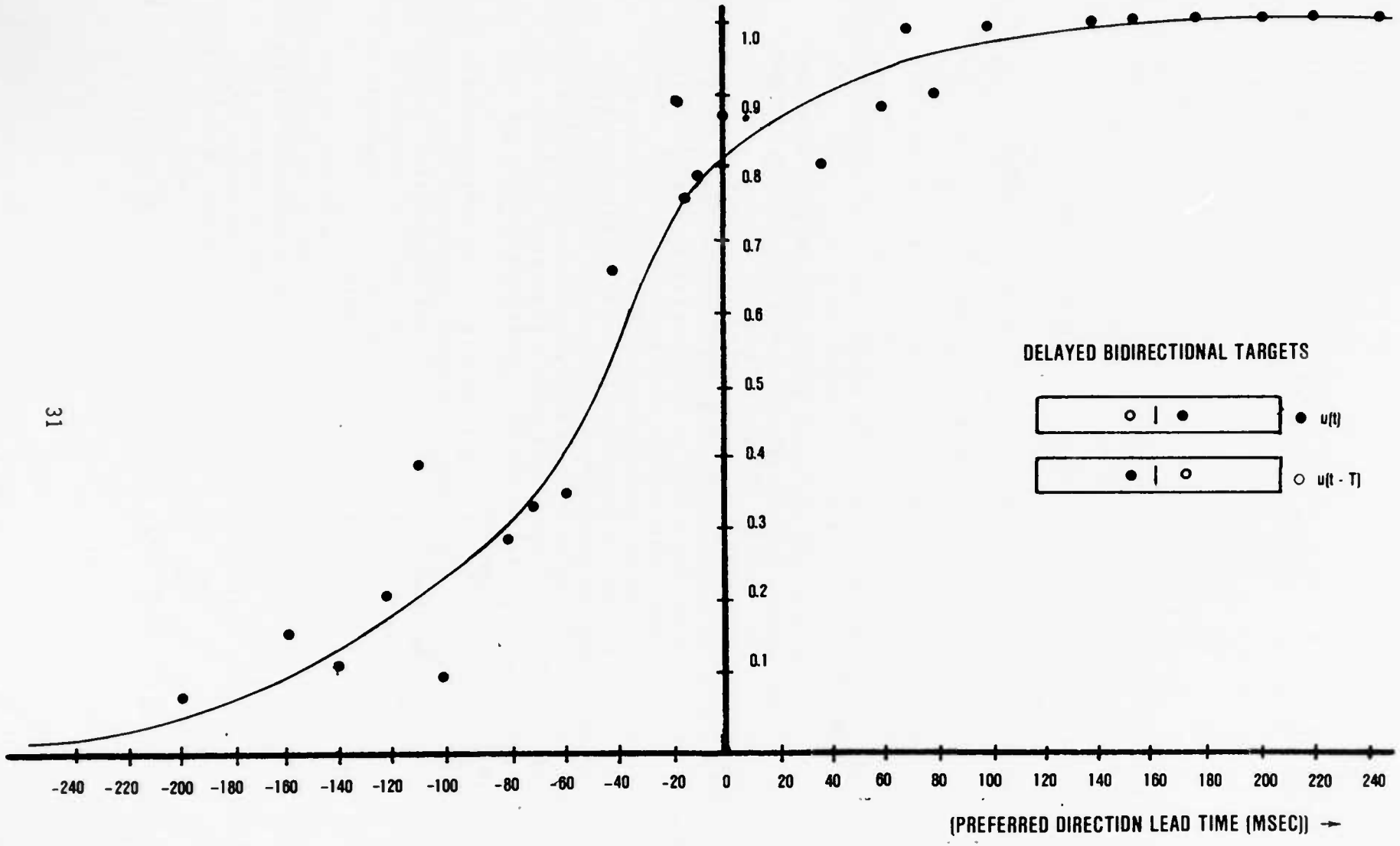

Figure 12 PROBABILITY OF RESPONSE IN THE PREFERRED DIRECTION FOR DELAYED BIDIRECTIONAL TARGETS

create a large sample size about the region of interest, only three delay times of 30, 60 or 120 msec were used. The results for BL are summarized in Table 4 and are quite consistent with previous performance. A difference of 34 msec was measured between the single target response mean and the bifurcation response mean, an increase of 19 percent. Response time increased still further but unequally when the delay was increased. The greatest increase in response latency occurred when the initial target displacement was in the reluctant direction. The effects of delay were inconsequential after 30 msec when the initial target displacement was in the preferred response direction.

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

Response to Unidirectional Stimuli

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

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

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

Table 4. Response to delayed bifurcating targets

SUBJECT (BL): PREFERRED RESPONSE DIRECTION - LEFT TARGET DISPLACEMENT: LEFT AND/OR RIGHT: 5 , 10 AND 15 DEGREES DELAY TIMES BETWEEN TARGETS: 0, 30, 60 AND 120 MSEC	
LEADING TARGET DIRECTION AND DELAY	PREFERRED RESPONSE
R 30 ms N = 28 $\bar{x}$ = 233 ± 31 ms	86 % LEFT
R 60 ms N = 21 $\bar{x}$ = 240 ± 55 ms	48 % LEFT
R 120 ms N = 23 $\bar{x}$ = 196 ± 37 ms	13 % LEFT
L 30 ms N = 25 $\bar{x}$ = 211 ± 31 ms	100 % LEFT
L 60 ms N = 29 $\bar{x}$ = 187 ± 35 ms	97 % LEFT
L 120 ms N = 25 $\bar{x}$ = 184 ± 29 ms	100 % LEFT
0 ms N = 21 $\bar{x}$ = 216 ± 25 ms	95 % LEFT
SINGLE TARGET N = 16 $\bar{x}$ = 182 ± 37 ms	-

Table 5. Unidirectional bifurcating stimuli -- percent response to delayed inner target

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

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

The differences between left and right unidirectional stimuli were not significant when the delay values were the same. The results of these response times at each delay are given in Table 6. The left and right responses at each delay were combined and were then statistically compared to the single target response mean of 206 ($\pm$ 31) msec (N=302). Significant differences between the single and delayed unidirectional response were found only within a narrow range of delays between 60 and 120 msec. On either side of these values, response decreased towards the single target response mean. The maximum difference found between single target and delayed unidirectional response was 22 msec, an increase of 11 percent over single target mean response (Figure 13).

The probability of response to the inner target, the preferred response, is given in Figure 14. The crossover point where the probability of response to the outer target is 0.5 occurs at approximately 100 msec delay. The critical unidirectional crossover delay value is roughly twice the delay value necessary for the equivalent probability of response to the reluctant direction with bidirectional stimuli.

Response to Repeated Bifurcating Stimuli

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

The results from each subject are given separately for each display (Table 7). The experiments with repeated bifurcations resulted in a greater variability. The differences between the mean values of these latencies and those generated by non-repetitive bifurcations were not statistically significant at the 0.05 level. This finding implies that knowledge of a bifurcating event does not affect the processing time; therefore, in future experiments involving bifurcating stimuli, a greater number can be included without affecting the experimental paradigm.

Comparison of Differences Between the New NFD and and the WFD

To explain the response latency differences between the NFD and WFD displays, two hypotheses were proposed. The first considered the differences between the target displacements. The second considered

Table 6 Change in response time as a function of inner target delay

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

FOUR SUBJECTS

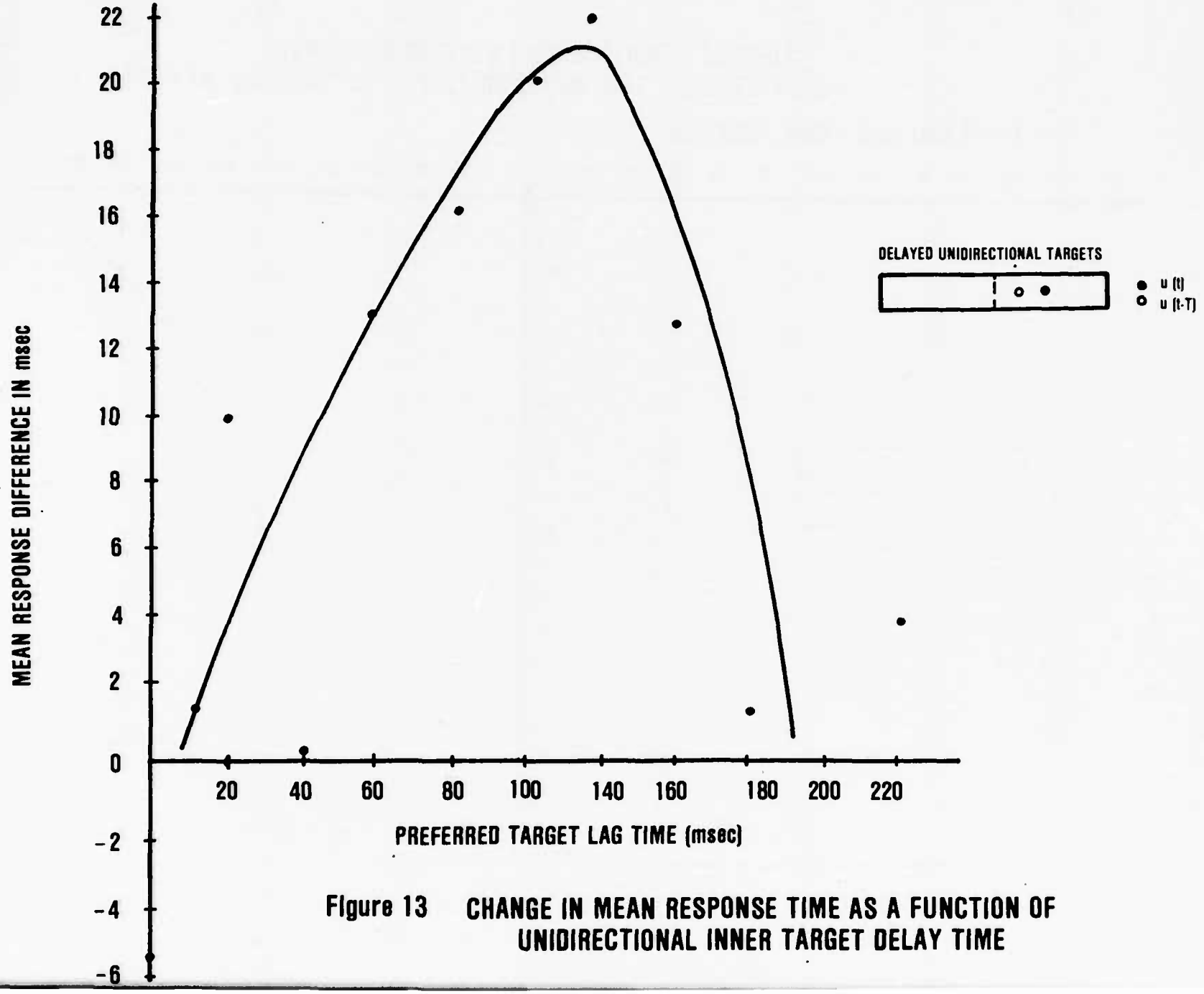

Figure 13 CHANGE IN MEAN RESPONSE TIME AS A FUNCTION OF UNIDIRECTIONAL INNER TARGET DELAY TIME

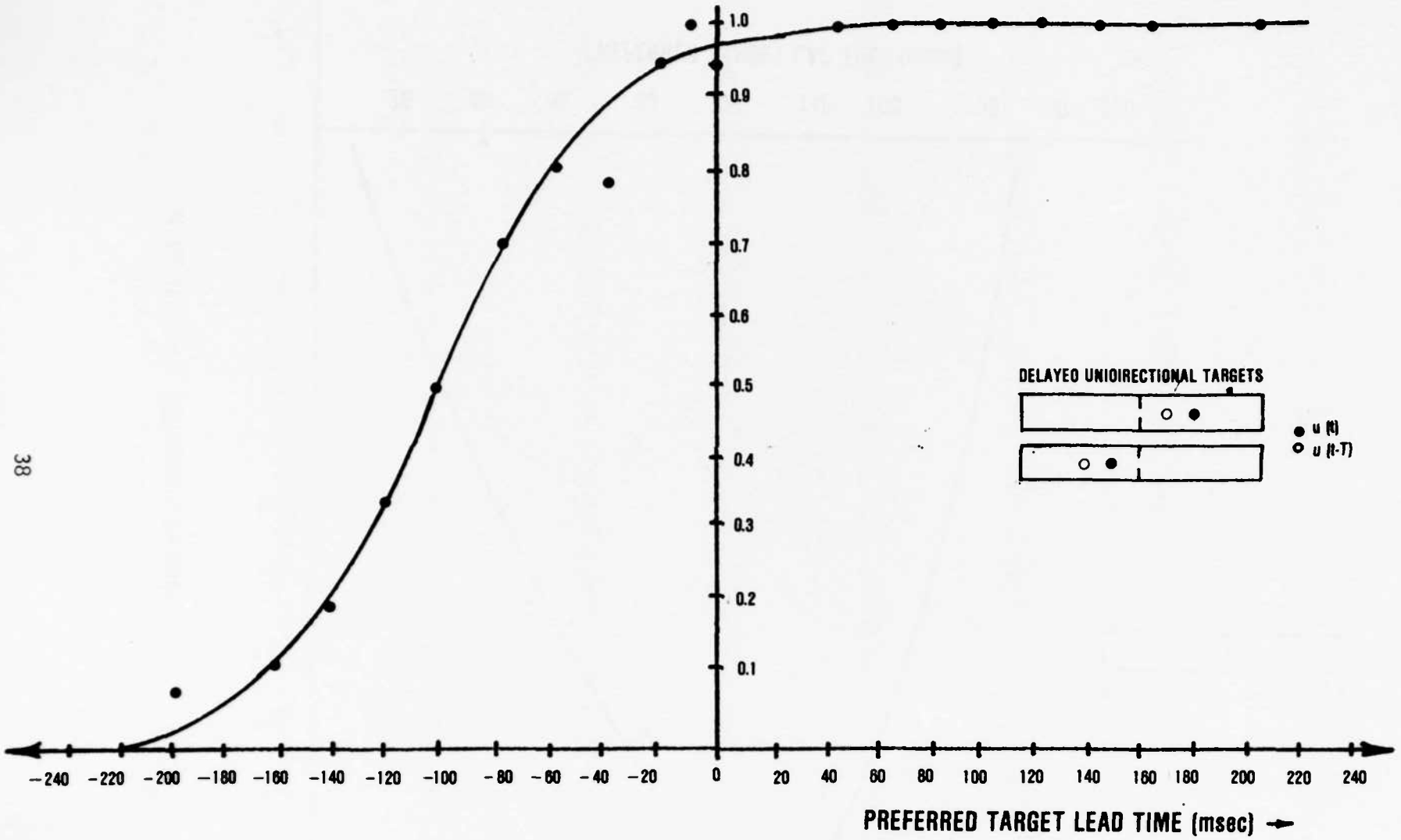

Figure 14 PROBABILITY OF RESPONSE TOWARDS THE PREFERRED TARGET FOR DELAYED UNIDIRECTIONAL TARGETS

Table 7. Comparison of response latency times for random appearance and consecutive presentation of bifurcating targets

SUBJECT	TYPE OF BIFURCATION PRESENTATION	DISPLAY TYPE	RESPONSE MEAN ± S.D.
MB	RANDOM	NFD	N = 27, $\bar{x}$ = 281 ± 43 ms
	CONSECUTIVE	NFD	N = 19, $\bar{x}$ = 284 ± 51 ms
	3 ms DIFFERENCE	t = 0.209, ρ = 0.8357, N.S.	
	RANDOM	WFD	N = 23, $\bar{x}$ = 264 ± 28 ms
	CONSECUTIVE	WFD	N = 20, $\bar{x}$ = 269 ± 50 ms
	5 ms DIFFERENCE,	t = 0.390, ρ = 0.6994, N.S.	
BL	RANDOM	NFD	N = 53, $\bar{x}$ = 232 ± 35 ms
	CONSECUTIVE	NFD	N = 19, $\bar{x}$ = 240 ± 43 ms
	8 ms DIFFERENCE,	t = 0.729, ρ = 0.4723, N.S.	
	RANDOM	WFD	N = 27, $\bar{x}$ = 226 ± 32 ms
	CONSECUTIVE	WFD	N = 19, $\bar{x}$ = 240 ± 43 ms
	22 ms DIFFERENCE,	t = 1.261, ρ = 0.2194, N.S.	
JM	RANDOM	NFD	N = 26, $\bar{x}$ = 307 ± 45 ms
	CONSECUTIVE	NFD	N = 18, $\bar{x}$ = 284 ± 83 ms
	23 ms DIFFERENCE,	t = 1.072, ρ = 0.2944, N.S.	
	RANDOM	WFD	N = 27, $\bar{x}$ = 274 ± 55 ms
	CONSECUTIVE	WFD	N = 16, $\bar{x}$ = 291 ± 78 ms
	17 ms DIFFERENCE,	t = 0.766, ρ = 0.4511, N.S.	

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

NFD: DISCRETE NFD

the effect of distance between the subjects and the display; that is, the hypothesis was that the level of accommodation and vergence could affect the response time to some extent. To resolve these issues, and to investigate further information processing over the central visual field which is mapped onto both hemispheres, a second NFD was constructed. The new NFD was identical in every respect to the WFD except the targets were spaced 1 degree apart when observed from a distance of 1 meter. Three subjects (MB, BL, and JM) were tested for single and bifurcating target response on both the new NFD and WFD. eResponses to target displacements of ± 3, ± 5 and ± 7 degrees were compared to target displacements of ± 5, ± 10, ± 15 degrees. The order of stimulus presentation was the same in both experiments and all efforts were made to collect the data within the same day. The data for MB and BL were collected over a period of two days. The results of these experiments are given in Table 8.

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

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

DISCUSSION

The intent of this research was to investigate, through the continuous measurement of eye position, the allocation of time necessary for the processing of visual context-free information, and the sequencing of events which take place prior to the execution of a saccade, by comparing the response time for single-target stimuli to the response means of other novel stimuli. In pursuance of this task, visual stimuli were presented to subjects which exploited the mapping of the visual fields into the cerebral hemispheres and the cortical organization involved in communication between the hemispheres .

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

The single-target response mean of 252 msec obtained from target displacements of 3, 5, or 7 degrees using the NFD was considerably slower than the frequently reported average of 200 msec obtained for much larger displacements (Westheimer, 1954; Bartz, 1962; Robinson 1964). Single target response latencies obtained from the wide field display were 40 to 50 msec less than those from the NFD and were more consistent with the previous investigators' results. To resolve these

Table 8. Comparison of new narrow field and wide field display response data

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

differences, several hypotheses were proposed, and a series of short experiments were run to test these hypotheses. The effect of target displacement was considered to be a factor in increasing the response time. Bartz (1962) found that the response time was greater to the left and right at 5 degrees than at 10 degrees, and it increased steadily from then on to 40 degrees. Similar results were obtained by White, Eason, and Bartlett (1962); however, they did not measure latency for displacement angles of less than 10 degrees. Frost and Poppel (1976) offered an explanation for the change in latency for small displacements of 10 to 15 degrees versus larger displacements and hypothesized two modes of information processing in the central and peripheral fields. Central field processing was considered to be mediated by the visual cortex, whereas the peripheral field was mediated by the superior colliculus. The transition from one mode to another occurs about 10 to 15 degrees from the fovea on the retina.

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

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

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

The effect of target luminance was shown by Wheeless et al. (1967), by Ueno (1977) and by Zeevi (1982) to be a significant factor affecting response latency time. Response time was shown to decrease and reach an irreducible or asymptotic latency as the luminance level

was increased to well above threshold. Wheeless showed that for every half log luminance change up to two log luminance levels above foveal threshold, response time decreased 20 msec. Based on this, finding the 40 to 50 msec difference in response time between the NFD and WFD would necessitate at least a one log unit difference in luminance level above the foveal threshold. A further property which was observed by Wheeless and by Zeevi, which seems to agree with the results obtained here, was the increase in response time variance associated with the lower levels of target luminance due to the narrow field CRT display. The spread of the response data was shown to decrease as the level of luminance was increased. A similar result was found in these experiments when the response variances from the NFD were compared to the variances from the WFD when the number of samples were nearly the same.

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

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

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

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

Over an 18 month period, consistency of single target response latency time has been observed in two subjects. Periods ranging from several days to more than 2 months elapsed before the same person was asked to participate again as a subject. The repeatability of results

suggests that a subject's response can be characterized by an underlying response time distribution. Since the exact nature of this distribution is unknown, one must be satisfied for the moment with a statistical model of it. The statistical model is a representation of the probability density function with the response latency time representing the outcome of a random variable for a specific stimulus. For most purposes it has been adequate to describe a subject's response with a statistical mean and standard deviation.

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

$$e^{-ca},$$

the log normal by

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

and the Weibull by

$$e^{-ca}.$$

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

The responses of each subject in this study were normalized with respect to their single target mean response. The normalization of

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

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

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

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

A basic finding of this study was the significant increase in response latency to symmetrically bifurcating targets. At first, this finding may not seem startling because various studies have shown that as the number of stimuli increase, response time increases at a rate proportional to the log number of bits of stimulus information

(Hick, 1952; Welford, 1968). Such a measure fails, however, to capture the quintessence of the spatial-temporal structure of the stimulus as it relates to the organizational properties of the visual system. Consequently, it cannot accurately predict response latency for certain types of stimulus patterns. The mean response to bidirectional stimuli was always significantly longer than response to unidirectional stimuli. The increase in response time therefore may not be related to the number of targets present but to the participation of the hemispheres. An elaboration of this idea will be forthcoming.

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

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

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

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

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

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

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

The left or right directional preference was not influenced by asymmetrical displacements of the targets. It would seem reasonable though, given the choice between extreme displacement of a target in the preferred direction versus small target displacement in the reluctant direction, that the response would be to the smaller of the two. The trade-off between the cost of a movement in terms of the extra programming of an intermediate saccade to reach an extreme outer target versus the closer target in the reluctant direction was not fully explored. The minimum target displacement at the time was limited to only 5 degrees, and no targets completely utilized the full 50 degree span of the display. Consequently, asymmetrical differences only up to 15 degrees were investigated.

The effect of target luminance and differential luminance between targets was also not investigated. The influence of target luminance would seem to have more effect on detection, but to what extent is not known. There was a tendency for the CRT NFD subject group to have a

preferred response to the right while the WFD subjects showed display preference in the opposite direction. The influence of target displacement magnitude and the effect of distance seemed to have little effect on response or directional preferences based on experiments using the WFD and the new NFD. The luminance levels may have played an important role in influencing the preferential direction. Even with the apparent lower levels of target luminance, the fact remains that the directional response biases were strong under both conditions. It would seem unlikely, therefore, that for such a small change in target luminance level between the two displays such a dramatic turnaround would occur in preferred response direction. To resolve the differences between the two groups may require further experimentation on the effects of target luminance.

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

There seemed to be a relationship between the time response and the preferred response direction. Again, exceptions to this observation were easily found. Such a result might suggest two internal independent timers which, upon detection of a stimulus, begin their time-out sequence for directional decisions. Whichever timer finishes first could determine the response direction. Thus if one timer runs slightly faster than the other, response in that direction might be expected more often. Such an idea has been suggested by Becker and Jurgens (1979), who proposed a saccadic model generator with two independent timers, either of which can be inhibited by the other.

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

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

but only if the delay between them was less than the window of time allowed by the decision process.

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

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

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

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

tion, and the order of these processes is first the directional decision, followed by selection.

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

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

Of the two dyslexic subjects recently tested, both showed a considerably lower percentage of response to their preferred direction than did non-dyslexic subjects; less than 64 percent versus 88 percent. The mean response time for the symmetrically bifurcating dual targets for dyslexic subjects was 33 msec longer than that for non-

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

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

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

It is not clear yet whether the differences between left-right response latency motor asymmetries can be related to the preferential asymmetries. In future experiments, a more concerted effort should be made to firmly establish left or right cerebral dominance and its degree. The data are inconclusive and, in fact, a strong preferential response direction does not necessarily indicate asymmetry between left-right motor responses. For the same group of subjects, the relationship between contextual and context-free stimuli should be explored. Contextual stimuli should be favored by one hemisphere or the other, depending on the presented form. Thus, for spatial type stimuli, response should be faster when presented to the left field;

with alphanumeric characters or numbers, response should be faster when they are presented to the right field. Since, in these experiments, a context-free stimulus was used, neither hemisphere should have been favored. Since single target left-right response latency differences may be a better indicator of oculomotor asymmetries, these differences may not be a good predictor of directional preference. Perhaps, then, preferred response may be due to a visual hemispheric dominance. Differences between context free preferred response and the preferred response to contextual stimuli may indicate an overriding influence that high levels of specialization may impose on the lowest level of preferred response direction as investigated here. Future experiments should consider this by changing the contextual information of the targets while examining the changes in response.

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

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

The way in which dual targets are presented can significantly affect the amount of time necessary to process the information and the response. In general, targets that were presented simultaneously had shorter latencies than did targets that were presented serially. The

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

CONCLUSIONS

In this study we have shown that eye movement measurement can be used to quantify differences between the processing of single and bihemispheric projected visual information and that these differences, measured by the eye movement response, can reflect to a certain extent the functional organization of the system. The primary dependent measures in these experiments were the initial saccadic response latency time, the direction of response, and, when applicable, the magnitude of the response.

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

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

Delayed bihemispheric stimulation produced changes in response latency that were similar in both directions, and the response latency increased still further when targets were presented sequentially rather than simultaneously. The delay furthermore had pronounced asymmetrical effects on the probability distribution of the response direction. Delayed dual-target, single hemispheric stimuli showed a similar, but, shifted probability distribution curve. The response time changed only when the appearance of the preferred inner target lagged behind the outer target. The directional response and/or selection of a target is therefore conditional on both the initial target displacement and the elapsed time before the appearance of the second target. When the second target appears in the opposite visual

field and is in the preferred direction, then the critical period of time separating these two targets is approximately 50 msec if the response is to be in the preferred direction. If, on the other hand, the second target is in the same visual field as the first but is the inner target of the two, then the critical period of time for response to the inner target is roughly twice that of a directional decision, or approximately 100 msec. Further, it seems that even a few milliseconds of difference between the appearance of the targets already triggers a sequential mode of processing of visual information, resulting in significant increase in processing time.

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

SUMMARY

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

In these experiments, the separation in retinotopic mapping of the left and right visual fields was exploited so that stimuli were selectively presented to either one or both hemispheres. The primary measure used in these experiments was the initial saccadic response latency time, the direction of response, and where applicable, the magnitude of the response.

An asymmetry in single target, left-right response latency time was observed in nearly all subjects. In all cases, there was a significant increase in response latency time when targets were presented to both hemispheres simultaneously. The increase in response time was greater using the CRT narrow field display than the wide field display. The additional increase in response time using the CRT display was however due to changes in target luminance level. No significant response latency differences were observed between single-target response latency and dual target single hemispheric response latency. Thus, the significant increase in response latency time is not due to the number of targets presented to an observer but rather to the simultaneous stimulation of both hemispheres. Dual targets presented simultaneously to an observer showed consistent subject-specific preferred response. Dual targets presented simultaneously to both hemispheres showed preferred response to the left or right 88 percent of the time. Dual targets presented simultaneously to one hemisphere showed preferred selection of the inner target 95 percent of the time. The response biases did not appear to be influenced by asymmetries between the targets or necessarily related to handedness. Preferred response could however, be offset by introducing a time delay between the appearance of both targets. The probability of preferred response and the response latency time were both influenced by the delay.

Delayed bihemispheric stimulation produced changes in response latency that were similar in both directions. The response latency increased still further when targets were presented sequentially rather than simultaneously, indicating differences between the sequential and parallel modes of processing of visual information. The delay had pronounced asymmetrical effects on the probability distribution of the response direction. Delayed dual target single hemispheric stimuli showed a similar but shifted probability distribution curve. The response time changed only when the appearance of the preferred inner target lagged behind the outer target. The directional response and/or selection of a target is therefore conditional on both the initial target displacement and the elapsed period of time between passing before the appearance of the second target.

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

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