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ISBN 0-315-30696-3

**Spatio-Temporal Processing of
Binocular Disparity Information
in Human Stereopsis**

Pardo Mustillo

A Thesis

in

The Department

of

Psychology

**Presented in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy at
Concordia University
Montréal, Québec, Canada**

July 1985

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ABSTRACT

Spatio-Temporal Processing of
Binocular Disparity Information
in Human Stereopsis

Pardo Mustillo, Ph.D.
Concordia University, 1985

This research examined the spatio-temporal characteristics of crossed and uncrossed disparity processing in human stereopsis. Using a two- or four-alternative, forced-choice psychophysical procedure, observers had to discriminate the direction of brief disparity pulses as seen relative to the plane of fixation. Parametric manipulations included (a) disparity direction, (b) disparity magnitude, (c) disparity pulse duration, and (d) type of stereogram. Three types of stereograms were used: Classical line stereograms, static random-dot stereograms (RDS), and RDS with superimposed line contours of the disparate target and background. The percentage of correct responses and the latency with which correct responses were made were used as the two measures of performance.

Regardless of the type of stereogram used, depth discrimination performance for disparity pulses in the crossed direction was superior to performance for pulses in the uncrossed direction. Seventeen out of 18 observers tested discriminated pulses with crossed disparities more accurately than those containing uncrossed disparities of identical magnitude and pulse duration, and 13 out of the 18 observers' data showed

a similar pattern with respect to mean reaction-time (MRT) performance. The main effects of disparity magnitude and pulse duration were, with a few exceptions, also significant; overall performance generally improved with increasing disparity and with longer pulse durations. (These main effects, however, were not observed for RDS). Nevertheless, discrimination performance was consistently more accurate and faster for pulses in the crossed direction than for those in the uncrossed direction across the entire range of disparity magnitudes and pulse durations tested and for all three types of stereograms. Finally, disparity pulses presented in the line and random-dot plus line stereograms were discriminated more accurately than when presented in RDS alone. Overall MRT performance, however, did not differ among the different types of stereograms.

The results of this study suggest that the human visual system is differentially sensitive to the direction of binocular disparity pulses. Furthermore, this difference in sensitivity can be observed with both the presence and absence of monocular contours. The asymmetric nature of disparity processing, both with respect to spatial and temporal manipulations, is consistent with the distinction between crossed and uncrossed stereopsis.

ACKNOWLEDGEMENTS

There are many individuals who have helped me throughout the years, and thus deserve special mention. Primarily, I would like to thank my supervisor, Dr. Melvin Komoda, for his patience, guidance, and intellectual support. He is a remarkable individual whose friendship and respect I will always cherish. His ideas and inspiration are reflected throughout this work.

I also wish to express my gratitude to Dr. Edward Brussell. An excellent educator, analytical thinker, and eloquent speaker, he guided me many times in the right direction with his insightful views and convincing arguments, and for this, I thank him.

Dr. Charles White has given me and others something to aspire to, both as an educator and as a researcher. His wisdom and breadth of knowledge are some of the things that I would one day like to attain. I am grateful for having known him.

I would also like to thank Dr. Hiroshi Ono for acting as my external examiner, and for suggesting many improvements to this dissertation. His comments and criticisms were greatly appreciated.

Dr. Robert Fox at Vanderbilt University generously provided me with a word processor, office space, and some spare time in order to complete the final version of the dissertation, and for this, I am grateful. I also wish to thank him for his encouragement and fruitful ideas.

Writing is never an easy task, and writing this dissertation was no exception. Life would have been less bearable had it not been for the

moral support that I received from several close friends and peers. I particularly wish to thank Diane Potvin and Nikki Pawliuk for the stimulating environment that they created for me during the last few months of writing, and Richard Thornton, for his friendship, understanding, and spiritual support. These individuals helped me greatly when I was struggling to find the right words, and their constant encouragement helped me get through many difficult periods of frustration. I owe them many apologies and a great deal of gratitude.

I would also like to extend a note of appreciation to the departmental secretaries. In particular, I wish to thank Dorothy Redhead-Spindleman and Kali Sakell, both good friends whom I called and relied on many times throughout my academic career. Their dedication to and excellence in their respective positions have earned them much respect, and they should be commended.

Finally and most importantly, I wish to thank my wife, whose continuous support (in every sense of the word), love, friendship, and countless sacrifices, enabled me to continue my education and complete this work. Without her, I doubt whether any of this would have been possible. I, therefore, wish to dedicate this dissertation to her.

Thank you, Eva.

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1

SPATIO-TEMPORAL PROCESSING OF
BINOCULAR DISPARITY INFORMATION
IN HUMAN STEREOPSIS

The study of stereopsis has long been the focus of considerable interest, and it remains very much in the mainstream of contemporary visual science. Since Wheatstone's (1838) early experiments demonstrating that the visual system can quickly resolve minute depth differences between objects in space, based solely on binocular disparity cues, there has been an concentrated effort to arrive at some understanding of the various mechanisms that may underly this remarkable ability.

An important source of information about the three-dimensional structure of the physical world comes from stereopsis. It is now generally recognized that the visual system uses information about the geometrical relationship that exists between objects in the external world and their respective images on the two retinas in order to recover stereoscopic depth. Because of the spatial separation between the two eyes, each eye views the world from a slightly different perspective. Consequently, images do not always fall on precisely corresponding points on the retinas; objects nearer or farther than fixation project onto disparate retinal locations in each eye, and it is these slight horizontal differences or spatial disparities that provide an important and sufficient source of information about the position and shape of an object in three-dimensional visual space. Objects that lie in front of

fixation are displaced temporally with respect to the foveas of the two eyes, and are said to have a crossed disparity. Conversely, objects that lie beyond or are more distant than fixation are displaced nasally, and are said to have an uncrossed disparity.

The basic goal of stereopsis, then, is to extract disparity information from a pair of retinal images and use this information to compute relative depth differences between them in a visual scene. The computational problem that the visual system must solve when trying to effectively localize an object in space, however, is that it must extract only those properties and features from a pair of two-dimensional images that will lead to a faithful and unambiguous reconstruction of the three-dimensional nature of the scene. How does the visual system recover depth and structure from binocular disparity?

Conceptually, the process of recovering such information might appear to be relatively simple and deceptively straightforward. In their computational theory of human stereopsis, Marr and Poggio (1979) proposed that there are essentially three steps. First, a particular location on the surface of the scene must be chosen from one image. Second, the corresponding location in the other image must be identified, and finally, the relative position of the two images must be measured and their disparity computed. The computational task, however, is more complicated and difficult than it appears. Specifically, how the visual system solves the so-called "correspondence problem," or how it arrives at a precise binocular match between the left and right retinal images, while avoiding false matches, is still a matter of considerable debate (T. Poggio, 1984; Prazdny, 1985). Given a pair of images, the problem is

how to extract pairs of correlated points, where one point in one image can potentially be paired with any one of a myriad of equally plausible points in the other image.

An even more fundamental question that lies antecedent to the correspondence problem is what has to be matched in order to determine the correct correspondence between two retinal images (Grimson, 1981a, 1981b; Poggio & Poggio, 1984). In other words, what are the candidates for matching? Although a number of different matching schemes have been suggested, based on neurophysiological findings (e.g., Sugie & Suwa, 1977), and several computer algorithms have been developed from theoretical considerations (e.g., Marr & Poggio, 1976; 1979; Mayhew & Frisby, 1980, 1981), the issue is still far from settled; for a review of these and other important issues concerning the computational aspects of stereopsis, see Poggio and Poggio (1984).

Two of the most significant achievements that have taken place in the last two decades in the study of stereoscopic vision have been the introduction of computer-generated, random-dot stereograms (RDS) and the discovery of disparity-selective neurons in the visual cortex of several species of animals. Julesz (1960) provided unequivocal evidence that stereopsis does not require the prior recognition of form, by demonstrating that stereoscopic depth can be perceived in RDS in the absence of all monocular contours, familiarity cues, or information of any other kind, except for binocular disparity. Julesz's work with RDS demonstrated convincingly that the extraction of disparity takes place very early in visual processing, before any recognition of what is being viewed. The use of RDS also provided the first elegant paradigm in which

stereopsis could be studied in its purest form, without the influence of monocular contour information. Moreover, work with RDS led to a radically different way of conceptualizing how stereopsis is achieved.

Prior to Julesz's seminal demonstrations, the classical view was that depth could only be perceived after form had been decoded, and that monocular contours were essential for the perception of stereoscopic depth (e.g., Ogle, 1959). Julesz demonstrated conclusively that monocularly recognizable global contours are not necessary for stereopsis, and that "instead of contours giving rise to depth, it is rather depth that gives rise to contours" (Gulick & Lawson, 1976, p. 52).

The second most impressive achievement that has led to a fundamentally new understanding of stereoscopic vision came from the pioneering neurophysiological studies of the late 1960s and early 1970s investigating the possible neural basis of stereopsis. Briefly, these early studies provided the first compelling evidence for the existence of highly specialized neurons in the visual cortex of the cat and monkey that are selective to horizontal binocular disparity, and suggested that these neurons might form the basis of stereoscopic depth perception.

A great deal has since been learned about the properties of these binocular cortical units and the role they may play in the early stages of stereoscopic vision. Within the last decade or so, an impressive body of psychophysical evidence has also been accumulated to support the idea of the existence of disparity-selective neurons in the human visual system (e.g., Blakemore & Hague, 1972; Mitchell & Baker, 1973).

Neural Basis of Disparity Processing

The processing of disparity information is one of the most basic functions of the visual cortex. Neurophysiological and electrophysiological studies have shown that the visual system contains binocular neurons that are selectively tuned to depth, and that respond optimally to physical objects whose retinal images have a particular horizontal positional disparity. The first wave of experimental evidence for the existence of such binocular cortical units came from the early studies of Barlow, Blakemore, and Pettigrew (1967), Nikara, Bishop, and Pettigrew (1968), Pettigrew, Nikara, and Bishop (1968), and Joshua and Bishop (1970), who described cells in the primary visual cortex (striate area 17 or V1) of the cat that display a high degree of selectivity to different stimulus disparities. More recent studies have confirmed these findings, and have further provided evidence for the existence of disparity-sensitive neurons in prestriate area 18 (V2) of the cat (e.g., Ferster, 1981; Fischer & Krüger, 1979; Pettigrew, 1973) and monkey visual cortex (e.g., Fischer & Poggio, 1979; Hubel & Wiesel, 1970; Poggio & Fischer, 1977). The presence of similar disparity-selective cortical units has also been established in areas 17 and 18 of the sheep visual cortex (Clarke, Donaldson, & Whitteridge, 1976) and in the visual Wulst (i.e., analog to the striate cortex) of the owl (Pettigrew & Konishi, 1976).

The binocular depth neurons described by these studies display several distinguishing properties. First, the majority of them are

binocularly driven, and thus require simultaneous stimulation before they will respond. Second, different neurons are maximally responsive to different horizontal disparities corresponding to objects at various distances. Finally, the separation of the receptive fields of binocular depth units in the two eyes varies from cell to cell. Some of these cells have receptive fields in exact binocular correspondence, whereas others have receptive fields that lie in noncorresponding positions in the visual field for the two eyes (i.e., show receptive field disparity), and they use this spatial noncorrespondence to compute the relative displacement of visible objects lying over a restricted spatial range of depths nearer or farther from the point of fixation (see Bishop, 1974, 1981, for integrative reviews).

Much has been learned about the neurophysiological and neuroanatomical basis of stereopsis since disparity-tuned cortical cells were first described by Barlow et al. (1967) and others. Perhaps the single most important discovery since then has come from the single-unit work of Poggio and Fischer (1977). They recorded from cells in the visual cortex of alert, unanesthetized rhesus monkeys that were trained to maintain steady fixation on a small target while an appropriate visual stimulus was physically moved in depth. The stimulus, which portrayed a pulsating bright bar of various sizes and orientations in depth, was presented in a dynamic random-dot background, and moved bidirectionally across the neuron's receptive field. Poggio and Fischer found that about 60% to 70% of cells in area 17 and an even higher proportion in area 18, are sensitive to horizontal disparity. More importantly, they discovered the existence of three basic classes of disparity-sensitive cells in

these cortical areas that respond in a highly selective manner to both the direction and magnitude of horizontal binocular disparity.

Briefly, one class of cells (tuned-excitatory and tuned-inhibitory cells), the most commonly observed, respond best when presented with small disparities, and display binocular facilitation and binocular suppression respectively, to small crossed and uncrossed disparities around of the plane of fixation (i.e., $\pm 0.1^\circ - 0.2^\circ$). Two other distinct classes of cells (near and far cells) are reciprocally organized for depth, and respond differentially to relatively large crossed and uncrossed disparities, respectively. Typically, near cells respond best to stimuli containing crossed disparities, but display response inhibition to stimuli containing uncrossed disparities. Far cells, on the other hand, are activated by disparities in the uncrossed direction, but display a marked insensitivity to disparities in the crossed direction. Furthermore, near and far cells both respond to a much broader range of disparities than the tuned-excitatory and tuned-inhibitory cells (i.e., $\pm 1^\circ$ or more).

These observations have been confirmed and extended by more recent studies demonstrating the existence of similar directionally-selective, disparity-tuned neural units in both major areas of the visual cortex of the cat (Ferster, 1981; Fischer & Krüger, 1979; von der Hedyt, Adorjani, Hännny, & Baumgartner, 1978) and monkey (Fischer & Poggio, 1979; Poggio & Talbot, 1981). Furthermore, Maunsell and Van Essen (1983) have recently found cells in the middle temporal (MT) visual area of the macaque monkey that display similar properties as those first described by Poggio and Fischer (1977). G. F. Poggio (1981, 1984) has written several reviews of

these discoveries and their implications for the study of stereoscopic vision.

Another interesting finding that has emerged from recent work in this area has been the discovery that many of the same depth-sensitive cells that respond to luminous line or bar stimuli, also respond to monocularly invisible "cyclopean" spatial patterns embedded within dynamic RDS (G. F. Poggio, 1980; Poggio & Talbot, 1981). In this respect, both binocularly simple and binocularly complex cells have been shown as being capable of responding to local disparity in line-contoured stereoscopic patterns, but only binocularly complex cells have been found to be selective uniquely to dynamic RDS (Poggio, Motter, Squatrito, & Trotter, 1985). Tentatively, these demonstrations provide preliminary neurophysiological evidence for the presence of highly specialized cyclopean neurons in the visual cortex of the monkey that are sensitive purely to binocular disparity, and suggest a possible neural candidate for the solution of the correspondence problem.

In summary, all studies investigating the neurophysiological substrates of stereopsis agree that disparity-selective units exist in the visual cortex of the cat and monkey, and that the activity of these neurons may play a critical role in conveying essential information about stereoscopic depth. Although there may not be a total consensus on several issues concerning how these neurons function or how they are organized and distributed within the different areas of the visual cortex, the discovery of distinct classes of binocular neurons that are differentially sensitive to both the direction and magnitude of disparity, has begun to shed new light on the manner in which disparity

information may be processed by the visual system. In particular, recent findings suggest that binocular disparity information in stereopsis may be encoded by different neural mechanisms that are selectively tuned to crossed and uncrossed disparities.

The following section will review a number of lines of empirical evidence from a variety of different research approaches in support of this distinction, and provide the necessary background for this dissertation. The review will focus on a selected group of representative studies whose findings are considered to be the most pertinent and compelling. It is suggested from a careful examination of these findings, that the human visual system is differentially sensitive to the direction of binocular disparity information. Moreover, the difference between the processing of crossed and uncrossed disparities appears to be a fundamental and critically important one.

Empirical Evidence Supporting the Distinction
Between Crossed and Uncrossed Stereopsis

Human Psychophysical Evidence

Richards' Work

The study of selective failures in the processing of binocular disparity information has led to many important ideas about how the normal visual system may process stereoscopic depth. Richards (1970), for instance, investigated individual differences in stereopsis for a

range of large disparities from $\pm 0.5^\circ$ to $\pm 2^\circ$ (coarse or qualitative stereopsis). Using a three-alternative, forced-choice discrimination procedure, he assessed observers' ability to discriminate relatively large crossed, uncrossed, and zero disparities, respectively, by having them report whether small vertical lines ($15' \times 2^\circ$), flashed on a screen for 80 ms, appeared in front of, behind, or on, the plane of fixation. Richards found that approximately 30% of his observers could not make the correct discriminations, and called these individuals "stereoanomalous."¹ Specifically, some observers seemed unable to discriminate crossed disparities from monocular stimuli that contained no disparity, yet could still discriminate between monocular stimuli and those having uncrossed disparities. Other observers confused uncrossed disparities with stimuli having zero disparity, but responded appropriately to crossed disparities. Finally, some observers confused crossed with uncrossed disparities. From these data, Richards hypothesized that normal stereopsis is based on at least two, and possibly three distinct mechanisms, which perform separate analyses for crossed, uncrossed, and zero-disparity information, respectively. He suggested that these mechanisms could be isolated by examining the depth responses made by individuals who lack the ability to discriminate one or the other of these disparity directions from monocular stimuli having no disparity.

In a subsequent study, Richards (1971a) used the same stimuli and presentation parameters to further assess observers' ability to discriminate large crossed and uncrossed disparities ($\pm 4^\circ$). As in his earlier experiment, he found that some observers were totally incapable of discriminating the direction of stimulus disparity. More importantly,

however, he found that when observers did have a difficulty in identifying a particular disparity direction, the difficulty was present for all crossed or all uncrossed disparities. These observations led him to suggest that a stereoanomaly may represent a situation in which not one disparity, but a whole class of similarly tuned disparity detectors may be missing or functioning improperly.

Empirical data consistent with Richards' original findings have been reported for a full range of retinal disparities, from as small as $3.6'$ of arc to as large as 4° (Richards & Kaye, 1974). Recently, Jones (1977) also demonstrated that individuals who display anomalous vergence responses to large disparities, often show corresponding deficits in disparity processing for whole ranges of disparities of a particular direction, despite having adequate binocular vision and normal stereoacuity.

On the basis of his data, Richards (1971a, 1971c) proposed a model of stereopsis in which perceived depth is calculated by comparing the relative activity in large groups or pools of disparity-sensitive neurons, rather than the activity in the neural units themselves, anticipating the conclusions of later psychophysical and neurophysiological studies. The central tenet of Richards' model is the postulation of two or even three different classes or hypothetical pools of neural disparity detectors to process the depth cues associated with crossed and uncrossed disparities, and possibly also zero disparity. According to the model, each pool is thought to perform a separate global computation, one for the entire range of crossed disparities, the second for uncrossed disparities, and possibly a third separate analysis for

zero disparity. Disparity information is thus encoded in the balance of activity in the appropriate neural pools, with a mean disparity being represented most often and extreme disparities occurring with less frequency. Richards (1971c) suggested that a stimulus of a given disparity elicits varying amounts of binocular activity, depending on its relation to the mean disparity.

This idea is consistent with the neurophysiology of the visual cortex. The work of Poggio and Fischer (1977) and others, has established that a common property of the near and far cells found the visual cortex of the monkey and cat is that they show steep disparity response gradients, from maximal excitation to maximal inhibition, with the midpoint of response activity along the disparity domain being centered around the mean disparity (Maunsell & Van Essen, 1983; G. F. Poggio, 1984). The notion that disparity information may be represented in the relative distribution of binocular activity in different neural pools of disparity detectors is an attractive one, and has been incorporated into a recent theoretical model of human stereopsis (i.e., Marr & Poggio, 1979; see Marr, 1982, for a review).

Following Richards' lead, a substantial amount of psychophysical evidence has rapidly accumulated in support of the idea that crossed and uncrossed disparity information may be mediated by different mechanisms. For example, Richards (1971b) reported asymmetric effects of convergence on the crossed and uncrossed disparity limits of Panum's fusional area. He found that when he increased convergence (i.e., by decreasing fixation distance), stimuli with uncrossed disparities became easier to detect, whereas performance for stimuli containing crossed disparities remained

virtually unchanged.

Findings similar to these were first reported by Ogle (1952) and Mitchell (1966), who suggested that the two limits might not be equivalent, and are consistent with the later findings of Richards and Foley (1971). These investigators demonstrated that the spatial limits of crossed and uncrossed disparity are qualitatively different, and are affected unequally by changes in fixation distance. They also showed that the qualitative upper limit for processing crossed disparities in some observers can be as much as four times greater than the maximum limit for which uncrossed disparities can reliably be detected. Richards and Foley estimated the upper limit for crossed disparities to be as large as 16°. In another study, Foley, Applebaum, and Richards (1975) showed that the disparity response functions obtained for perceived depth in discrimination tasks are often not symmetrical. In particular, they found that observers typically report seeing less depth for stimuli with uncrossed disparities than they do for stimuli containing crossed disparities.

Other types of psychophysical experiments have also provided support for the basic distinction between crossed and uncrossed disparity encoding. Richards (1973), for example, showed that the contrast of the stimulus can have a marked influence on the way some observers process stereoscopic information. Specifically, he found that the effects brought about by contrast reversals (i.e., changing from light bars on a dark background to dark bars on a light background) can lead to depth discriminations being reversed. In his study, observers who could previously discriminate only crossed (but not uncrossed) disparities with

light-bars on a dark background, were no longer able to do so when the contrast was reversed, but could now discriminate uncrossed disparities. The converse was also observed. Richards was careful to point out, however, that these effects were not entirely symmetrical.

Spatial Asymmetries

There is a considerable body of human psychophysical data in addition to the work of Richards and his colleagues, to support the notion that crossed and uncrossed disparity information may be mediated by different mechanisms. For example, Woo (1974) showed that the threshold for diplopia is significantly lower for crossed disparities than it is for uncrossed disparities. In another study, Woo and Sillanpaa (1979) reported significant differences between the spatial threshold values obtained for crossed and uncrossed disparities. Specifically, they found that the averaged absolute threshold of stereopsis for crossed disparities in 30 observers was 5.6" of arc, compared with 14.5" of arc for uncrossed disparities. Woo and Sillanpaa also observed that disparities in the crossed direction were significantly easier to detect than those in the uncrossed direction across a whole range of disparity values, from 3.2" to 80" of arc.

In a recent study, Grabowska (1983) investigated visual hemifield differences in human stereopsis with static RDS. She used small disparities ($\pm 18'$ of arc, in 6' steps) and brief, 30-ms exposure durations. The observers' task was to detect the presence of a square in depth, which could be presented either in the left or right side of the

RDS. Grabowska not only observed a left visual-field superiority for stereoscopic depth detection, but also found that the detection of depth was significantly better when stimulus targets were presented in front of the fixation plane than when they were presented behind it. In fact, 16 out of the 19 observers she tested performed significantly better for targets containing crossed disparities than for those containing uncrossed disparities.

Comparable results have also been reported with large disparities. For example, Lasley, Kivlin, Rich, and Flynn (1984) found that observers who were presented with narrow, vertical line stimuli having large, diplopic retinal disparities (1.6°) of either direction and flashed for 100 ms, consistently perceived crossed disparities more accurately than uncrossed disparities. (The overall proportion of correct responses across all observers was .90 for crossed disparity, compared to .49 for uncrossed disparity). In their study, 74% of the observers showed a greater sensitivity to crossed disparities than to uncrossed disparities of identical magnitude. Lasley (1985) recently extended these findings, and provided additional theoretical justification for the idea of separate mechanisms for crossed and uncrossed stereopsis.

In another recent study, Shipley, Garfinkel, and Van Houten (1984) reported some evidence to suggest that rather large image-size differences can be tolerated by human observers when viewing RDS. This observation is not new since Julesz (1971) showed that stereopsis can easily be obtained even when the left or right image of a RDS differ by 15% in linear size. What is novel, however, is that they found that observers could tolerate a greater percentage of overall image

magnification for uncrossed disparities than for crossed disparities before perceived depth was lost in the stereograms (i.e., 21% vs. 11%, respectively). This finding, however, was based on partial data from only 2 observers. Furthermore, the size of the crossed-uncrossed difference was found to decrease as the densities of the textures for each image were reduced or mismatched. Nevertheless, the existence of such a difference is certainly interesting, and deserves to be studied more closely.

Schor and Wood (1983) recently used a depth-matching task to examine the disparity range for human stereoscopic spatial sensitivity. The luminance profile of the stimulus patterns was produced by taking the difference of two Gaussian (DOG) functions. Using the psychophysical method of adjustment, the observers' task was to make suprathreshold depth matches of dichoptically viewed stimulus patterns containing varying amounts of crossed and uncrossed disparity until the stimuli appeared to lie on the same depth plane. Schor and Wood reported that the depth-matching curves of all their observers were different for crossed and uncrossed disparities; all observers required significantly greater amounts of uncrossed disparity than crossed disparity to make suprathreshold depth matches. Furthermore, the depth-matching curves for crossed disparities showed a sharper rate of elevation than those for uncrossed disparities, and this asymmetric elevation occurred at narrower DOG widths for crossed than for uncrossed disparities.

Temporal Differences

Although much attention has been focused on the investigation of spatial asymmetries in the processing of crossed and uncrossed disparity information, considerably less attention has been given to the study of possible temporal differences. In a recent study, Alexander (1979/1981) used a reaction-time (RT) paradigm to measure the latency of correct responses to static RDS of different disparity directions and magnitudes, and to non-stereoscopic control stimuli. He found evidence for a uniform superiority in depth discrimination performance for crossed disparities over uncrossed disparities in 11 out of 26 observers. Furthermore, Alexander also reported that 9 of the 12 observers who were tested in a backward-masking paradigm to assess the minimum exposure duration required to perceive depth, showed a significant crossed-uncrossed disparity difference, although he did not elaborate in which direction.

In a series of experiments, Breitmeyer, Julesz, and Kropfl (1975) and Julesz, Breitmeyer, and Kropfl (1976) assessed the extent of human temporal sensitivity to briefly presented stereoscopic information in various areas of the visual field. The targets consisted of small-disparity ($\pm 6'$ of arc) squares that were embedded in dynamic RDS. The observers' task was to detect the presence of a square in depth, but not to identify its disparity. Stimulus duration thresholds were established for many retinal points on the retina where the targets were presented, within an area of $\pm 1^\circ$ around fixation.

No evidence for a left-right hemifield anisotropy for stereopsis was found in either study (but see Grabowska, 1983, for conflicting results).

Interestingly, however, both studies did find evidence for an upper-lower hemifield difference, with the upper hemifield being more sensitive to uncrossed disparities and the lower hemifield being more sensitive to crossed disparities. That is, targets having an uncrossed disparity were detected at consistently shorter durations when they were presented in the upper hemifield than when they were presented in the lower hemifield. Conversely, targets presented in the lower hemifield produced lower temporal limits for crossed disparities. Similar upper-lower hemifield differences were also reported with respect to various spatial manipulations (e.g., target width, Julesz et al., 1976, Experiment 5).

Human Developmental Differences

Further psychophysical evidence in support of the notion of independent, directionally-sensitive disparity mechanisms has come from several recent studies examining the development of stereoacuity for crossed and uncrossed disparities in human infants. The first study to provide positive results with respect to this issue was conducted by Held, Birch, and Gwiazda (1980). These investigators used a two-alternative, forced-choice preferential looking procedure, in which the stimulus pair consisted of two vertical bar gratings of high contrast and low spatial frequency. The stimulus pair was identical except that one contained a horizontal disparity, which could range from 1' to 58' of arc in either crossed or uncrossed directions. By examining which of the two stimuli the infants preferred to look, they determined the minimum disparity to which each infant responded. (Preferential looking takes

advantage of infants' natural preference to look at the more interesting or complex of two stimulus patterns).

Their data indicated that virtually all infants could reliably respond to large disparities by about 4 months. Held et al. did note, however, that responses to crossed disparities emerged prior to responses to uncrossed disparities. The results showed that the mean age at which most infants were able to first discriminate the largest disparity was about 12 weeks, compared to about 17 weeks for uncrossed disparities of identical magnitude. Furthermore, these investigators reported that stereoacutities for crossed disparities were significantly higher than those for comparable uncrossed disparities.

Reuss (1981) confirmed these findings with dynamic RDS, and also showed that stimuli carrying a crossed disparity are detected at a significantly earlier age than stimuli of identical magnitude but with an uncrossed disparity (i.e., 130.2 days vs. 149.9 days, respectively). More recently, Birch, Gwiazda, and Held (1982) examined systematic variations in the direction of disparity preferences in human infants, and found that stereoacuity for crossed disparities develops earlier, but at approximately the same rate as stereoacuity for uncrossed disparities. Finally, Birch, Gwiazda, and Held (1983) provided additional evidence for significant differences in the age of onset of crossed and uncrossed stereopsis, and firmly demonstrated that the development of accurate vergence in human infants does not account for these differences.

Clinical Evidence

Visual-Field Differences

The development of novel approaches and new noninvasive techniques to probe various regions of the visual fields, has led to several unique insights into the manner in which binocular disparity information may be encoded by the visual system. Particularly provocative has been the idea that different patterns of stereoscopic losses (i.e., sensitivity losses) imply different underlying mechanisms, as first suggested by Richards (1970), and that these losses may be reflected in the perimetric visual-field profiles of stereoanomalous individuals. Using this rationale as a starting point, Richards (1972b) performed stereoperimetry in a group of 10 observers. By presenting narrow vertical bars ($0.20^\circ \times 1^\circ$) that modulated in depth at the rate of 2 Hz, he probed each observer's sensitivity to stimuli of different disparities as a function of their position in the visual field. Briefly, Richards found two basic visual-field patterns--one pattern was highly correlated with crossed disparities, and the other pattern was highly correlated with uncrossed disparities.

In a conceptually similar study, Richards and Regan (1973) later provided additional evidence in support of the hypothesis that crossed and uncrossed disparity information may be processed by different neural mechanisms in stereoscopic vision. They found that most of the visual-field plots obtained from their observers showed different

stereoperimetric sensitivity profiles for crossed and uncrossed disparities, even in the same individual. An even more compelling observation was that when a deficit was detected, it was present throughout an entire range of crossed or uncrossed disparities, and was not isolated to a particular disparity magnitude.

In a study investigating possible visual-hemifield differences in the detection-duration thresholds of stereoscopic targets, Breitmeyer et al. (1975) reported data from an observer who showed evidence of a markedly reduced depth sensitivity for targets having a specific disparity direction and magnitude in several regions in his visual field. Surprisingly, however, his sensitivity was quite normal when probed in the same visual area but with slightly different disparities. In addition, this observer showed a large stereoscotoma in the lower hemifield for uncrossed disparities that disappeared for crossed disparities. Except for the presence of this impaired region in this individual, stereopsis appeared quite normal everywhere else. These observations lead to the interesting hypothesis that sensitivity to crossed and uncrossed disparities may be distributed unequally in the visual fields, and that this sensitivity may be jeopardized in different ways by the onset of ocular pathology or by other possible visual-field abnormalities.

Human Electrophysiological Evidence

Visual-Evoked Potential (VEP) Differences

Data consistent with the hypothesis that crossed and uncrossed stereopsis may be mediated by separate mechanisms have also been reported in several human electrophysiological studies. Regan and Spekreijse (1970), for instance, demonstrated that the response amplitudes of scalp-evoked potentials are smaller for uncrossed disparities than for crossed disparities of the same magnitude. Regan and Beverley (1973) later showed that stimuli with crossed or uncrossed disparity not only evoke different cortical-response amplitudes, but also display different waveforms. The existence of such differences in cortically-evoked activity with respect to disparity information, presumably reflects the differential sensitivity of those mechanisms that may be responsible for the processing of crossed and uncrossed disparities in stereoscopic vision.

In another study, Bouldin (1976) examined visual-evoked cortical potentials (VECPs) to dynamic RDS, and found that the magnitude of these potentials varied directly with the direction of disparity. Specifically, the potentials became markedly attenuated as the direction of disparity of a stereoscopic target was changed from crossed to uncrossed. In addition, Bouldin observed greater VECP amplitudes for crossed disparities than for uncrossed disparities.

Behavioral Evidence from Animals

An area of research that has provided critical support for the idea that information about the direction of disparity may be encoded by different mechanisms has been that of behavioral research in animals. Incidentally, this area of research has also contributed directly to the idea that many species of animals possess stereoscopic vision. For instance, many behavioral demonstrations of stereopsis in the cat have been reported (e.g., Fox & Blake, 1971; Lehmkuhle & Fox, 1977; Packwood & Gordon, 1975). Similarly, there is qualitative evidence for the existence of stereoscopic depth perception in the monkey (e.g., Bough, 1970; Cowey, Parkinson, & Warnick, 1975; Harwerth & Boltz, 1979a, 1979b; Sarmiento, 1975), as well as in a number of nonmammalian species, such as the toad (Collett, 1977) and the falcon (Fox, Lehmkuhle, & Bush, 1977). A comprehensive review of these and other behavioral investigations of stereoscopic vision in animals can be found in Fox (1981).

With respect to the main topic under discussion, Packwood and Gordon (1975) reported evidence suggesting that the upper spatial limit of fusion for normal cats is asymmetric. They examined the qualitative fusional limits of crossed and uncrossed disparity in three groups of cats (i.e., normal, Siamese, and monocularly occluded), and found that normal cats could fuse crossed disparities up to 50' of arc, but could only fuse uncrossed disparities up to 30' of arc. (Siamese cats and monocularly occluded cats could not perform this task).

More recently, Harwerth and Boltz (1979a) demonstrated that rhesus monkeys also show better discrimination performance for crossed

disparities than they do for uncrossed disparities under various viewing conditions and across a number of disparity levels. These investigators used a two-alternative, forced-choice form discrimination task (discrimination between a single, vertically-oriented rectangle or two such rectangles), in which the stereoscopic forms to be discriminated were created by displacing the central disparate areas in static RDS. Target disparities ranged from 0' to 54' of arc, in 6' steps, for both crossed and uncrossed directions.

Their data revealed the presence of a large asymmetry between discrimination performance for crossed and uncrossed disparities, ranging from 6' to at least 30' of arc in all 6 animals tested. Furthermore, 4 of the 6 animals performed significantly better with crossed disparities than with uncrossed disparities. Harwerth and Boltz also found that animals' performance improved as a function of increasing disparity magnitude for both crossed and uncrossed directions, but not at the same rate. Depth discrimination functions for crossed disparities showed steeper slopes and became asymptotic much sooner than those for uncrossed disparities. In addition, the functions for the two directions tended to approach each other at larger disparity magnitudes.

In a separate study, Harwerth and Boltz (1979b) examined the effects of viewing duration on the ability of rhesus monkeys to discriminate stereoscopic forms in static RDS. Spatial parameters and stimulus configurations were identical to their other study. In agreement with that study, they found the majority of animals showed higher depth discrimination performance for crossed disparities than for uncrossed disparities. Furthermore, differences in the level of performance for

each direction remained consistent across the full range of exposure durations used (i.e., 15 ms to 4 s). Harwerth and Boltz did observe, however, that the functions relating the two disparity directions to disparity magnitude and exposure duration converged at larger disparities and at longer durations. With brief viewing durations and smaller disparities, the discrimination rate for both disparity directions increased steadily as a function of increasing disparity magnitude.

The results obtained from the animals were later replicated in a group of human observers under the same conditions; 7 out of 9 observers discriminated crossed disparities significantly better than uncrossed disparities of identical magnitude and exposure duration.

Synopsis of Findings, Unresolved Issues, and Some Shortcomings

The foregoing discussion has focused on empirical evidence from a number of experimental approaches in support of the idea that binocular disparity information in stereopsis may be encoded by different mechanisms that are selectively responsive to crossed and uncrossed disparities, respectively. The available data demonstrate that the direction of binocular disparity (i.e., whether a stimulus carries a crossed or uncrossed disparity) plays a critical role in the way that stereoscopic information is processed by the visual system. Taken together, the findings also suggest that disparities in the crossed direction are discriminated more accurately, more readily, and perhaps are encoded with greater efficiency than disparities in the uncrossed

direction. Such diverse findings as disparity-selective direction-dependent asymmetries in the spatial and temporal resolution limits of stereopsis, different stereoperimetric sensitivity profiles for crossed and uncrossed disparities, as well as other findings demonstrating well-defined developmental differences between crossed and uncrossed stereoacuity, for instance, strongly support the idea that the direction of disparity may be important and influential in processing such information in stereoscopic vision. Finally, the neurophysiological data converge to suggest that information about the direction of binocular disparity may be processed by separate neural pools or classes of cells that have different peak sensitivities, different spatial properties, and perhaps even different temporal constants.

Despite these important advances, several issues remain unresolved. First, although much appears to be known about the differential spatial aspects of stereoscopic vision, substantially less is known about the temporal processing of binocular disparity information. With the exception of those studies reviewed here (e.g., Alexander, 1979/1981; Breitmeyer et al., 1975; Julesz et al., 1976), this aspect of research has received surprisingly little attention. For instance, it is not known whether the asymmetric effects that are observed between crossed and uncrossed stereopsis under various spatial manipulations also exist for temporal manipulations. Second, although several studies have examined the effect of exposure duration on observers' ability to perceive depth in various types of stereoscopic displays, all of the findings that have shown that reductions in exposure duration lead to corresponding reductions in performance, have been obtained by using

flashed (i.e., repetitive) stimulus presentations of various durations. Finally, most studies investigating crossed and uncrossed stereopsis have relied on the use of relatively large-disparity stimuli of various configurations (e.g., Lasley, 1985; Lasley et al., 1984; Richards, 1970, 1971a). Apart from Grabowska's (1983) study with human observers, very few studies have explored the possibility of the existence of similar asymmetries for small-disparity, fused stimuli (e.g., Harwerth & Boltz, 1979a, 1979b). With these considerations in mind, the following section will develop the purpose of this study, which was to systematically assess the spatio-temporal characteristics of crossed and uncrossed disparity processing in human stereopsis, using pulsed disparity information.

Research Questions, and Rationale for the Present Study

The primary question that this research addressed was whether there exist fundamental spatio-temporal asymmetries in the manner in which crossed and uncrossed disparity information is processed in human stereopsis when this information is pulsed for various durations. The rationale for taking this approach stems from two sources. The first reason for using disparity pulses was that previous findings showing systematic effects of exposure duration on depth performance have been established by studies using flashed presentations. In this respect, the existing data indicate that the discrimination of depth decreases systematically as exposure duration is decreased, both for classical

line-drawn stereograms (Ogle, 1952; Sarmiento, 1975) and for RDS (Harwerth & Boltz, 1979b; Harwerth & Rawlings, 1977; Uttal, Fitzgerald, & Eskin, 1975). For example, Uttal et al. (1975) examined the effects of several parametric manipulations, including exposure duration, on briefly presented RDS, and found that the main effect of decreasing exposure duration was to progressively reduce depth discrimination performance. In another study, Harwerth and Rawlings (1977) found a linear relationship between the logarithm of stereothreshold and the logarithm of exposure duration. Similarly, Harwerth and Boltz (1979b), in investigating the effect of viewing duration on the stereoscopic resolution of static RDS in rhesus monkeys, also demonstrated that reductions in stimulus exposure duration led invariably to significant and systematic reductions in the accuracy of discrimination performance. These investigators did report, however, that statistically reliable differences in performance between crossed and uncrossed disparities could still be observed at every exposure duration tested. Comparable findings were also reported for several human observers. With the exception of this study, little research has been conducted to examine the specific effects of varying temporal parameters on the processing of crossed and uncrossed disparity information. More importantly, however, whether performance for crossed and uncrossed disparities is affected in a similar way with different temporal presentation modes is not presently known. For example, does pulsing disparity information contained in a target once for varying durations produce similar results as flashing such information?

The second reason for using disparity pulses was that there are two

previous studies that have manipulated this temporal presentation mode to investigate various aspects of stereoscopic visual processing in human observers. Both studies, however, used different paradigms and manipulated different parameters such that it is difficult to compare them directly. Furthermore, the interpretation of their data is equivocal and open to discussion. For example, Beverley and Regan (1974) used two narrow vertical bar targets located on either side of a central fixation point. In the threshold task, observers had to adjust a potentiometer until they could just see the right-hand bar move. In the suprathreshold task, observers had to match the position in depth of the right-hand bar with that of the left-hand bar. In both tasks, the left-hand bar always remained stationary, but the initial position of the right-hand bar could either be behind (uncrossed disparity), on (zero disparity), or in front of (crossed disparity), the plane of fixation. At some variable interval, this target appeared to execute a rapid pulsed movement in depth ($\pm 12'$ of arc) toward or away from the observer, and then it returned to its original position.

Beverley and Regan found that for a given direction of movement in depth, observers' responses to targets located in front of the fixation plane were different from their responses to targets located behind the fixation plane, both qualitatively and quantitatively. In particular, the data revealed that disparity pulses directed towards or away from the fixation plane produced quite different psychophysical sensitivity curves. Observers' visual sensitivity for disparity pulses directed from either location towards the fixation plane was similar to their sensitivity for pulses directed from either location away from the

fixation plane. In other words, what was important was not whether the disparity pulse was directed toward or away from the observer, but its direction relative to the plane of fixation. Since the target began either in front, on, or behind, the fixation plane, these results seem to suggest that visual sensitivity is different for different disparity directions, but not necessarily for crossed and uncrossed disparities per se. As such, they are difficult to reconcile with the idea of separate neural mechanisms for crossed and uncrossed disparity, especially in light of the fact that in current neurophysiological models, crossed and uncrossed disparities are retinotopically defined.

In the second study, Norcia and Stevenson (1982) assessed observers' stereoacuity for single, sinusoidal disparity pulses as a function of their temporal rate and direction over a range of temporal frequencies (0.2 - 51.2 Hz). The test stimulus consisted of a dynamic random-bar stereogram, and the disparity pulses crossed the plane of fixation rather than staying on one side of it. That is, the disparity pulses began and ended at the fixation plane, but differed in their initial direction of motion.

Norcia and Stevenson found that observers' stereoacuity for disparity pulses that initially moved toward them and then returned to the fixation plane was better than for those that initially moved away from them and then returned to the fixation plane. A significant difference in stereoacuity (i.e., 2' vs. 4' of arc) between these different sinusoidal movements was seen at all temporal frequencies below a critical frequency of 3.2 Hz in one observer. In another observer, a similar difference in sensitivity was seen at 0.4 Hz and 1.6 Hz. At

higher temporal frequencies, sensitivity for both observers fell off rapidly at the rate of about 3-dB/octave, and differences in stereoacuity disappeared.

A similar kind of argument can be made against this study. In particular, it is unclear as to whether sensitivity to retinotopically crossed and uncrossed disparities was being assessed because observers may have based their responses on either the leading or the receding movement of the disparity pulse in either direction.

Experimental Paradigm

Given the preceding rationale, the present study examined the effect that several manipulations of spatial and temporal parameters had on the ability of observers to discriminate the direction of brief disparity pulses under several different stimulus conditions. The psychophysical tasks consisted of either two- or four-alternative, forced-choice discriminations, in which observers had to identify the direction of a single pulsed movement in depth as seen relative to the plane of fixation. Performance was assessed in two ways: (a) determining the percentage of trials on which observers correctly identified the direction of the disparity pulses, and (b) computing the latency with which they made correct depth discriminations. The independent variables that were systematically manipulated included (a) disparity direction, (b) disparity magnitude, (c) disparity pulse duration, and (d) type of stereoscopic stimulus (i.e., presence or absence of monocular outlines of the disparate target). An "infinite" pulse duration (IPD) was also

included to examine how prolonged viewing time affected observers' ability to discriminate the direction of the disparity pulses.

Three types of stereoscopic stimuli were tested. The first type of stimuli consisted of simple, two-dimensional line stereograms containing a small central square outline within a larger outer square outline. The second type of stimuli consisted of static, Julesz-type RDS, in which a central disparate square matrix of dots could be displaced by varying amounts in one image relative to the other in order to create the appropriate direction and disparity size. RDS were used because they allow one to assess stereopsis in isolation, without the confounding influence of correlated monocular cues. The third type of stimuli consisted of static RDS, in which the outer square and the inner, central disparate square were both outlined with a monocularly discriminable line contour.

The primary reason for using the first two types of stereograms was that there is evidence indicating that the resolution of depth in classical stereograms containing physical contours and the resolution of depth in RDS may be mediated by different mechanisms (e.g., Bishop & Henry, 1971; Cowey & Porter, 1979; Julesz, 1971, 1978; Julesz & Schumer, 1981). Julesz (1971, 1978), for instance, distinguished between "local" and "global" stereopsis. He proposed that local stereopsis is used for distinguishing monocular local features, and serves as the basis for identifying contours in depth, such as in classical line stereograms. Global stereopsis, on the other hand, is a higher-level module of vision, which is used to localize and identify ambiguous depth surfaces in RDS. Fox (1981) has recently argued, however, that global stereopsis is not

unique to RDS, but also extends to natural images that contain highly complex, textured surfaces and inherent ambiguities (e.g., heavily camouflaged scene).

There are a number of qualitative perceptual differences between local and global stereopsis. For example, depth can be defined with diplopic images in local stereopsis but not in global stereopsis (Julesz, 1971). Global stereopsis can be obtained with stimuli containing vernier cues that are equal to or below the normal threshold of vernier acuity (Julesz & Spivack, 1967). Furthermore, global stereopsis with random-letter stereograms can be produced by brightness differences alone, in the absence of any retinal disparity, and in the presence of retinal rivalry (Kaufman, 1964). Finally, line-contoured stereograms are resolved more quickly than RDS (e.g., Chung & Berbaum, 1984; Julesz et al., 1976; Staller, Lappin, & Fox, 1980), suggesting that local stereopsis is more rapid than global stereopsis. Interestingly, however, neither is affected by stimulus uncertainty, such as by the number of target alternatives (Staller et al., 1980).

In an interesting study, Cowey and Porter (1979) provided evidence that lends additional confirmation to the idea that local and global stereopsis are functionally distinct. They assessed the ability of rhesus monkeys to resolve stereoscopic forms in depth with RDS, prior to and after removing different parts of the visual cortex. Cowey and Porter found that the removal of the inferotemporal cortex resulted in a significant impairment in global stereopsis. The removal of this area, however, produced no substantial impairment in local stereopsis (i.e., resolution of depth with simple bar stimuli). These findings suggest

that there may be independent neural sites for local and global stereopsis.

Recent neurophysiological findings have also suggested that the neural basis of local and global stereopsis may rest on different mechanisms. For example, G. F. Poggio (1984) and Poggio et al. (1985) have tentatively identified binocularly simple cells as the neural candidates for local stereopsis, and have suggested that the operation of binocularly complex cells may underly global stereopsis. The main finding is that although both types of cells can detect unambiguous disparity in simple line-contoured patterns, only binocularly complex cells are able to detect depth correctly under highly ambiguous disparity situations (i.e., dynamic RDS).

The rationale for using the third type of stereogram stems from the conflicting findings in the literature concerning the influence of monocular contours on the perception of depth in RDS. Several studies have shown that the addition of conspicuous monocular cues (i.e., contours that delineate a disparate target in RDS) can aid in the resolution of depth in RDS, but only under certain conditions (e.g., Saye, 1976; Saye & Frisby, 1975). Saye and Frisby (1975), for example, demonstrated that monocular features that enclosed the disparate area were helpful in reducing the amount of time required to perceive depth in RDS, but only for simple, two-planar stereograms containing a relatively large disparity ($1^{\circ}17'$). With small-disparity ($5'$) stereograms, latencies were found to be relatively short, irrespective of whether such monocular cues had been added or not. Saye and Frisby suggested that the relatively long time needed to resolve depth in large-disparity RDS may

be due to the fact that observers must learn to make correct vergence eye movements in order to bring large disparate retinal images into proper registration. Similar results were later obtained by Saye (1976), who found that monocular features that enclosed the disparate area produced the shortest latencies for perceiving depth in large-disparity RDS.

Saye and Frisby (1975) also reported that when dissimilar monocular features, such as a centrally positioned outlined cross, were added to small-disparity RDS, they interfered with the resolution of depth in these stereograms. When a monocular square outline enclosed the disparate region, however, it did not significantly affect the speed with which depth was resolved in these stereograms. Finally, with large-disparity RDS, both types of monocular cues proved helpful. Saye and Frisby suggested that monocular cues can interfere in certain situations (e.g., when they are dissimilar) because they capture the viewers' attention, and thus prevent them from effectively allocating their attention to other regions within the stereogram. On the other hand, monocular features that enclose the disparate area may be effective in aiding sensory fusion because they can quickly guide conjugate eye movements to the disparate region.

In contrast with these findings, Chung and Berbaum (1984) recently reported some evidence showing that the addition of monocular contours to RDS can interfere with the resolution of depth when the two kinds of information are presented simultaneously. These deleterious effects were observed despite the fact that the stereoscopic stimuli that they used contained a relatively small disparity (i.e., $\pm 11.46'$ of arc). Chung and Berbaum's results are inconsistent with the earlier findings of Saye and

Frisby (1975) and Saye (1976), although the underlying reasons for the discrepancy in the results still remain obscure.

In another experiment, Richards (1977) used a magnitude estimation task to examine the effects of monocular contours on the ability of observers to perceive depth in briefly flashed, static RDS. His targets consisted of white, narrow vertical bars ($20' \times 2^\circ$), which could be added to the RDS. In one condition, he presented RDS alone, and in another, RDS with a monocular outline of the disparate target. In all cases, the stereoscopic displays were flashed for 200 ms, and target disparities ranged over $\pm 3^\circ$. The observers' task was to make depth judgments as to the amount of depth seen in the displays with respect to the fixation plane.

Richards found that his observers could not reliably perceive depth with RDS alone, but could only do so when the monocular outline of the target was present. In particular, when monocular contours were present, observers performed quite well, achieving about 80% in accuracy. When such cues were completely eliminated, however, performance dropped dramatically, down to about 15% in accuracy. Richards concluded from these findings that monocular cues not only help in resolving depth in briefly flashed RDS, but are essential.

Richards' conclusions have been criticized on several grounds. Julesz and Schumer (1981) and Schumer and Julesz (1984), for instance, criticized his conclusions on the basis that the particular stimulus configuration that he used violated the essence of RDS. They argued that his RDS targets were too narrow (i.e., in terms of spatial frequency) to be properly resolved within a 200-ms flash. On a different note, Fox

(1981) suggested that Richards' negative findings may have been due to the particular display system that he used to present his stimuli. Specifically, Richards' cathode-ray tube (CRT) displays had a refresh rate of 15 Hz, whereas most investigators use CRTs with higher recycle rates (30-60 Hz). As a possible consequence, the lower rate may have produced apparent motion that interfered with the normal resolution of depth in the stereograms. Finally, numerous studies have shown that both static and dynamic RDS can be fused well within 80 ms with foveal presentations (e.g., Breitmeyer et al., 1975; Julesz et al., 1976), and that depth can reliably be perceived in small-disparity, flashed RDS with exposure durations below 60 ms (e.g., 30 ms, Grabowska, 1983; 60 ms, Julesz & Chang, 1976; 60 ms, Mayhew & Frisby, 1979; 48 ms, Tyler & Julesz, 1980).

These and other sources of empirical evidence strongly suggest that monocular contours are not essential to effectively resolve depth in briefly flashed RDS. Nevertheless, when they are available, monocular cues can aid or interfere in the solution of RDS, depending on the magnitude of disparity and the nature of the cues (e.g., Chung & Berbaum, 1984; Saye, 1976; Saye & Frisby, 1975).

Experimental Hypotheses

On the basis of the existing evidence, five specific hypotheses were formulated for this study. First, it was hypothesized that if the reported superiority of performance for processing crossed over uncrossed disparity information is generalizable across various stimulus conditions

and experimental paradigms, then observers in this study should discriminate disparity pulses in the crossed direction more accurately and more rapidly than equivalent pulses presented in the uncrossed direction, regardless of the type of stereogram used. Furthermore, this asymmetry in discrimination performance should be present across all disparity magnitudes and disparity pulse durations tested. Second, given previous psychophysical evidence (e.g., Harwerth & Boltz, 1979a, 1979b; Uttal et al., 1975), depth discrimination performance should improve as a function of increasing disparity magnitude (up to the disparity limit set in this study) for disparity pulses in both crossed and uncrossed directions, and for both dependent measures. Third, performance should be best with prolonged viewing (i.e., "infinite" pulse duration), and show a progressive decline with decreasing disparity pulse duration. Fourth, it was hypothesized that both the accuracy and latency of depth discrimination performance would be lower in RDS alone than in identically configured, classical line stereograms and in RDS containing monocularly superimposed outlines of the central disparate target and background. This hypothesis was based on the fact that (a) line-contoured stereograms have generally been found to be resolved more accurately and rapidly than RDS (e.g., Chung & Berbaum, 1984; Julesz et al., 1976; Staller et al., 1980), and (b) RDS require the perception of both the discontinuity that occurs at the border of the disparate regions and of the disparity itself (Marr & Poggio, 1979). Finally, it was hypothesized that mean reaction-time performance for the RDS containing monocularly superimposed contours of the central target to be perceived in depth would not differ from that of RDS alone (Saxe, 1976; Saxe &

Frisby, 1975; but see Chung & Berbaum, 1984).

The ultimate goal of this psychophysical inquiry was to establish whether crossed and uncrossed disparity information is processed differently as a function of various spatio-temporal manipulations and in the context of different types of stereoscopic stimuli. It was hoped that these manipulations would also shed some light on the spatio-temporal sensitivities of those mechanisms that have been hypothesized to mediate crossed and uncrossed stereopsis, and possibly begin to suggest how they may function within the visual system.

Method

Observers

Eighteen observers, 9 males and 9 females, between the ages of 19 and 37 years participated in the study. All of the observers were orthophoric, had normal or corrected-to-normal visual acuity (20/20 or better in both eyes), and normal stereopsis and fusion, as assessed with the Keystone Visual Skills battery of tests. Stereoacutities were measured with the Keystone Aviators' Test Set (D.C. 31, to D.C. 53), and ranged from 19" to 45" of arc. Because these tests crudely measure stereoacuity for crossed disparities only, however, observers' ability to process static cues for both disparity directions was also assessed with the use of simple RDS (Figures 1.0-1 and 2.4-1, from Julesz, 1971), portraying two planar surfaces in depth. All observers were able to fuse these stereograms and discriminate the texture surfaces projecting in

depth for both crossed and uncrossed disparity directions. Observers were naive with respect to the purpose and design of the study, and none had any previous experience with RDS. Observers who wore glasses normally used them during the experiment.

Apparatus

The optical viewing system consisted of a modified Wheatstone stereoscope. Observers viewed the stimuli dichoptically through a pair of 50 mm x 50 mm beam splitters, one in front of each eye. A septum separated the two beam splitters, which sat on standard adjustable tilt and rotation platforms. (Beam splitters were used instead of front-surface mirrors because they were readily available. Furthermore, the back and the appropriate side of each beam splitter were occluded, such that observers could only see the stimuli presented on the CRTs). The stimuli were presented on two 12-in. monochromatic, raster-scan CRT displays (Amdex Corp., Model Video 100) with white P4 phosphors, positioned at a viewing distance of 1.575 m to the left and right of the observers at the midline, respectively. Proper positioning and alignment of the beam splitters ensured that each image was channelled independently to the appropriate eye. In addition, head movements were minimized by the use of a chin and forehead rest. The CRTs were controlled by an Apple II microcomputer, and matched for luminance using a calibrated reflex-viewing photometer (Photo Research Division, Kollmorgen Corporation, Burbank, CA, Model UBD). Reaction-times (RTs) and observers' responses were recorded via a commercially available

joystick, and RTs were measured in milliseconds with a programmable real-time clock (California Computer Systems, Model 7440AK). The optical viewing apparatus and corresponding experimental setup are schematically illustrated in Figure 1.

Stimuli

Three types of stereoscopic stimuli (one type for each condition) were used. Each stimulus type was generated by the microcomputer using the high-resolution graphics mode and displayed simultaneously at a 60-Hz frame rate on the face of the two CRTs. All stimuli were presented foveally.

The first type of stereoscopic display (TDL condition) consisted of pairs of simple, line-contoured stereograms containing an outline of the small central square target and an outline of the larger square background. These outlines were white on a uniformly dark background. The square outlines that enclosed the background subtended a visual angle of $2.18^\circ \times 2.29^\circ$ horizontally and vertically, respectively. The square outlines of the central target subtended 0.73° horizontally and 0.76° vertically. (Although the stimulus displays were plotted in an identical fashion on the face of each CRT, they appeared somewhat higher than wide, due to unequal vertical magnification of the images on the CRTs. This horizontal compression, however, was negligible). The field of view presented to each eye on the CRTs was shielded by black mat paper, through which a square-shaped aperture, slightly larger than each stimulus half-field had been cut. Thus, each eye always viewed only one half of

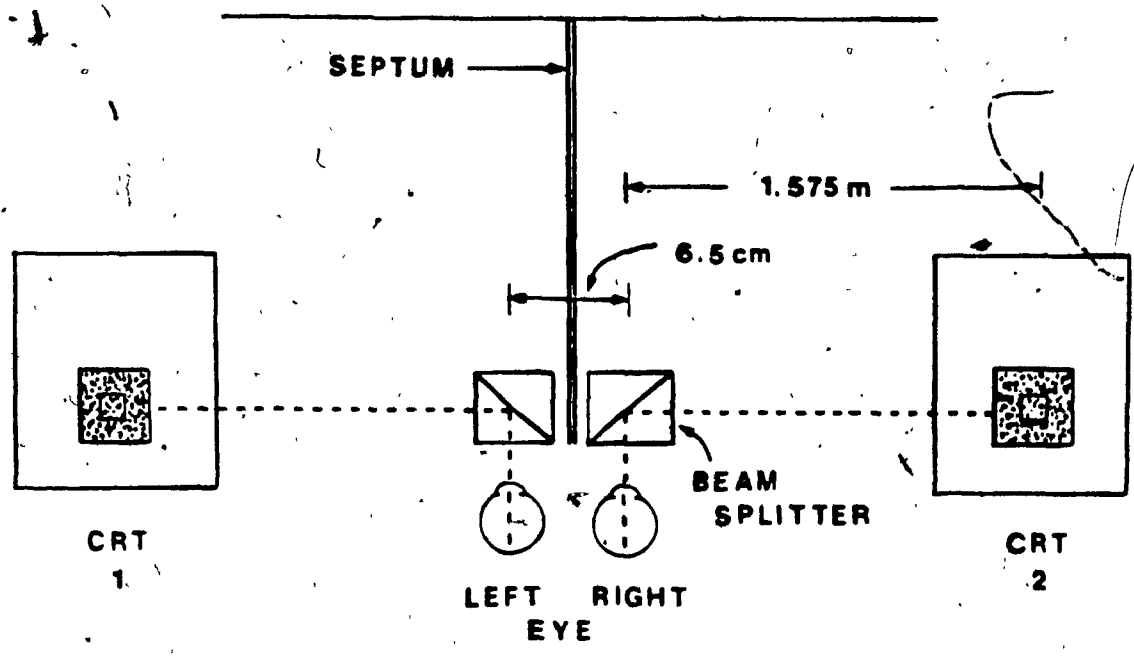


Figure 1. Schematic illustration of the optical viewing apparatus (not to scale).

the stereogram pair; the other half-field was never visible to that eye.

The second type of stereoscopic display (RDS condition) consisted of static Julesz-type RDS, portraying a central square in depth relative to the surround. Each stereogram half-field was composed of a matrix of 84 x 84 randomly positioned achromatic dots. At the viewing distance used in this study, each dot measured 0.7143 mm on the screen, and subtended a visual angle of approximately 1.56' of arc in diameter. The global density (i.e., the ratio of black to white dots) of the stereograms was approximately 50%, and the stereogram pairs were perfectly correlated, such that for each dot in one image there was a corresponding dot in the other. The left- and right-eye images were symmetrical with respect to the plane of fixation and identical to each other, except for the central portion of the images that formed a 28 x 28 matrix of achromatic dots. This central square region was visible only when the dots were shifted laterally to produce the required disparity. The overall dimension and configuration of the RDS were identical to the TDL stereograms.

In the third type of stereoscopic display (RTL condition), each half of the stereograms contained a central outline square embedded in the random dots and a larger square outline that enclosed the background random dots. The depth of the central square outline always coincided with the depth of the RDS target. In all other respects, however, this stimulus type was identical to the other two. An example of the three types of stereograms is represented in Figure 2.

For all three types of stereograms, precise and systematic variations of crossed and uncrossed disparities were produced by shifting the centrally located inner square (or the dots forming the central

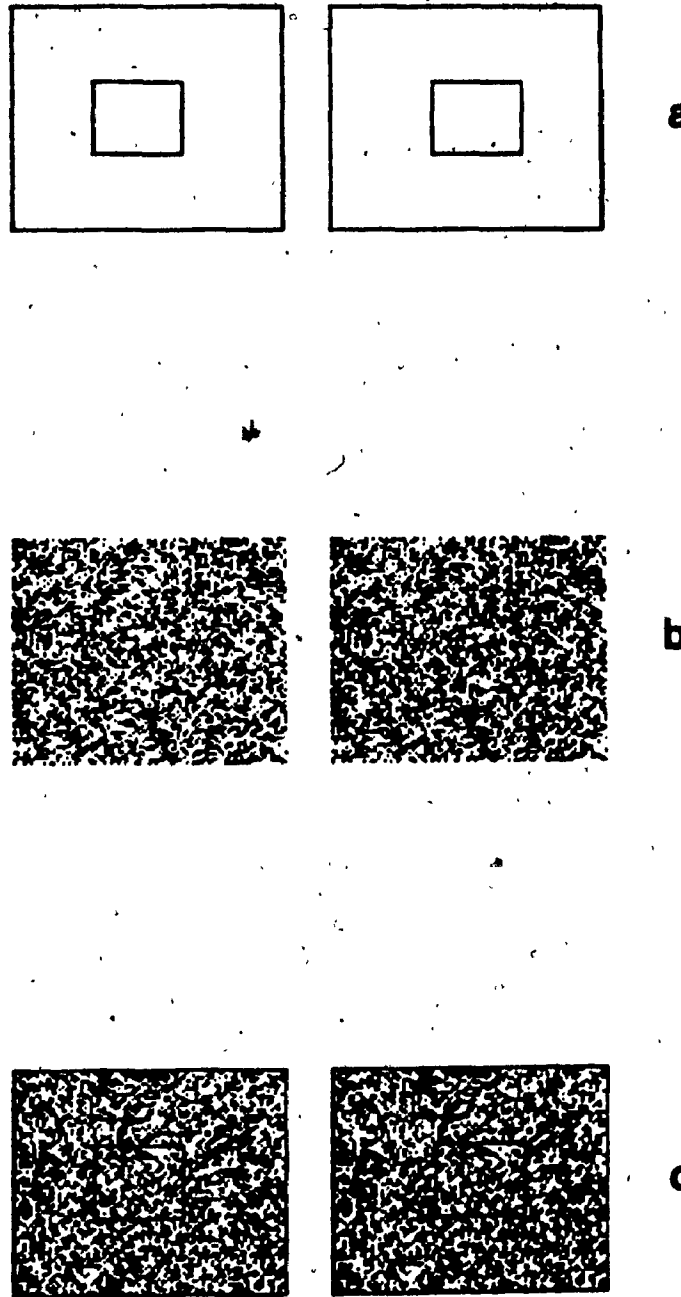


Figure 2. Representative examples of the stimulus displays used in each condition: (a) TDL, (b) RDS, and (c) RTL. In each example above, the central disparity is 4 dots. (The actual stimuli appeared as white figures on a dark CRT face).

disparate square region in RDS) horizontally in one image relative to the other. To create a crossed disparity (i.e., the central square being perceived as nearer), the target boundaries or points were shifted to the right in the left image and to left in the right image (nasal displacement). The reverse (temporal displacement) was done to create an uncrossed disparity. (In the RTL stimuli, both the dots and contours were shifted to create the appropriate disparity). The gap introduced by the shift was replaced with a homogeneously dark area in the monocularly outlined (TDL) stimuli, and completely filled in with an independent set of non-disparate random dots in the RDS and RTL stimuli. In this manner, five disparity magnitudes, ranging from 1.56' to 7.80' of arc, in 1.56' steps, were created for each disparity direction. Each discrete disparity step represented one dot or physical column-width shift on the CRTs. These disparity values were well within the range of "fine" stereopsis (Bishop, 1981), and were chosen such that with the constraints of equipment and viewing distance, they produced perceived depth without ever giving rise to diplopic retinal images.

The central square region's retinal disparity changed with a pulsed waveform, producing a target that appeared to execute a single pulsed movement in depth. The exposure duration of each disparity pulse was carefully controlled, with each disparity pulse being synchronized with the onset of each video raster scan on the CRTs. With a 60-Hz noninterlaced frame rate, the theoretical time unit is $1/60$ s or 16.67 ms, which is the duration of a single frame. This means that an image can only be changed or "refreshed" every 16.67 ms at best. In this study, five distinct disparity pulse durations were used, and they ranged

from about 33 ms to 100 ms, in multiples of 16.67 ms. In addition, an "infinite" pulse duration (IPD) was also included to provide a situation in which observers had a prolonged time to process the disparity information. The range of disparity pulse durations was chosen such that the upper limit was well below the latency required to initiate vergence eye movements, and the lower limit was long enough to allow reliable above-chance discrimination data to be collected. (The latter finding was established on the basis of preliminary pilot work).

When the RDS were viewed monocularly, each of the two stereo patterns appeared as a field of uniformly black and white dots; no contours within the stereograms were evident, and no depth was perceived. When viewed stereoscopically and fused, however, the stimulus patterns revealed a small central square executing a single pulsed movement in depth, either in front of (crossed disparity), or behind (uncrossed disparity), the plane of fixation (zero disparity), depending on the direction of shifting. The amount of perceived depth differed according to the magnitude of shifting. The stereograms contained no information about contour surfaces other than disparity, such that the target could only be resolved by perceiving the apparent depth of the pulsed target with respect to its surround.

The luminance of all three types of stereoscopic displays was measured against a homogeneously lit background and equated at 9.25 cd/m^2 .

Procedure

Prior to the beginning of the study, 6 observers were randomly

assigned to each of the three stimulus conditions (i.e., stereogram types). In the study proper, each observer was tested individually following a repeated-measures design.

For any condition and on any given trial, the initial starting position of the central square target was always located at the center of the background and on the plane of fixation (zero static disparity). Following the initiation of a trial, the target executed a single disparity pulse of a given duration, either toward (crossed disparity) or away (uncrossed disparity) from the observer, and then it returned to its original position. In the TDL and RTL stimulus conditions, the central square target could also execute a sudden displacement either to the left or to the right, and then return to its original position. These lateral displacements were equivalent in magnitude to one discrete disparity step (i.e., 1.56' of arc in total), and for each direction, the target was shifted in equal amounts and in synchrony for both halves of the stereograms.

When the target was displaced to the left or to the right, the target always moved in the same direction for each eye. Under these conditions, only purely lateral displacements were seen; the central square never appeared to move in depth. Left- and rightward displacements of the central target were used to control for direction of shift as a possible cue to perceived depth. Discrimination performance for these planar displacements was not assessed in the RDS condition because preliminary pilot data indicated that observers could not reliably judge the direction of sudden lateral displacements in these stereograms under the viewing conditions of this study.

Disparity movements in the prolonged viewing situation (i.e., "infinite" pulse duration) appeared somewhat different from those cases in which disparities were briefly pulsed. In this situation, a disparity of particular direction and magnitude could be pulsed, but the target remained in this position until the observer initiated a response or until 11 s elapsed; and then it returned to its original position. This value represented the longest possible pulse duration for which a visual display could be exposed.

Observers completed a total of five sessions, each consisting of 10 blocks of 36 trials. Within each block, disparity magnitude was held constant, but disparity direction and pulse duration varied randomly, such that crossed and uncrossed disparity shifts appeared 12 times each, and left and right target displacements each appeared six times. This configuration of trials resulted in disparity pulse durations being paired twice with each disparity direction and once with each left or right target shift within each block. (In the RDS condition, crossed and uncrossed disparity shifts were randomly presented 18 times each. Consequently, each disparity pulse duration was paired three times with each disparity direction). Disparity magnitudes were completely randomized and counterbalanced across blocks of trials.

Each session began with a block of 36 practice trials. These trials were always presented at the largest disparity value (i.e., 7.80' of arc), and served to ensure that observers began the test sessions thoroughly practiced. Practice data were not included in the final analysis, but were carefully screened for the presence of any irregularities in depth discrimination performance from one session to

the next. In addition, response feedback was given on these trials. Only one session per observer was conducted on each day, and each session lasted approximately 1 hr.

All testing took place in a dark room; the only light in the room was provided by the CRT displays. Prior to the beginning of each experimental session, the two CRTs were carefully matched for brightness. Subsequently, observers dark-adapted for several minutes while the experimenter reviewed the instructions and answered any questions. In all cases, observers were instructed to discriminate the direction of the disparity movements in the stereoscopic displays as seen relative to the plane of fixation.

On any given trial, observers initially viewed a static stereogram display containing no horizontal disparity. The display consisted of one of the three stereogram types being presented to an observer. When viewed stereoscopically, observers saw a flat surface on the fronto-parallel plane (i.e., no perceived depth). This display served as the fixation target, and was used to ensure that observers were properly converged on the fixation plane prior to the initiation of a trial. If observers were converged correctly, the two halves of the stereogram appeared fused and were seen as a single stereogram. If convergence was not correct, the two halves were not seen as a single fused image. Fixation points or nonius markers were not used in this study in order to avoid any possible interaction or interference with the measured effect, especially in the RDS and RTL conditions. (This finding was established from preliminary pilot work). To promote proper fusion of the brief disparity pulses, the visual displays being presented to each eye were

carefully aligned and matched in every respect. Observers were asked to report if the stimuli failed to overlap completely at any time during the study.

When the fixation target appeared properly fused, observers initiated a trial by depressing a button located on the top of a self-centering joystick. This joystick was positioned in front of the observers and could be reached and manipulated with ease. Upon depressing the button, the central square target executed a single disparity pulse, either toward or away from the observer (all conditions), and/or to the left or to the right of its original starting position (TDL and RTL conditions). Depressing the button also started the real-time RT clock.

Observers were instructed to move the joystick toward or away from themselves if they judged the direction of the disparity movement to be nearer or farther from the background, respectively, or to the left or to the right if they thought that the target moved in either of those two directions. Movement of the joystick in any direction immediately extinguished the visual display and stopped the real-time clock. A brief warning tone, emitted from the microcomputer's internal speaker, always preceded the presentation of a trial. RTs were measured in milliseconds from the onset of the target disparity pulse to the onset of the observer's response (i.e., movement of the joystick in a particular direction). After a brief 500-ms interval following a response, the fixation target reappeared, and the next trial was ready to begin. At all times when the target was not being presented, the zero-disparity fixation target was on, corresponding to the particular type of

stereogram being presented to that observer. Intertrial intervals varied according to each observer's pace.

Observers were not informed about the proportion of stimuli having a particular direction within each block of test trials, and no response feedback of any kind was provided on these trials. They were instructed to respond as quickly and accurately as possible to the direction of the disparity pulses.

Provisions were made in the programming of the target disparity jumps for incorrect manual movements of the joystick. For example, if the joystick was accidentally moved in a diagonal direction, the microcomputer emitted a series of audible clicks to warn the observer. When these occurred, they were subsequently excluded from further data analysis. Likewise, if observers made an anticipatory response to a target (i.e., arbitrarily defined as RTs below 200 ms), the trial was discarded. Similar precautions were also taken to guard against the joystick being held for too long in a particular position other than its natural center. (Practice trials ensured that these types of inappropriate manual responses were kept at a minimum, and indeed, these problems were seldom encountered on test trials). Observers were encouraged to make a response in the appropriate direction and immediately release the joystick. They were requested to maintain good fusion throughout each block of trials, and never to initiate a trial if fusion was not present. Finally, if observers failed to make a response within 11 s, the trial was aborted and the next one began. These trials were not repeated and were subsequently excluded from the data analyses.

Results

The ability of observers to discriminate the direction of the disparity movements in depth in each stimulus condition was systematically evaluated by examining (a) the percentage of total correct responses, and (b) the latency in milliseconds with which the responses were made. Only correct trials were included in the analysis of the RT data. Aborted trials, due to anticipatory, improper, or no responses, were examined but not included in the analysis of these data. Within each block of trials, percent correct responses (PCRs) and mean reaction times (MRTs) for each observer were computed for each trial type. The data for each dependent variable were subsequently averaged for each observer. In the TDL and RTL stimulus conditions, 25% represented chance performance because of the four-alternative, forced-choice procedure. Similarly, in the RDS condition, the a priori basis for making a correct response by chance alone was 50%, given the two-alternative, forced-choice discrimination task. Observers were not informed about these limits.

Because the study examined the effects of disparity direction, magnitude, and pulse duration on two dependent measures simultaneously, separate three-way, repeated-measures multivariate analyses of variance (MANOVAs) were conducted on the mean data of each stimulus condition. These analyses were performed by BMDP4V (Dixon, 1981), using equal cell weights, and run on a CDC Cyber 835 computer. MANOVAs were conducted because they allow one to assess the linear combination of multiple

dependent variables, and take into account the interrelationship between the dependent measures and the possibly increased alpha (Type I) error levels. Multiple MANOVAs were performed for each condition rather than a single overall MANOVA incorporating all the variables in three conditions because each condition contained a different number of levels associated with the independent variables. Separate univariate analyses of variance (ANOVAs) were also performed on the mean data of each dependent variable because of the difficulty in interpreting a significant main effect in MANOVA. When one is found, it is often not immediately apparent which of the dependent variables contributed most to the differences between the groups being compared. The Scheffé test ($\alpha = .05$) was used to determine if significant differences existed among various comparisons of the treatment means. The normal-curve approximation to binomial values, with correction for continuity, was used to compare the overall mean accuracy results against chance level.²

The results that follow were obtained by first analyzing the data of each observer and from each stimulus condition separately in order to detect any individual trends or specific patterns. The mean data for all observers combined were then subjected to an overall analysis in order to make appropriate comparisons among the three stimulus conditions. The results obtained from this overall analysis were also used in a final step-down analysis (Roy & Bargmann, 1958) in order to evaluate the relative contribution of each dependent measure.

Analysis of the TDL Data

No statistically significant, multivariate main effect of practice was found, $F(8, 48) = 0.93, p > .05$. This main effect was also not significant when each dependent variable was evaluated separately: PCR, $F(4, 25) = 1.30, p > .05$; MRT, $F(4, 25) = 1.72, p > .05$.

The percentage of trials excluded from the analysis of the RT data for each observer was relatively low, and ranged from 1.17% for Observer 6 to 12% for Observer 3. A repeated-measures MANOVA (Direction x Disparity x Pulse Duration), conducted on the observers' mean data, indicated that the main effects of each independent variable were statistically significant for both dependent measures. A detailed summary table of this analysis is presented in Appendix A, Table A-1.

In addition to showing that the combined dependent variables were significantly affected by the experimental manipulations, the results of this condition also revealed that about 76% of the variance in the linear combination of PCR and MRT scores was accounted for by the effect of disparity direction. Similarly, the data also demonstrated a strong degree of association between disparity magnitude and disparity pulse duration and the combined dependent variables, $\eta^2 = .91$ and $\eta^2 = .77$, respectively.

The results showing the overall main effect of disparity direction averaged across all other factors and across all 6 observers, are presented in Figure 3. There was a significant multivariate main effect of disparity direction, $F(6, 28) = 4.79, p < .001$, as well as significant univariate main effects of this variable for each dependent measure:

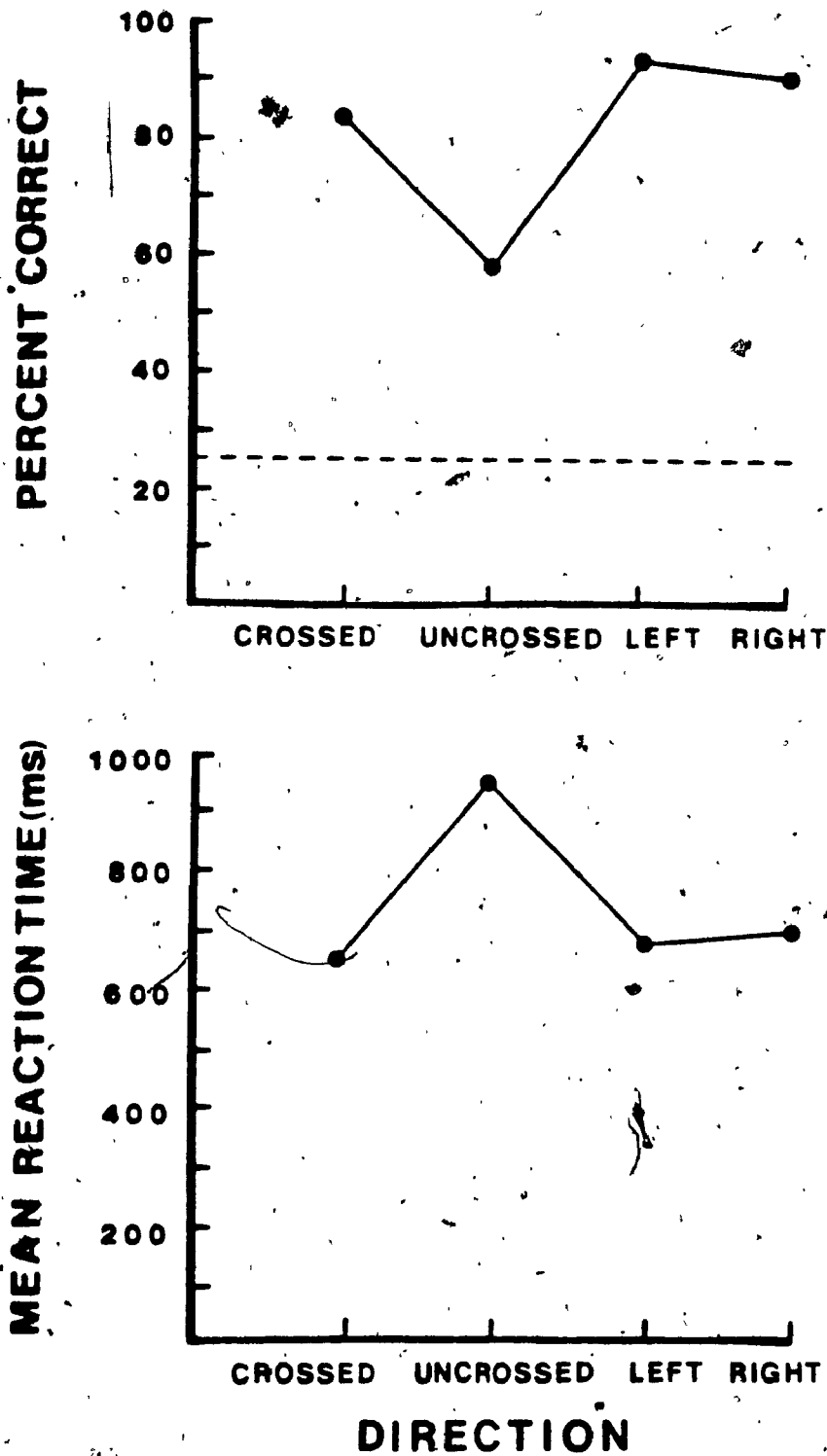


Figure 3. Mean number of correct depth discriminations (PCR) and mean reaction-time (MRT) data as a function of disparity direction in Condition TDL. Chance level (25%) for the mean accuracy data is indicated by the dashed horizontal line.

PCR, $F(3, 15) = 7.70$, $p < .001$; MRT, $F(3, 15) = 5.23$, $p < .005$. Pairwise comparisons of the mean data indicated that the overall level of performance for crossed disparities was clearly superior to that for uncrossed disparities, both in terms of accuracy, $F(3, 15) = 10.09$, $p < .05$, and speed, $F(3, 15) = 10.16$, $p < .05$. Indeed, responses to disparity pulses in the crossed direction were consistently faster than to those in the uncrossed direction, and this finding was reflected in the overall MRT data (656.95 ms vs. 918.62 ms, respectively). Individual analyses performed on each observer's data showed that 5 out of the 6 observers tested in this condition exhibited this crossed-uncrossed asymmetry in depth discrimination performance. Incidentally, the same observer (i.e., Observer 4) who did not show a difference in his accuracy of performance for the two disparity directions, also failed to show a similar difference in MRT performance.

Interestingly, the overall level of performance for discriminating crossed-disparity pulses was not different from the level of performance for discriminating left or right target displacements, neither in terms of accuracy nor latency, all $F_s(3, 15) < 1.01$, $p > .05$. Discrimination performance with uncrossed-disparity pulses, on the other hand, was significantly depressed in comparison to performance for both left and right target displacements, and for both dependent variables, all $F_s(3, 15) > 13.13$, $p < .025$. The overall level of performance for discriminating left and right target displacements did not differ for either of these directions, and this was observed for both the PCR and MRT data, both $F_s(3, 15) < 0.10$, $p > .05$. Finally, the results revealed the presence of a highly negative correlation between the two dependent

variables, $r = -.86$, indicating that higher accuracy of performance was generally accompanied by shorter MRTs.

When the main effect of disparity magnitude was evaluated, it was found that performance generally improved with increasing amounts of disparity for both PCR and MRT responses when they were considered simultaneously, $F(8, 38) = 11.52, p < .001$. When considered separately, this main effect was also significant for each dependent measure: PCR, $F(4, 20) = 46.57, p < .001$; MRT, $F(4, 20) = 10.92, p < .001$. Post hoc comparisons revealed that PCR performance was significantly lower at the smallest disparity value (1.56') when compared to each of the other levels of magnitude, all $F_s(4, 20) > 16.21, p < .025$. A similar analysis of the MRT data indicated that the mean level of performance differed significantly at each disparity level, all $F_s(4, 20) > 11.68, p < .05$. The only instance where this pattern did not hold was found when comparing mean latency performance between the two smallest disparity levels, $F(4, 20) = 4.08, p > .05$.

The robustness of the crossed-uncrossed disparity difference was further confirmed when mean performance levels for each disparity direction were evaluated against disparity magnitude. Figure 4 illustrates the two principal findings. First, there was a clear and consistent difference between the level of depth discrimination performance for crossed and uncrossed disparities at every disparity level tested, with performance for crossed disparities being superior to that for uncrossed disparities. This was true for both PCR and MRT performance, all $F_s(3, 15) > 31.24, p < .001$, and all $F_s(3, 15) > 32.49, p < .001$, respectively. The mean level of performance for discriminating

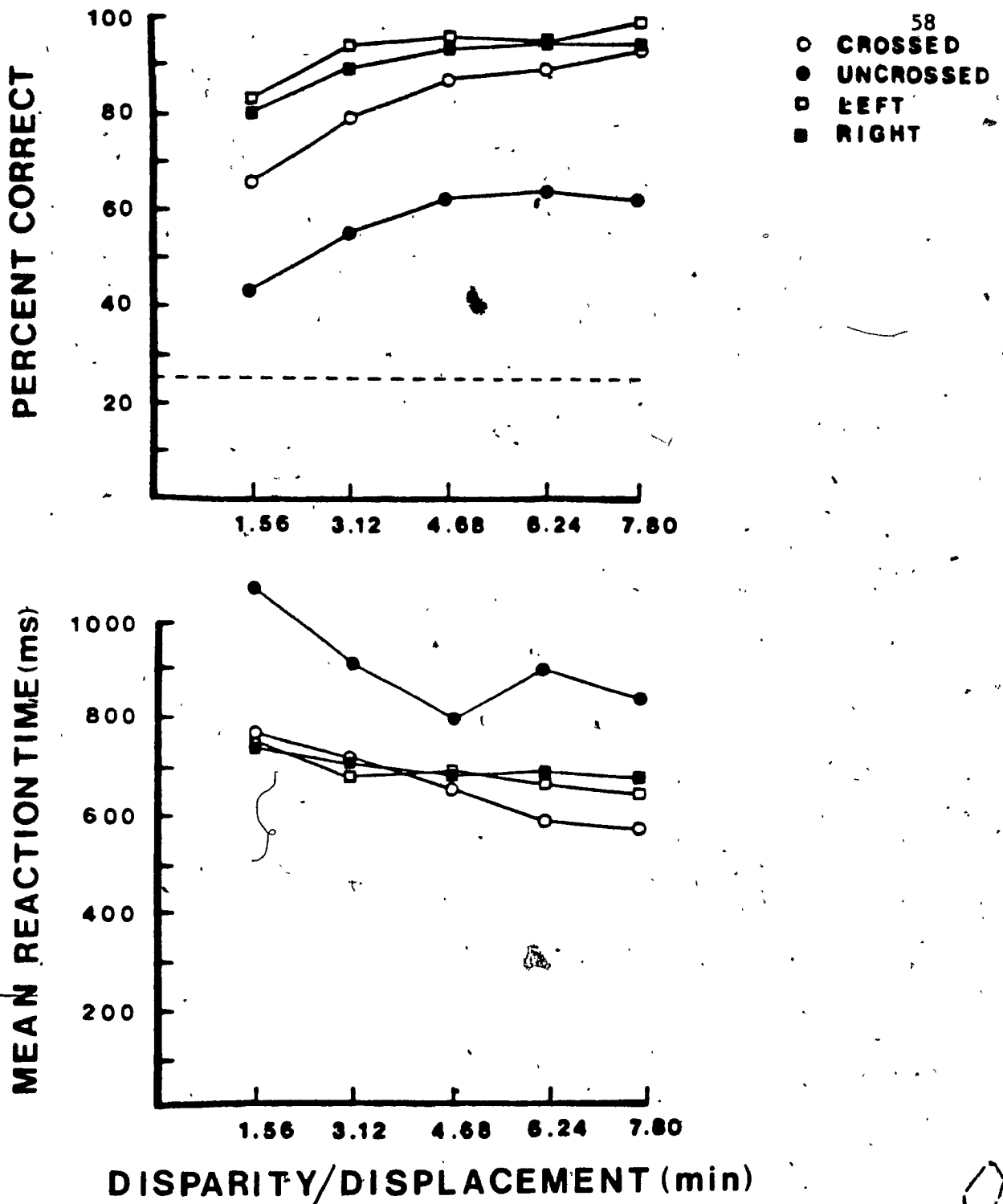


Figure 4. Mean number of correct depth discriminations (PCR) and mean reaction-time (MRT) data as a function of disparity direction and disparity magnitude in Condition TDL. Chance level (25%) for the mean accuracy data is indicated by the dashed horizontal line.

uncrossed disparities was consistently lower than the mean level of performance for discriminating left and right target displacements for both dependent variables, all $F_s(3, 15) > 16.00$, $p < .025$. The mean level of accuracy for discriminating crossed disparities differed from that for discriminating left target displacements only at 1.56' and 3.12' of arc, both $F_s(3, 15) > 12.16$, $p < .05$, and from that for discriminating right target displacements, only at the smallest disparity value, $F(3, 15) = 10.85$, $p < .05$. The MRT data did not show any comparable differences at any disparity level, all $F_s(3, 15) < 9.74$, $p > .05$. Finally, discrimination performance for left and right target displacements did not differ for either of these directions. This nonsignificant difference was observed for both dependent variables and across all disparity levels, all $F_s(3, 15) < 1.61$, $p > .05$.

The results shown in this figure also revealed that the MRT data for both crossed and uncrossed disparities declined more rapidly as a function of increasing disparity magnitude than they did for left and right target displacements. Interestingly, these data also revealed the presence of a reversal in the uncrossed-disparity function between 4.68' and 6.24' of arc. The asymmetric decline in MRT performance with respect to disparity/displacement magnitude, or the reversal in performance, may account for the presence of the significant interaction between the direction and amount of disparity observed for the MRT data in this condition (see Appendix A, Table A-1).

Second, the data also revealed that accuracy improved and latency decreased steadily with increases in disparity magnitude for both crossed and uncrossed directions, all $F_s(4, 20) > 11.98$, $p < .05$. The only

instances where this trend did not hold were observed in the MRT data for pulses presented in the crossed direction between the two smallest disparity levels, $F(4, 20) = 2.12$, $p > .05$, and in the inversion of the MRT data between 4.68' and 6.24' for disparity pulses in the uncrossed direction. Discrimination performance for left and right target displacements did not show any systematic variation as a function of increasing displacement magnitude, all $F_s(4, 20) < 10.63$, $p > .05$.

A further examination of the mean data of all observers in this condition indicated that their overall level of performance was also affected by manipulations of disparity pulse duration when both dependent measures were considered together, $F(10, 48) = 5.24$, $p < .001$. Only the PCR data, however, showed a significant univariate main effect of pulse duration, $F(5, 25) = 12.01$, $p < .001$. Subsequent post hoc analyses of these data revealed that the mean level of accuracy was significantly higher when disparities were pulsed for an "infinite" duration than when they were pulsed for the shortest duration, $F(5, 25) = 22.29$, $p < .005$. Furthermore, mean discrimination performance at the shortest pulse duration was significantly depressed in comparison with performance at the two longest pulse durations: 83 ms, $F(5, 25) = 13.67$, $p < .05$, and 100 ms, $F(5, 25) = 17.88$, $p < .025$. The PCR data for each direction, on the other hand, did not differ from one another at the longer disparity pulse durations, all $F_s(5, 25) < 3.72$, $p > .05$. Finally, the manipulation of disparity pulse duration had no significant effect on observers' overall MRT scores, $F(5, 25) = 1.58$, $p > .05$.

The parametric functions shown in Figure 5 serve to illustrate the rather sizeable differences that were found between depth discrimination

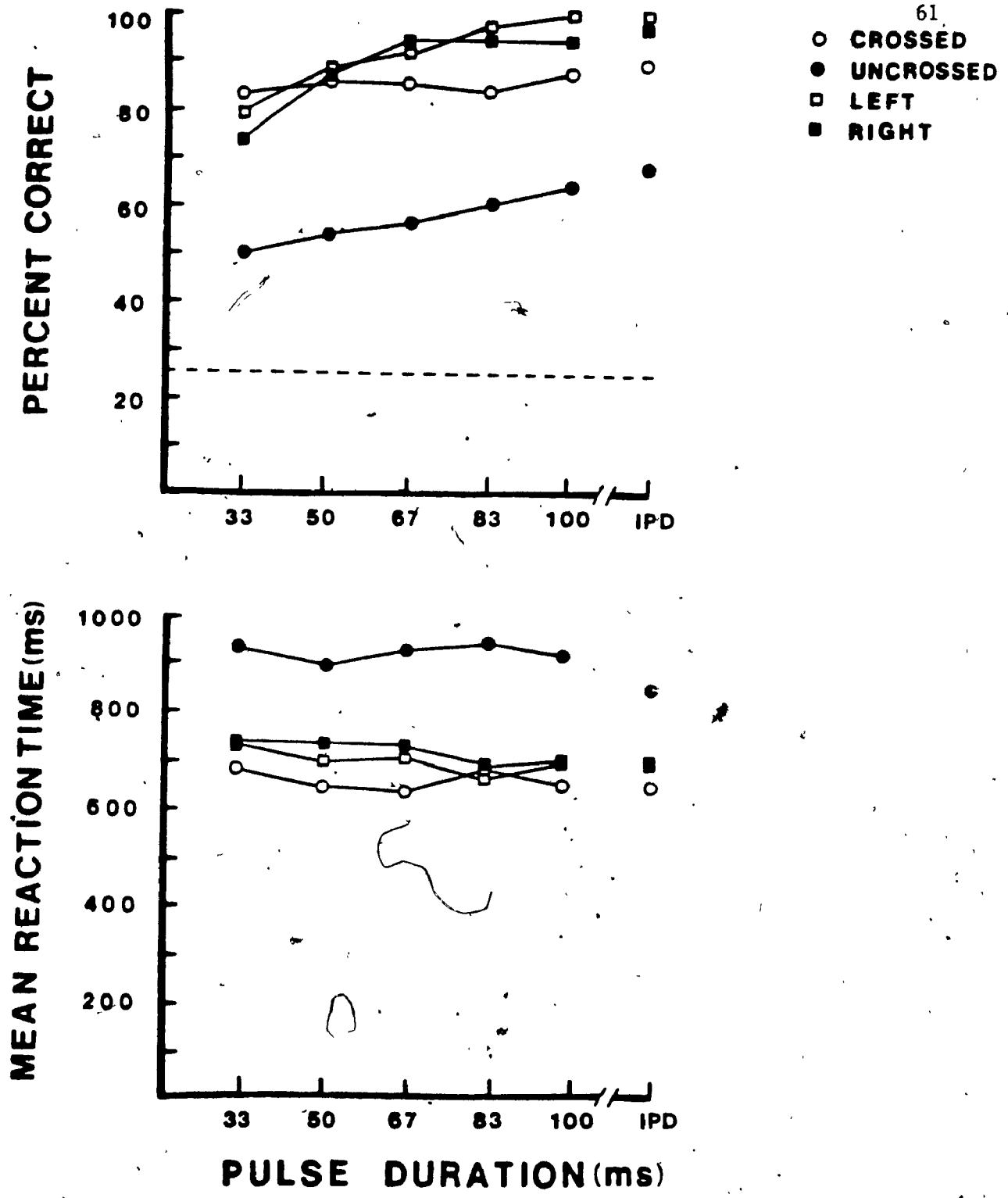


Figure 5. Mean number of correct depth discriminations (PCR) and mean reaction-time (MRT) data as a function of disparity direction and disparity pulse duration in Condition TDL. Chance level (25%) for the mean accuracy data is indicated by the dashed horizontal line. IPD refers to "infinite" pulse duration.

performance for crossed and uncrossed disparities with respect to manipulations in disparity pulse duration. Statistically reliable differences between the performance for crossed and uncrossed disparities were observed at every disparity pulse duration tested, with the differences becoming progressively smaller as the pulse durations increased. At each pulse duration, the mean level of performance for discriminating disparity pulses in the crossed direction was clearly superior to that for discriminating disparity pulses in the uncrossed direction, both for the PCR, all $F_s(3, 15) > 12.81$, $p < .025$, and MRT data, all $F_s(3, 15) > 64.17$, $p < .001$. By contrast, the level of performance for discriminating pulses having an uncrossed disparity was consistently poorer than the level of performance for discriminating left and right displacements of the central target for both dependent variables, all $F_s(3, 15) > 16.28$, $p < .01$. Discrimination performance for left and right target movements did not differ significantly for either dependent variable, all $F_s(3, 15) < 0.64$, $p > .05$.

Figure 5 also shows that the overall level of accuracy for discriminating crossed disparities was not affected by manipulations of disparity pulse duration, neither for the PCR nor the MRT scores, all $F_s(5, 25) < 9.72$, $p > .05$. The mean level of accuracy for discriminating left and right target displacements was significantly higher at the "infinite" pulse duration than it was at the 33-ms disparity pulse duration, $F(5, 25) = 13.19$, $p < .05$, and $F(5, 25) = 14.70$, $p < .05$, respectively. Pulsing disparities for an "infinite" duration also produced significantly lower MRTs to uncrossed disparities, but only when compared to MRTs obtained with the shortest pulse duration, $F(5, 25) =$

13.48, $p < .05$. No other systematic differences were observed in the MRT data.

Finally, an analysis of how performance varied with respect to disparity magnitude and pulse duration revealed several noteworthy results, and these data are presented in Figure 6. First, it can be seen that both the mean accuracy and speed of depth discrimination performance improved as a function of increasing disparity magnitude and increasing disparity pulse duration, all $F_s(4, 20) > 12.17$, $p < .05$, and all $F_s(5, 25) > 13.08$, $p < .05$, respectively. The only exception to this general trend was observed for the "infinite" pulse duration situation in the PCR data, which did not show any systematic variation as a function of disparity magnitude, all $F_s(4, 20) < 5.16$, $p > .05$. Second, the mean level of accuracy achieved with the shortest disparity pulse duration was significantly lower than that achieved with the "infinite" pulse duration at 1.56' and 3.12' of arc, $F(5, 25) = 33.79$, $p < .001$, and $F(5, 25) = 23.33$, $p < .005$, respectively. The fairly large initial differences seen in the overall accuracy of performance at the smallest disparity levels, and the convergence of the data at the largest disparity levels, probably represent the source of the significant interaction between the amount of disparity and the duration of the disparity pulses found for these data (see Appendix A, Table A-1).

The MRT data did not show any significant differences in performance with respect to manipulations of both disparity magnitude and disparity pulse duration, all $F_s(5, 25) < 1.68$, $p > .05$. The overall analysis, however, did reveal the presence of a small but significant three-way interaction among the independent variables for these data, $F(60, 300) =$

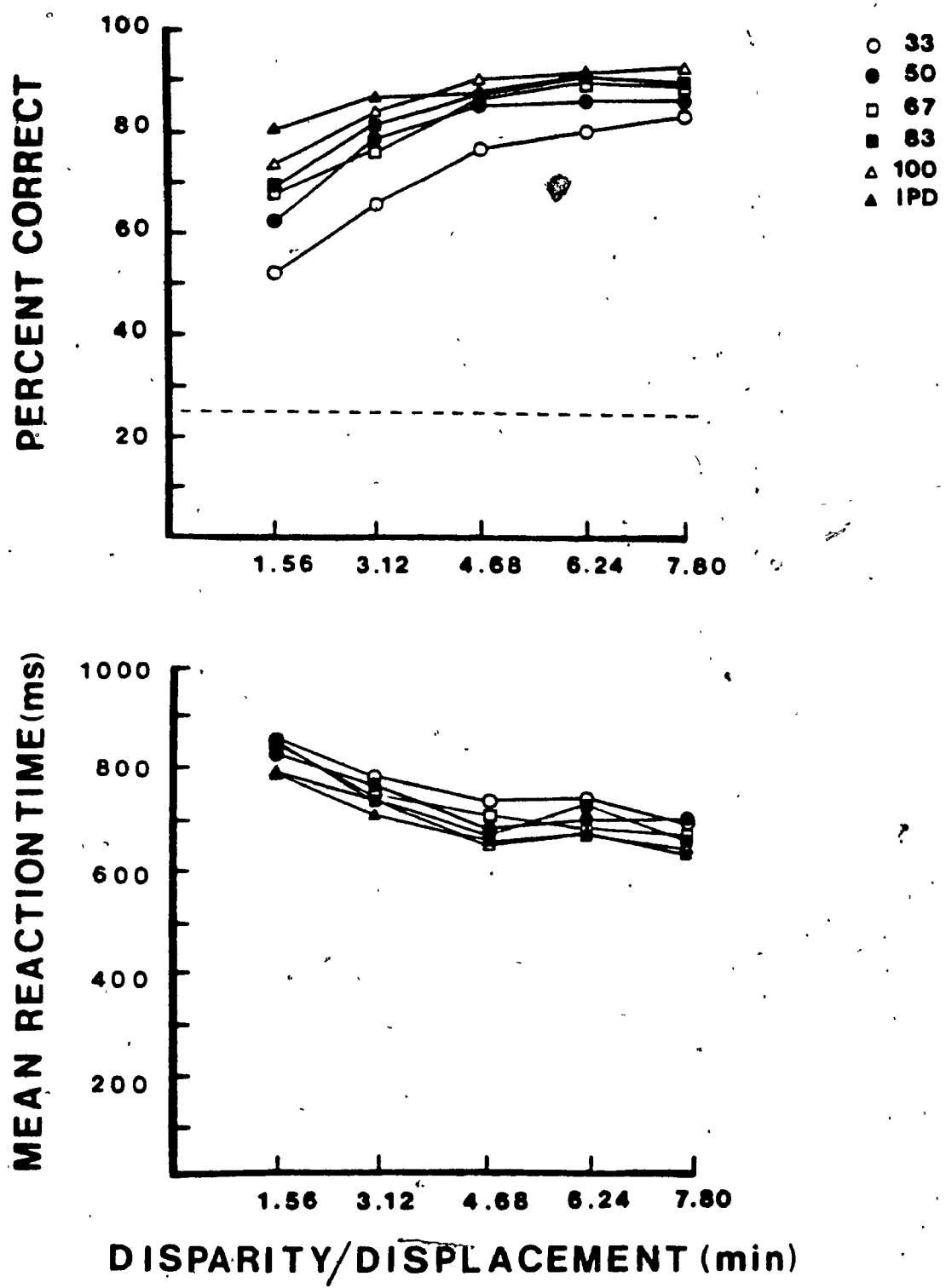


Figure 6. Mean number of correct depth discriminations (PCR) and mean reaction-time (MRT) data as a function of disparity magnitude and disparity pulse duration in Condition TDL. Chance level (25%) for the mean accuracy data is indicated by the dashed horizontal line. IPD refers to "infinite" pulse duration.

1.53, $p < .05$.

The combined mean data of all observers in this condition are presented in Appendix C, Table C-1, and the mean data of each observer are presented in Appendix D, Tables D-1 to D-6.

Analysis of the RDS Data

The only difference between this condition and the TDL condition was that there were only two levels of disparity direction, namely, crossed and uncrossed. (Data for left and right target displacements were not obtained in this condition because pilot work showed that observers could not reliably identify the direction of these lateral movements in RDS). The other independent variables and their corresponding levels remained identical and were factorially combined.

A preliminary analysis of each observer's data indicated that two observers failed to perform significantly above chance when their mean accuracy data were pooled across both disparity directions: Observer 5, $\bar{z} = 0.63$, $p > .05$, two-tailed; Observer 6, $\bar{z} = -0.53$, $p > .05$, two-tailed. When the data of these observers were removed and the remaining data were subjected to a subsequent overall analysis, the same pattern of results was obtained with or without the inclusion of their data. Therefore, all of the analyses for this stimulus condition were performed on the mean data of all observers and are reported as such.

The results of a preliminary MANOVA indicated that the combined dependent variables were not significantly affected by practice, $F(4, 48) = 0.51$, $p > .05$. Furthermore, performance did not vary to a

significant extent from one session to the next, neither in terms of overall accuracy nor speed, $F(4, 25) = 0.25$, $p > .05$, and $F(4, 25) = 0.46$, $p > .05$, respectively. Of the 6 observers who participated in this condition, only one observer's mean data (i.e., Observer 1) showed any evidence of improvement over sessions, $F(4, 9) = 7.30$, $p < .01$.

The percentage of trials excluded from the analysis of the RT data for each observer in this condition was relatively low, ranging from 0.67% (Observer 1) to 11.33% (Observer 5). Results of the principal data analysis ($2 \times 5 \times 6$ repeated-measures MANOVA) revealed that only the main effect of disparity direction was significant when both dependent variables were considered simultaneously, $F(2, 4) = 13.31$, $p < .025$. However, this main effect was significant only for the PCR data when evaluated in a separate univariate ANOVA, $F(1, 5) = 30.86$, $p < .001$. Furthermore, neither disparity magnitude nor disparity pulse duration had any significant multivariate effect on overall mean depth discrimination performance, and only a univariate main effect of pulse duration was found for the accuracy data. No other significant main effects or interactions were detected for these data. The principal results of the analysis are summarized in Appendix A, Table A-2.

With the use of Wilks' criterion, the disparity direction scores (i.e., crossed vs. uncrossed) and the combined dependent variables were found to be very highly associated, $\eta^2 = .98$. By contrast, the association between the disparity magnitude and pulse duration scores and the combined dependent variables was substantially smaller, $\eta^2 = .22$ and $\eta^2 = .49$, respectively.

When the univariate main effect of disparity direction was explored

further with a series of Scheffé tests, the results of these tests revealed that the overall level of accuracy for discriminating disparity pulses in the crossed direction was significantly better than it was for discriminating disparity pulses in the uncrossed direction, $F(1, 5) = 15.12$, $p < .025$. In fact, all 6 observers performed more accurately with crossed-disparity pulses than with uncrossed-disparity pulses when their data were evaluated in this manner, all $F_s(1, 240) > 47.44$, $p < .001$. By contrast, no statistically reliable differences in depth discrimination performance were found between crossed and uncrossed disparities when the combined MRT data were subjected to a similar analysis, $F(1, 5) = 2.23$, $p > .05$. Moreover, only 2 of the 6 observers discriminated crossed-disparity pulses more rapidly than pulses of the opposite direction: Observer 2, $F(1, 207) = 17.08$, $p < .001$; Observer 3, $F(1, 206) = 21.37$, $p < .001$. The overall mean latency for discriminating crossed-disparity pulses for all observers was 722.40 ms, compared to 781.10 ms for uncrossed-disparity pulses. These findings are illustrated in Figure 7.

All of the observers discriminated pulses containing crossed disparities above chance, all $z_s > 5.06$, $p < .001$, two-tailed, but only one observer (i.e., Observer 1) was able to discriminate pulses with uncrossed disparities consistently above chance, $z = 7.13$, $p < .001$, two-tailed. In other words, most observers performed better when the depth plane of the RDS was pulsed in front of the background rather than behind it, but only in terms of accuracy. The pooled within-cell correlation between the PCR and the MRT data was found to be marginal, $r = -.54$.

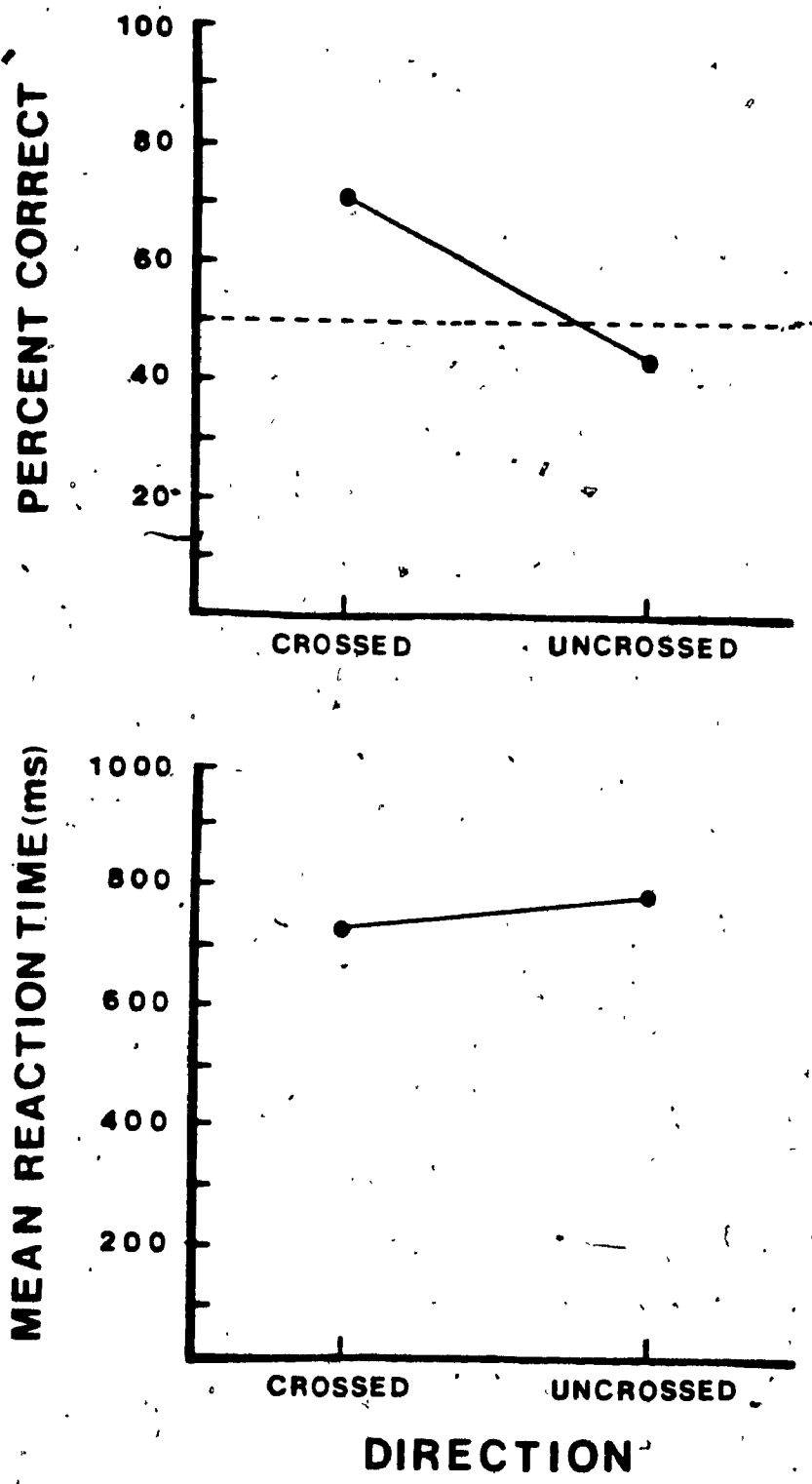


Figure 7. Mean number of correct depth discriminations (PCR) and mean reaction-time (MRT) data as a function of disparity direction in Condition RDS. Chance level (50%) for the mean accuracy data is indicated by the dashed horizontal line.

Although the results obtained in this condition demonstrated that the combined dependent variables were not affected by either the amount of disparity in the RDS or the duration for which the disparity information was pulsed, the univariate main effect of disparity pulse duration was significant for the PCR data, $F(5, 25) = 3.39, p < .025$. (The lack of a disparity and duration main effect in the MANOVA but one in the ANOVAs, indicates that the two dependent measures did not contribute equally to the observed significance of the multivariate analysis). Furthermore, post hoc comparisons indicated that the mean accuracy with which depth discriminations were made was greatest when disparities were pulsed for an "infinite" duration than when they were pulsed for 33 ms, $F(5, 25) = 13.87, p < .05$. The MRT data, on the other hand, did not reveal any systematic differences as a function of disparity pulse duration, all $F_s(5, 25) < 2.20, p > .05$.

The mean data presented in Figures 8 and 9 illustrate additional principal findings of this condition. Figure 8 reveals that the mean level of performance for discriminating disparity pulses in both crossed and uncrossed directions was not affected by manipulations of disparity magnitude, neither in terms of accuracy nor speed, all $F_s(4, 20) < 6.99, p > .05$. Moreover, the pooled mean accuracy scores for both directions did not differ from chance at any disparity level, all $z_s < 1.38, p > .05$, two-tailed. When each direction was evaluated separately, however, the overall accuracy level for discriminating crossed-disparity pulses was found to be consistently above chance at each disparity magnitude, all $z_s > 1.97, p < .05$, two-tailed. By contrast, depth-discrimination performance for uncrossed-disparity pulses did not differ

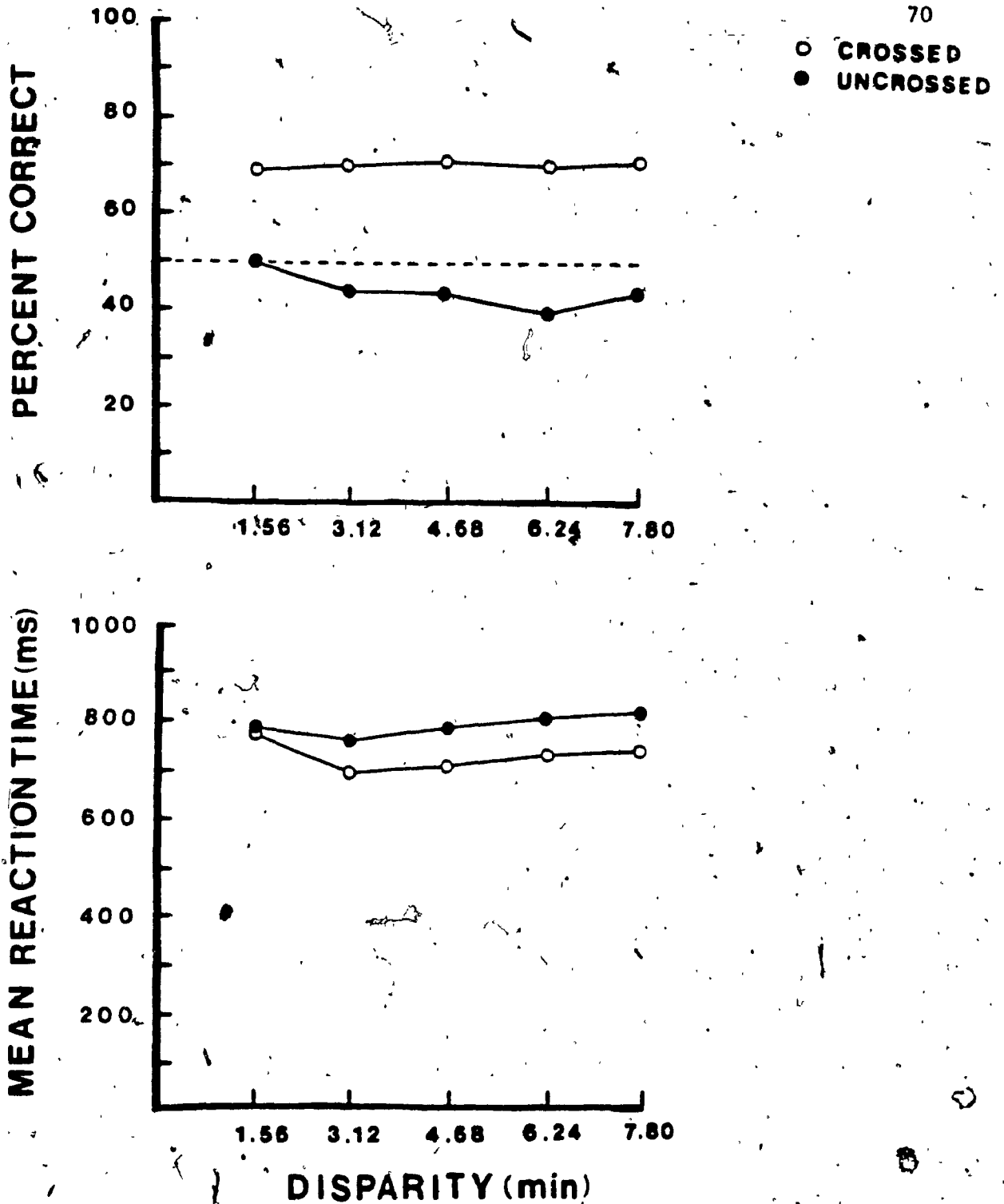


Figure 8. Mean number of correct depth discriminations (PCR) and mean reaction-time (MRT) data as a function of disparity direction and disparity magnitude in Condition RDS. Chance level (50%) for the mean accuracy data is indicated by the dashed horizontal line.

significantly from chance at any disparity level, all $z_s < -1.20$, $p > .05$, two-tailed. Nevertheless, there was a consistent and reliable difference between the mean accuracy of performance for crossed and uncrossed disparities at every disparity level, all $F_s(1, 5) > 9.48$, $p < .05$, with crossed-disparity pulses being discriminated more accurately than pulses with uncrossed disparity across the entire range of disparities tested. The MRT data, on the other hand, did not reveal the presence of a similar difference in observers' ability to resolve between crossed- and uncrossed-disparity pulses, all $F_s(1, 5) < 6.44$, $p > .05$.

Figure 9 compares the overall level of performance for each direction as a function of disparity pulse duration, and it reveals a similar pattern of results. Except for the significant differences that were observed in the accuracy data for uncrossed disparities between the "infinite" pulse duration situation and the other disparity pulse durations, all $F_s(5, 25) > 18.05$, $p < .025$, the parametric curves clearly demonstrate the lack of any reliable effect of disparity pulse duration on either the PCR or MRT scores, all $F_s(5, 25) < 8.76$, $p > .05$. In fact, the pooled PCR scores for both directions did not differ from chance at any disparity pulse duration except at the "infinite" pulse duration, $z = 2.17$, $p < .05$, two-tailed. On the other hand, the higher mean accuracy of performance for crossed disparities over uncrossed disparities was clearly evident at every disparity pulse duration tested, except at the "infinite" pulse duration, $F(1, 5) = 1.90$, $p > .05$.

Crossed-disparity performance was significantly above chance at every pulse duration tested, except at 33 ms, $z = 1.46$, $p > .05$, two-tailed.

The overall level of performance for discriminating pulses with uncrossed

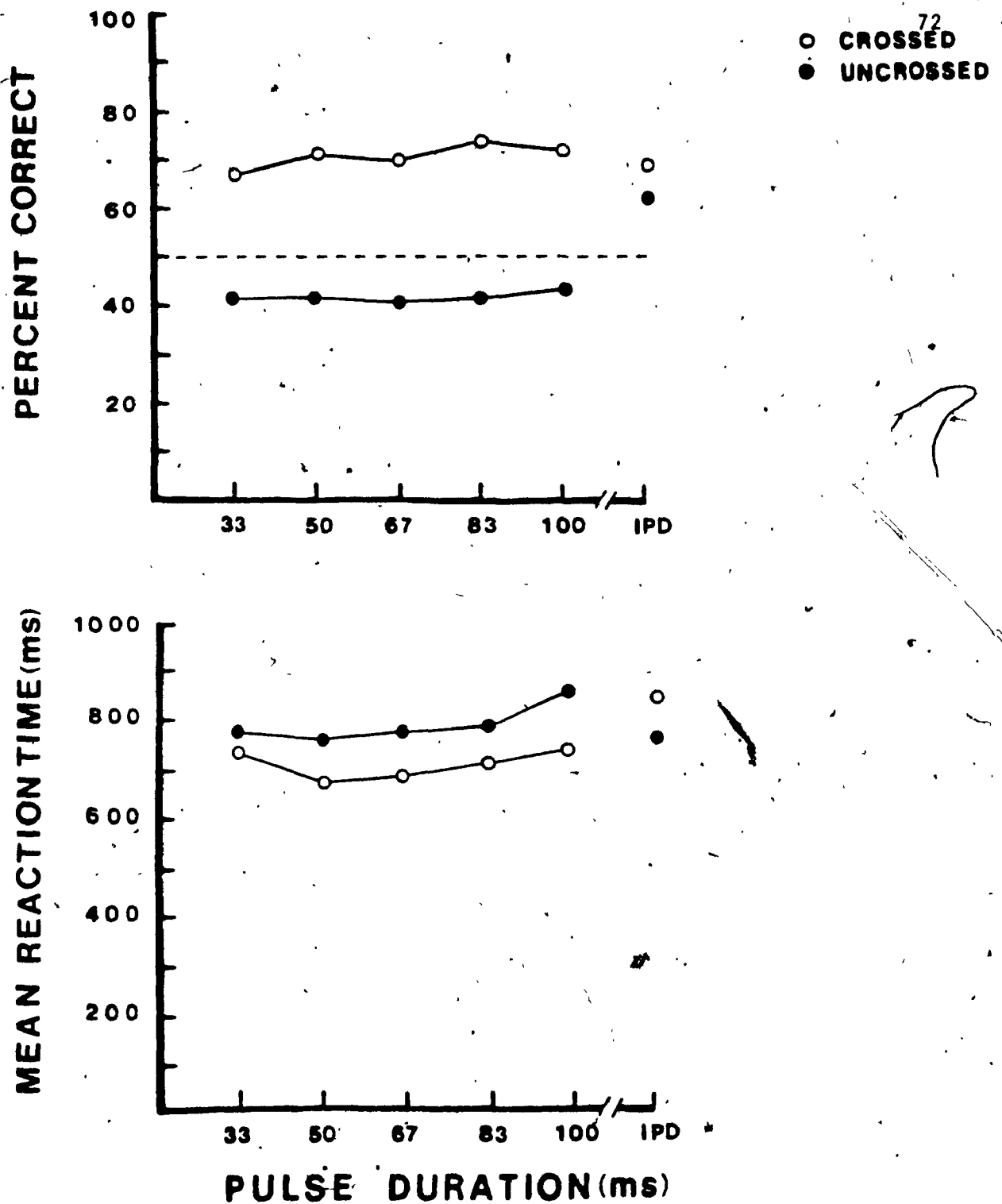


Figure 9. Mean number of correct depth discriminations (PCR) and mean reaction-time (MRT) data as a function of disparity direction and disparity pulse duration in Condition RDS. Chance level (50%) for the mean accuracy data is indicated by the dashed horizontal line. IPD refers to "infinite" pulse duration.

disparities, on the other hand, did not differ from chance at any disparity pulse duration, except at the "infinite" pulse duration, where it was found to be significantly above chance, $z = 1.99$, $p < .05$, two-tailed.

The MRT data, shown in the lower portion of this figure, revealed similar but much smaller overall differences between the levels of performance for discriminating crossed- and uncrossed-disparity pulses. Significant differences were observed at every pulse duration, except at 33 ms, $F(1, 5) = 2.26$, $p > .05$.

In a subsequent analysis, the mean data for each dependent variable were further analyzed as a function of disparity magnitude and disparity pulse duration, and the results are illustrated in Figure 10. These data revealed that the level of accuracy for discriminating disparity pulses with an "infinite" duration was initially high at the smallest disparity levels when compared with performance for the other pulse durations, and then decreased steadily as a function of increasing disparity. Furthermore, the PCR data showed a convergence toward the highest disparity magnitude, but this trend was not significant, $F(20, 100) = 1.68$, $p > .05$. The MRT data did not show any systematic variations in performance, either with respect to disparity magnitude or pulse duration, all $F_s(5, 25) < 9.76$, $p > .05$.

The combined mean data of all observers in this condition are presented in Appendix C, Table C-2. The mean data of each observer are presented in Appendix D, Tables D-7 to D-12.

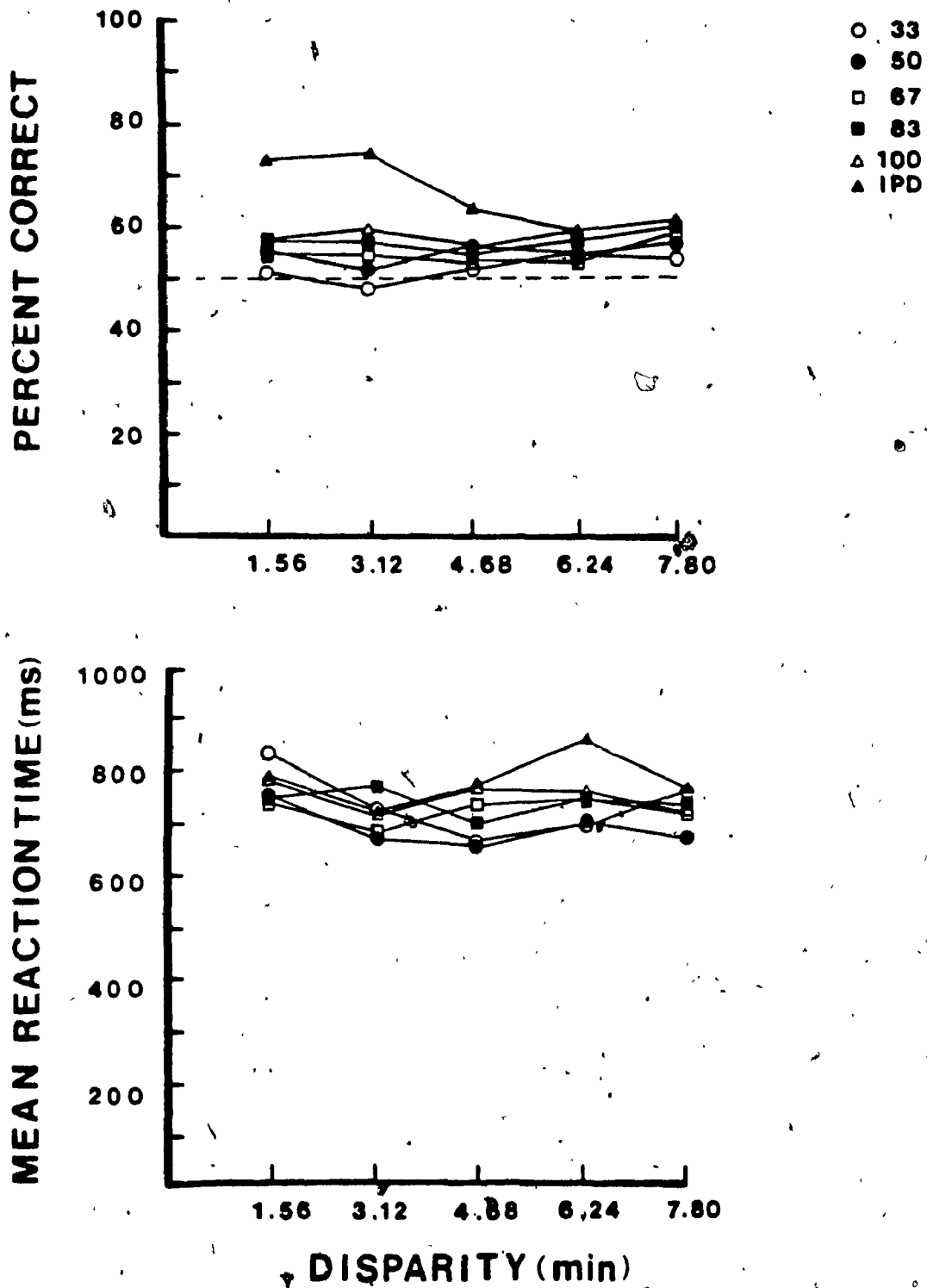


Figure 10. Mean number of correct depth discriminations (PCR) and mean reaction-time (MRT) data as a function of disparity magnitude and disparity pulse duration in Condition RDS. Chance level (50%) for the mean accuracy data is indicated by the dashed horizontal line. IPD refers to "infinite" pulse duration.

Analysis of the RTL Data

The percentage of trials discarded from the analysis of the RT data for each observer remained relatively low throughout the study, and ranged from 0.33% (Observer 6) to 17% (Observer 2).

None of the observers in this condition showed any evidence of improvement over sessions, all $F_s(4, 12) < 2.69$, $p > .05$. Although the mean data suggested a trend toward better performance over time, both in terms of increased accuracy and decreased latencies, this improvement was not found to be significant when evaluated in a MANOVA, $F(8, 48) = 0.69$, $p > .05$. Furthermore, this main effect was not found to be significant for either dependent variable: PCR, $F(4, 25) = 0.12$, $p > .05$; MRT, $F(4, 25) = 1.11$, $p > .05$.

A three-way MANOVA, with repeated measures on each factor, was performed on the mean data of this condition, and produced significant multivariate main effects of disparity direction, magnitude, and pulse duration. An examination of Wilks' lambda indicated that there was a high degree of association between the dependent variables and the disparity direction scores, with $\eta^2 = .89$. A somewhat weaker association was found between the combined dependent variables and the main effect of disparity magnitude, $\eta^2 = .70$, but the degree of association between the main effect of pulse duration and the combined dependent variables was very strong, $\eta^2 = .94$. A detailed summary table of this analysis is presented in Appendix A, Table A-3.

Figure 11 shows the percent correct data and the corresponding MRTs to make correct depth discriminations as a function of the direction of

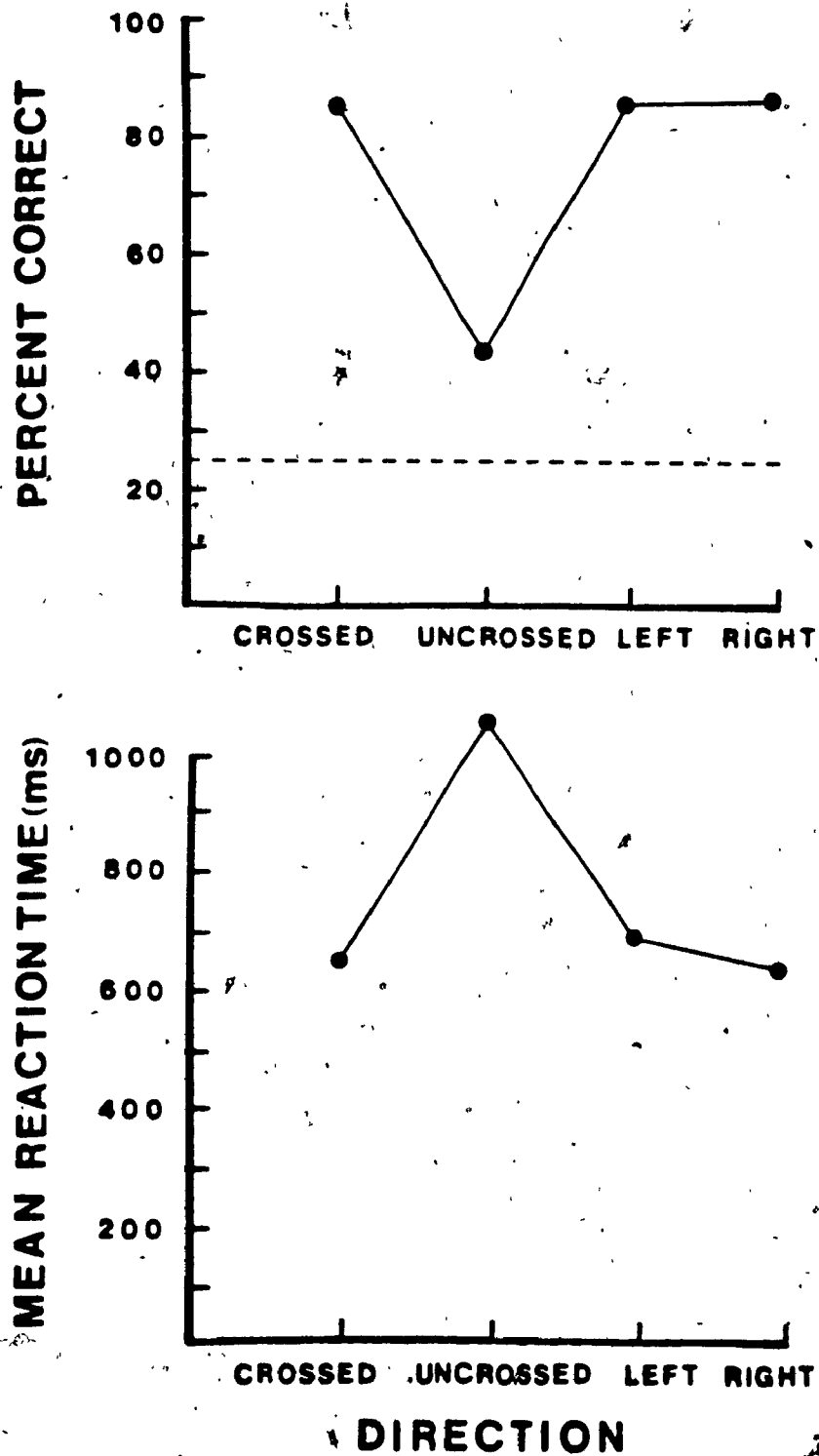


Figure 11. Mean number of correct depth discriminations (PCR) and mean reaction-time (MRT) data as a function of disparity direction in Condition RTL. Chance level (25%) for the mean accuracy data is indicated by the dashed horizontal line.

the disparity pulses. The overall level of performance for discriminating disparity pulses in the crossed direction was significantly higher than that achieved in discriminating disparity pulses in the uncrossed direction. Not only were crossed-disparity pulses discriminated with greater accuracy than uncrossed-disparity pulses, (83.17% vs. 42.16%), $F(3, 15) = 19.88$, $p < .005$, but they were also discriminated more rapidly ($M = 645.65$ ms vs. 1023.48 ms), $F(3, 15) = 13.64$, $p < .025$. Moreover, each observer's mean data showed this superiority in performance for crossed-disparity pulses, all $F_s(3, 480) > 18.79$, $p < .001$.

Overall mean discrimination performance for crossed-disparity pulses did not differ in any systematic way from performance for left or right target displacements for either dependent measure, all $F_s(3, 15) < 0.15$, $p > .05$. Responses to uncrossed-disparity pulses, however, required significantly more time to make and were less accurate than responses to either left or right target displacements, all $F_s(3, 15) > 10.46$, $p < .05$. No left-right response asymmetries were observed for these data for either dependent variable, both $F_s(3, 15) < 0.12$, $p > .05$, indicating that these directional shifts were consistently localized at or very near the plane of fixation. Finally, as expected, there was a fairly high negative correlation between the two dependent variables in this stimulus condition, $r = -.81$.

Although the overall main effect of disparity magnitude was found to be significant for each dependent variable, both $F_s(4, 20) > 3.46$, $p < .05$, multiple pairwise comparisons using the Scheffé test failed to detect any significant individual differences in the mean accuracy data

at any of the disparity levels, all $F_s(4, 20) < 5.79, p > .05$. The results of these post hoc tests, however, did reveal the presence of a rather sizeable and consistent difference between the discrimination performance for crossed and uncrossed disparities at every disparity level, but only in terms of the accuracy of depth discriminations, all $F_s(3, 15) > 16.78, p < .01$. The MRT data did not reveal any crossed-uncrossed differences in performance as a function of the amount of disparity present, except at the smallest disparity level, $F(3, 15) = 11.35, p < .05$.

No significant differences were found between observers' mean performance for discriminating crossed-disparity pulses and their performance for discriminating left or right displacements of the central target at any disparity level, neither with respect to mean accuracy nor speed, all $F_s(3, 15) < 1.44, p > .05$. Their mean level of performance for discriminating disparity pulses in the uncrossed direction, however, was significantly poorer than their discrimination performance for both left and right displacements, but only with respect to accuracy, all $F_s(3, 15) > 11.34, p < .05$. The only differences detected in the MRT data were found when comparing observers' discrimination performance for uncrossed-disparity pulses with their performance for left and right displacements at 1.56' of arc, $F(3, 15) = 12.14, p < .05$, and $F(3, 15) = 14.78, p < .025$, respectively. These findings are presented in Figure 12.

The data in this figure also reveal the presence of relatively flat depth discrimination functions with increasing disparity magnitude. The only significant improvement in the accuracy data with respect to this

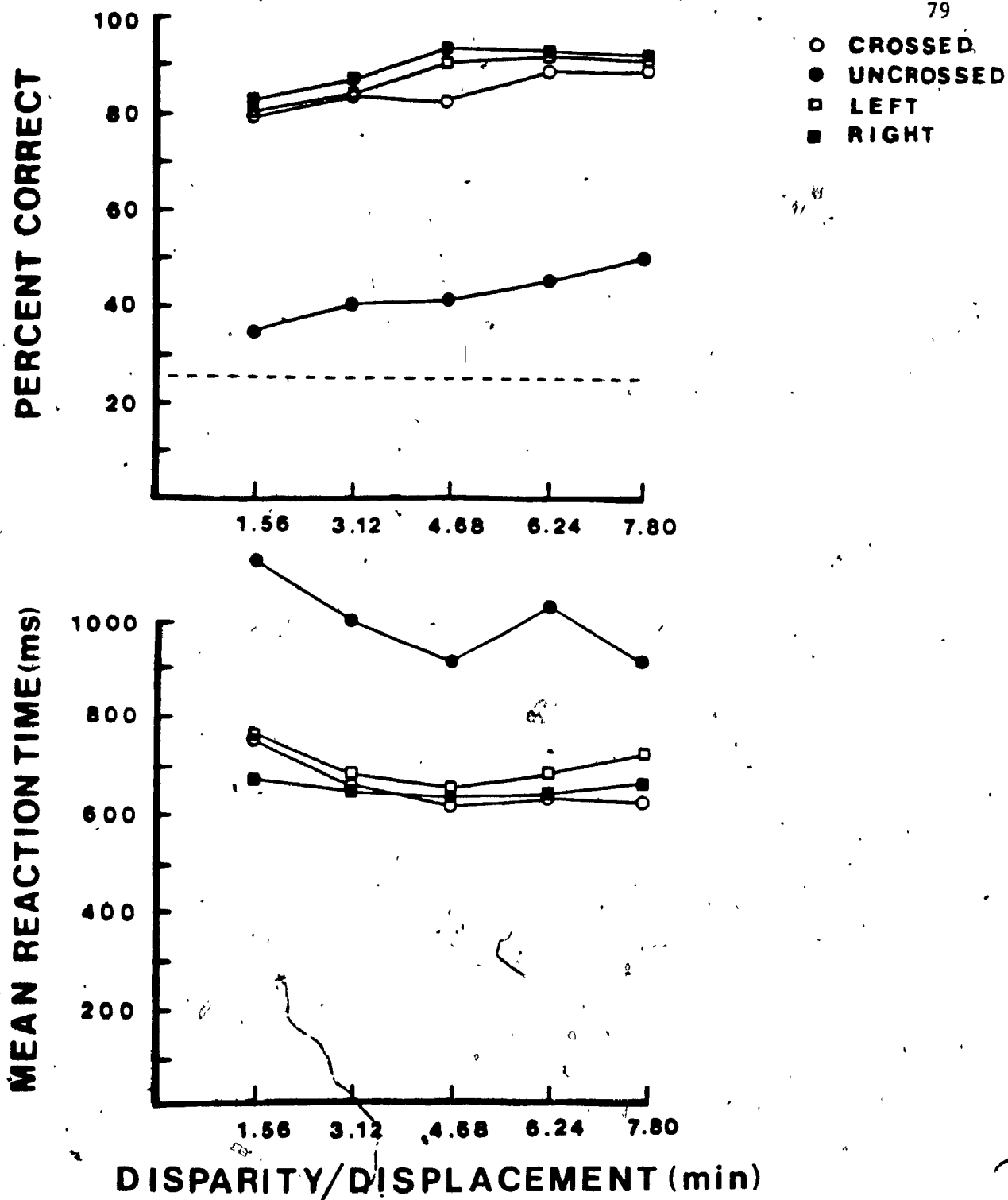


Figure 12. Mean number of correct depth discriminations (PCR) and mean reaction-time (MRT) data as a function of disparity direction and disparity magnitude in Condition RTL. Chance level (25%) for the mean accuracy data is indicated by the dashed horizontal line.

variable was found when comparing performance between the smallest and the two largest disparity levels for uncrossed-disparity pulses, $F(4, 20) = 11.60, p < .05$, and $F(4, 20) = 17.01, p < .05$, respectively. A similar pattern was also observed in the MRT data; observers' performance for discriminating uncrossed-disparity pulses generally improved as a function of increasing disparity magnitude for all disparity values tested, except from 4.68' to 6.24' of arc, $F(4, 20) = 4.47, p > .05$, where a reversal in the data was observed.

The results of the MANOVA that was performed on the mean data of this condition revealed the presence of a significant Direction by Disparity interaction when both dependent variables were considered simultaneously, $F(24, 118) = 1.94, p < .01$. This interaction was also found to be significant for the PCR data, $F(12, 60) = 2.15, p < .05$. The data displayed in Figure 12 may shed some light on the source and nature of this interaction. It can be seen that whereas performance for uncrossed disparities improved with increasing disparity magnitude, corresponding levels of performance for the other directions remained essentially stable. The different shapes of the curves in this figure, together with the different effects of disparity magnitude on mean accuracy performance, may represent the likely source of the significant interaction observed for these data. The possible contribution of the results obtained with uncrossed disparities to the trend in these data, however, cannot be overlooked.

The data relating overall depth discrimination performance to disparity pulse duration demonstrated that similar to the other two conditions, observers were most accurate when disparity information was

pulsed for an "infinite" duration than when it was pulsed for the briefest pulse duration, $F(5, 25) = 21.07, p < .01$. Furthermore, overall accuracy of performance was also found to be lowest when disparity information was pulsed for 33 ms as compared to longer durations, such as 83 ms, $F(5, 25) = 13.75, p < .05$ and 100 ms, $F(5, 25) = 15.77, p < .025$. Interestingly, like the data in the other two conditions, the univariate main effect of disparity pulse duration was not significant for the MRT data, $F(5, 25) = 2.38, p > .05$, indicating that the speed with which observers responded to disparity pulses in these stereograms did not vary with respect to manipulations of this temporal parameter.

The question concerning whether there were any differences in the level of performance for discriminating the direction of disparity as a function of pulse duration was examined more closely in a series of Scheffe tests, and the mean data are represented in Figure 13. The data for both dependent variables reflected the same asymmetric effect of disparity direction; the mean accuracy with which observers discriminated disparity pulses in the crossed direction was superior to that with which they discriminated disparity pulses in the uncrossed direction at every pulse duration tested, all $F_s(3, 15) > 10.76, p < .05$, but not significantly different from their performance for discriminating either left or right directional shifts of the disparate central target, all $F_s(3, 15) < 4.54, p > .05$. The MRT data also revealed a similar asymmetry between the level of performance for each disparity direction. The only exceptions to this pattern of results were observed at the two longest disparity pulse durations: 83 ms, $F(3, 15) = 3.97, p > .05$; 100 ms, $F(3, 15) = 3.02, p > .05$. The overall level of performance for

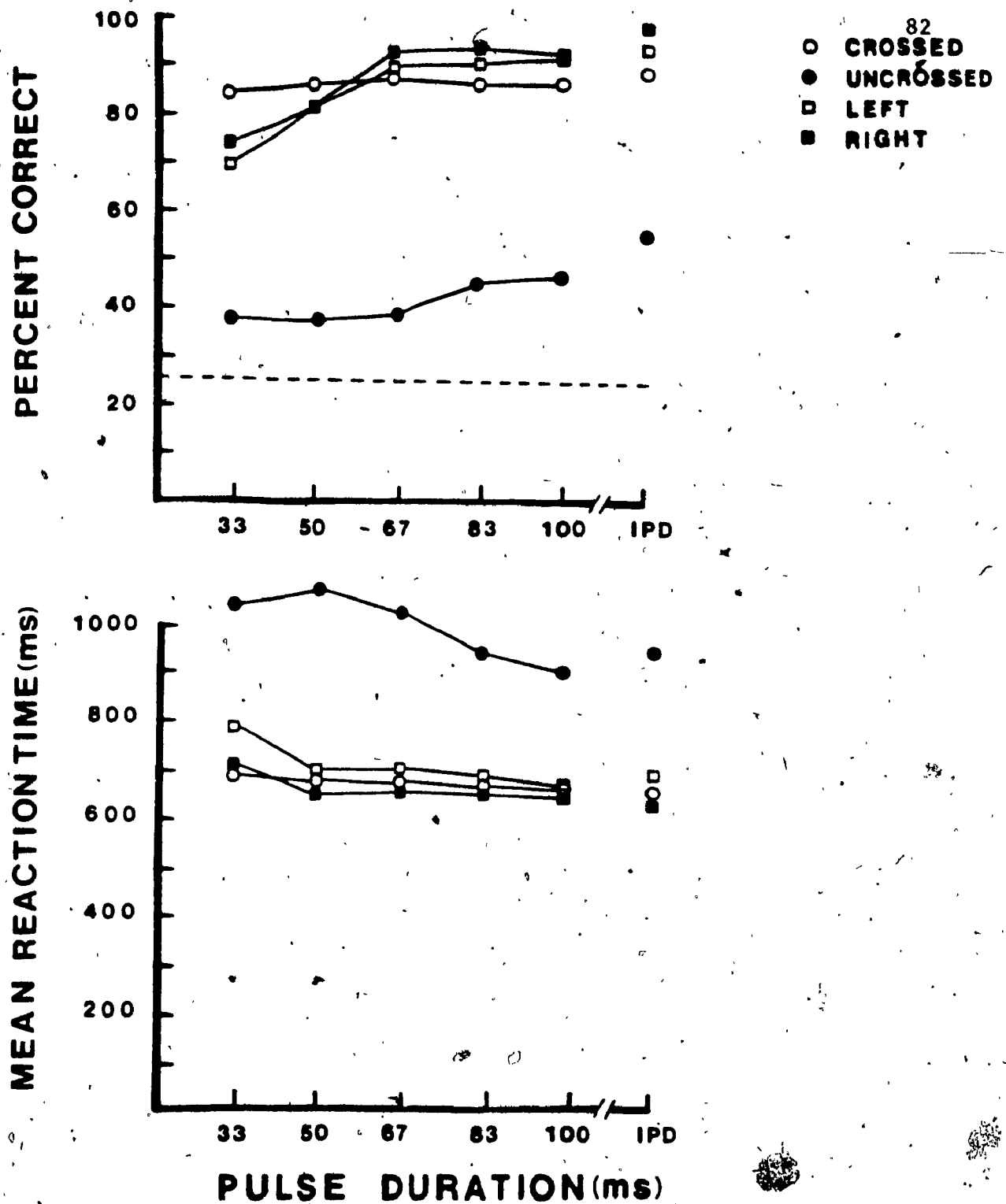


Figure 13. Mean number of correct depth discriminations (PCR) and mean reaction-time (MRT) data as a function of disparity direction and disparity pulse duration in Condition RTL. Chance level (25%) for the mean accuracy data is indicated by the dashed horizontal line. IPD refers to "infinite" pulse duration.

discriminating pulses with uncrossed disparities was significantly inferior to performance for discriminating left and right displacements of the central target at every pulse duration and for both dependent variables, all $F_s(3, 15) > 10.26$, $p < .05$. Finally, the overall level of discrimination performance did not differ significantly for left or right target displacements at any time, neither in terms of accuracy nor speed, all $F_s(3, 15) < 0.41$, $p > .05$.

When the mean data for each direction were examined as a function of disparity pulse duration, they revealed that performance for each disparity direction was affected differently by manipulations of this temporal parameter (see Figure 13). In particular, performance for crossed disparities did not show any systematic variation with respect to manipulations of disparity pulse duration, neither in terms of overall accuracy nor speed, both $F_s(5, 25) < 7.72$, $p > .05$. Mean performance for uncrossed disparities, however, did show some improvement as a function of disparity pulse duration. Disparity pulses presented in the uncrossed direction were discriminated with greater accuracy when they were presented for an "infinite" duration than when they were presented for the three shortest pulse durations, all $F_s(5, 25) > 19.63$, $p < .01$. The mean level of accuracy for discriminating left and right target displacements also showed a gradual improvement with increasing pulse duration, but this improvement could be seen only when comparing the level of performance at the longest pulse duration with that at the two shortest ones: Left, both $F_s(5, 25) > 13.19$, $p < .05$; Right, both $F_s(5, 25) > 29.66$, $p < .001$. Indeed, the relatively flat performance functions for crossed-disparity pulses, coupled with the monotonic

increases in accuracy for the other directions as a function of disparity pulse duration, probably represent the likely source of the significant interaction between these two factors, $F(15, 75) = 2.33, p < .01$.

When the mean data were plotted as a function of disparity magnitude and pulse duration, as in Figure 14, they revealed that observers performed more accurately when disparity pulses were presented for an "infinite" duration than when they were presented for the shortest duration of 33 ms. This pattern was observed at every disparity level except 4.68' of arc, $F(5, 25) = 9.08, p > .05$. The MRT data, on the other hand, did not reveal any significant differences in performance when they were analyzed in a similar manner, all $F_s(5, 25) < 12.17, p > .05$.

The collapsed mean data of all observers in this condition are presented in Appendix C, Table C-3, and the mean data of each observer are presented in Appendix D, Tables D-13 to D-18.

Analysis of the Mean Data from the Three Conditions

In order to analyze the overall mean data obtained from the three stimulus conditions simultaneously, a final $3 \times 2 \times 5 \times 6$ mixed MANOVA was performed on the two dependent variables, without the influence of the left or right discrimination data. The data for this analysis were thus averaged across only the two levels of disparity direction (i.e., crossed and uncrossed) for each condition. In addition, the averaged percent correct scores for all observers combined were converted to corresponding values of d' as a function of the number of alternatives,

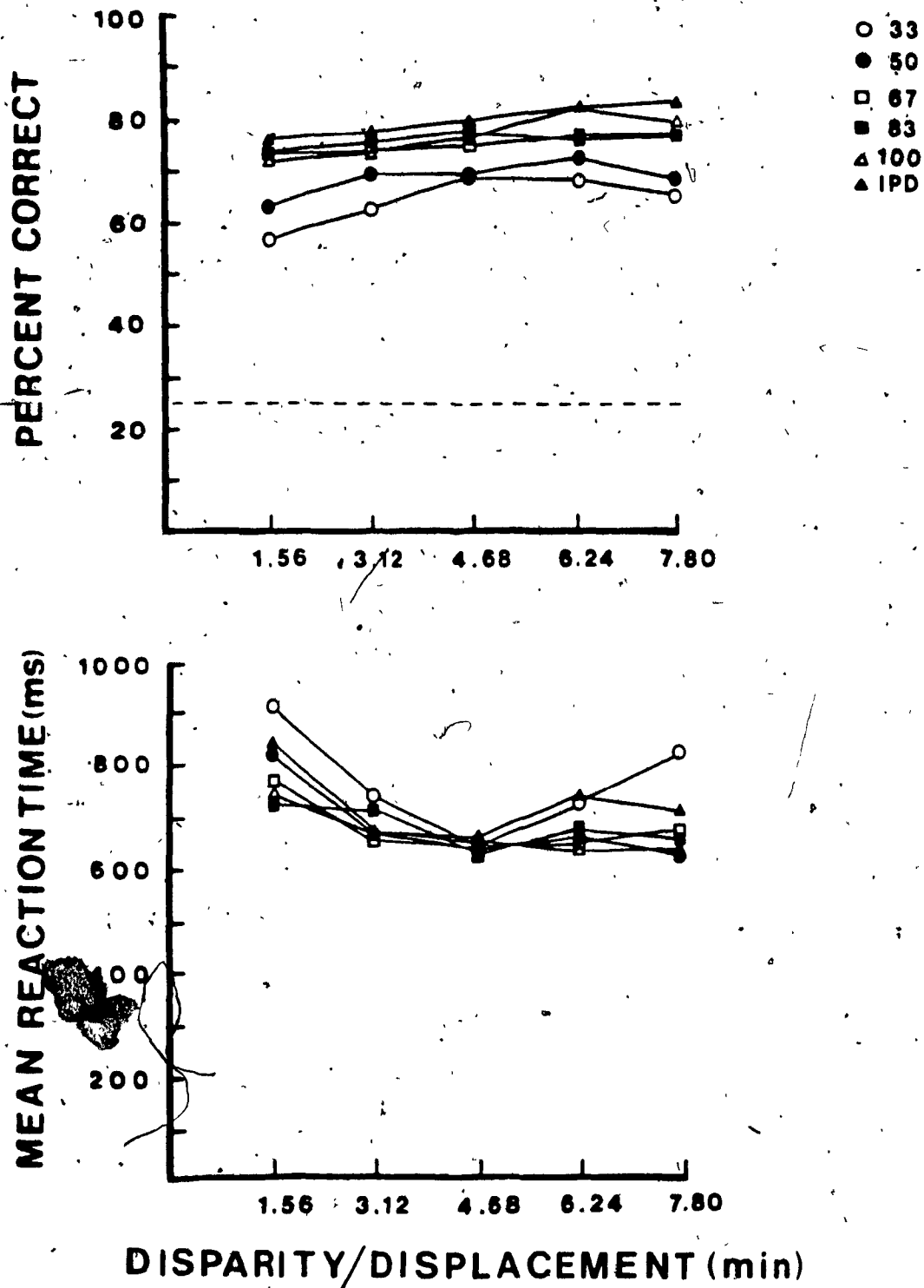


Figure 14. Mean number of correct depth discriminations (PCR) and mean reaction-time (MRT) data as a function of disparity magnitude and disparity pulse duration in Condition RTL. Chance level (25%) for the mean accuracy data is indicated by the dashed horizontal line. IPD refers to "infinite" pulse duration.

using the revised forced-choice table of Hacker and Ratcliff (1979). These data were converted to d' so that (a) the mean levels of accuracy could be compared directly across the three conditions, and (b) chance level of performance (i.e., $d' = 0$) for each type of stereogram would reflect zero depth sensitivity.

When the overall mean data of the three conditions were analyzed in this manner, the results indicated that the multivariate main effect of stimulus condition was significant, $F(4, 28) = 4.30, p < .001$. Furthermore, this main effect was also significant for the d' data when evaluated in a univariate ANOVA, $F(2, 15) = 5.55, p < .05$. The three stimulus conditions, however, did not differ significantly with respect to overall MRT, $F(2, 15) = 0.13, p > .05$. Relevant data showing these main effects are presented in Figure 15.

Post hoc comparisons of the d' data, which are shown in the upper portion of this figure, revealed that depth discrimination performance was better for the line-contoured stereograms (i.e., Conditions TDL and RTL) when compared to Condition RDS. Performance in the TDL condition was significantly better than performance in Condition RDS, $F(2, 15) = 9.68, p < .025$, but did not differ significantly from performance in Condition RTL, $F(2, 15) = 0.30, p > .05$. In addition, performance in Condition RDS was significantly depressed relative to that of the RTL condition, $F(2, 15) = 7.57, p < .05$. Finally, the overall level of performance was significantly above chance in each of the three stimulus conditions, all $z_s > 4.43, p < .01$, two-tailed.

Both the d' and the MRT data were significantly affected by each of the independent variables when these data were analyzed simultaneously:

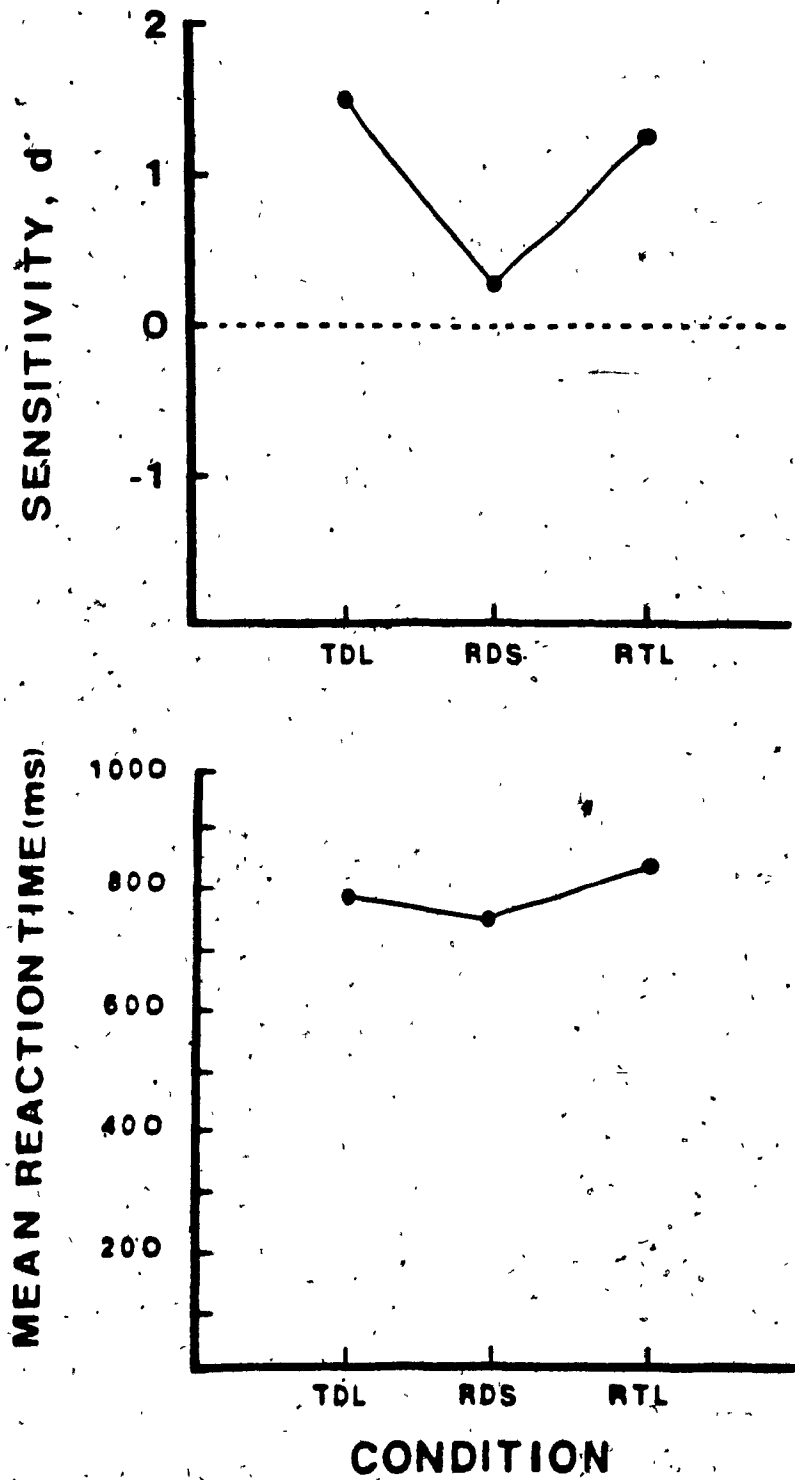


Figure 15. Mean values of d' and mean reaction-time (MRT) data for all observers as a function of stimulus condition.

Direction, $F(2, 14) = 18.14, p < .001$; Disparity, $F(8, 118) = 6.65, p < .001$; Pulse Duration, $F(10, 148) = 3.09, p < .01$. An examination of Wilks' criterion revealed that there was a strong association between the direction scores (i.e., crossed and uncrossed) and the combined dependent variables, $\eta^2 = .92$. The degree of association was less substantial between disparity magnitude and disparity pulse duration scores and the combined dependent variables, $\eta^2 = .52$ and $\eta^2 = .32$, respectively. It is interesting to note that similar to the results of Conditions TDL and RTL, there was no evidence of a significant univariate main effect of disparity pulse duration for the MRT data, $F(5, 75) = 1.12, p > .05$. A detailed summary of this analysis, including all interactions, can be found in Appendix A, Table A-4.

The overall values of d' and the corresponding MRT data as a function of stimulus condition and disparity direction are shown in Figure 16. Irrespective of stimulus condition, observers discriminated disparity pulses presented in the crossed direction more accurately than those presented in the uncrossed direction ($d' = 1.61$ vs. 0.47), $F(1, 15) = 32.11, p < .001$, and also responded more rapidly to crossed-disparity pulses than to pulses of the opposite direction ($M = 675.60$ ms vs. 907.73 ms), $F(1, 15) = 20.23, p < .001$. Post hoc pairwise comparisons performed on these data indicated that the mean level of performance for discriminating crossed-disparity pulses was significantly higher than that for discriminating uncrossed-disparity pulses in every case except for the MRT data in Condition RDS, $F(1, 15) = 0.39, p > .05$. Results of statistical analyses comparing the overall values of d' across the three conditions revealed that performance for the TDL stereograms

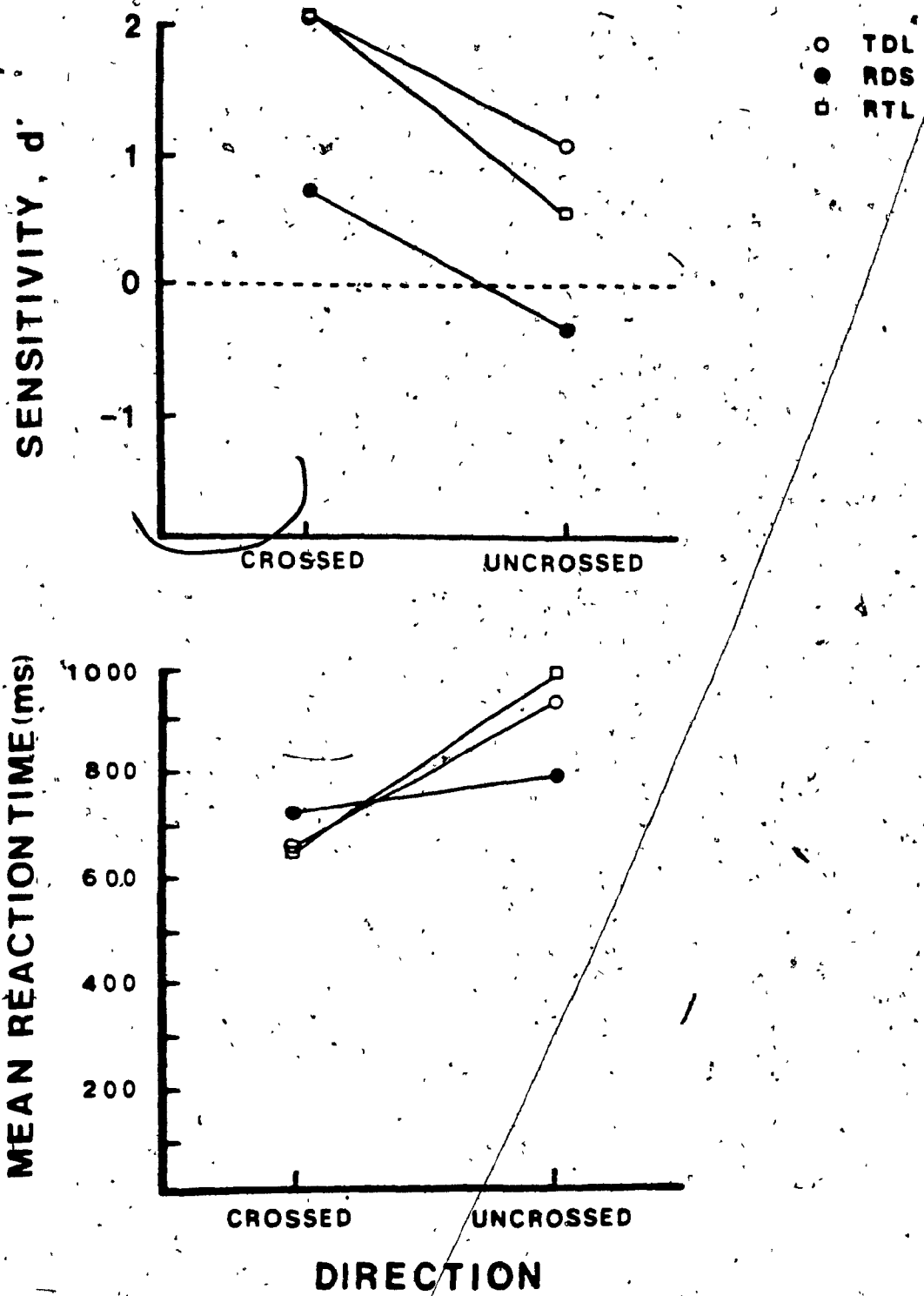


Figure 16. Mean values of d' and mean reaction-time (MRT) data for all observers as a function of stimulus condition and disparity direction (crossed vs. uncrossed).

was significantly better than performance for RDS for both disparity directions, both $F_s(2, 15) > 13.92$, $p < .01$. Performance for the TDL stereograms, however, was not significantly different from performance for the RTL stereograms for either disparity direction, both $F_s(2, 15) < 1.82$, $p > .05$. In addition, the overall level of performance for RDS was significantly lower than performance for the RTL stimuli for both crossed and uncrossed directions, both $F_s(2, 15) > 7.81$, $p < .05$. Finally, the MRT data did not show any significant differences among any of the stimulus conditions, all $F_s(2, 15) < 4.63$, $p > .05$.

When the overall values of d' were further analyzed to see if they differed from chance, performance was found to be significantly above chance for both disparity directions in both Conditions TDL and RTL, all $z_s > 5.31$, $p < .01$, two-tailed. The overall data for the RDS condition, however, showed above-chance performance levels only for the crossed disparity direction, $z = 12.89$, $p < .001$, two-tailed. Mean performance for discriminating disparity pulses in the uncrossed direction did not differ from chance for these stimuli, $z = 1.92$, $p > .05$, two-tailed.

Finally, a step-down analysis (Roy & Bargmann, 1958) was performed in order to assess the influence of each main effect and interaction on the individual dependent variables. A step-down analysis is a form of analysis of covariance, in which the dependent variables are entered in a specified order in order to test the relative contribution of successive measures. The PCR data (converted to d' in this final analysis) were tested first, with appropriate adjustment of the alpha level in a univariate ANOVA since the results of the individual analysis of each stimulus condition suggested that the spatio-temporal manipulations used

in this study affected observers' mean accuracy to a greater extent than their mean latency performance. Using the d' data as the covariate, the MRT data were then tested in the step-down analysis to see if these data added significantly to the overall values of d' . The results of this analysis are presented in Appendix B, Table B-1. A comparison of the results obtained from this analysis with those of overall univariate ANOVAs on each dependent variable is shown in Table 1. Because there were only two dependent variables, individual alpha levels were set at .025 each, while keeping the overall experimentwise error rate at approximately .049.³

The results of the step-down analysis indicated that the mean accuracy data made a significantly greater contribution to the main effects being investigated than the MRT data. The fact that none of the step-down F -ratios for the MRT data exceeded the critical values required at an alpha level of .025, suggests that most, if not all of the significant results that were observed in the original MANOVAs were due mainly to changes in the mean level of accuracy, with little or no additional change being uniquely represented by the MRT data. Also, the fact that some of the MRT data showed significant univariate but no significant corresponding step-down F -ratios, further indicates that these data made no unique contribution to the between-group differences beyond those found in the mean accuracy data.

Table 1

Comparison of Univariate and Step-Down F-Ratios Obtained from Analyses of the Mean Data of the Three Stimulus Conditions

Independent Variable	Dependent Variable	Univariate F	Df	Step-Down F	Df	Alpha ^a
SC	PCR	5.55**	2/15	5.55**	2/15	
	MRT	0.13	2/15	1.06	2/14	
A	PCR	44.20***	1/15	44.20***	1/15	
	MRT	20.23***	1/15	0.01	1/14	
A x SC	PCR	1.54	2/15	1.54	2/15	
	MRT	3.22	2/15	3.58	2/14	
B	PCR	12.98***	4/60	12.98***	4/60	
	MRT	5.60***	4/60	2.53*	4/59	
B x SC	PCR	6.40***	8/60	6.40***	8/60	
	MRT	1.38	8/60	0.81	8/59	
C	PCR	6.08***	5/75	6.08***	5/75	
	MRT	1.12	5/75	1.33	5/74	
C x SC	PCR	1.08	10/75	1.08	10/75	
	MRT	1.56	10/75	1.69	10/74	
AB	PCR	0.99	4/60	0.99	4/60	
	MRT	0.74	4/60	0.81	4/59	
AB x SC	PCR	0.58	8/60	0.58	8/60	
	MRT	0.70	8/60	0.57	8/59	
AC	PCR	2.58*	5/75	2.58*	5/75	
	MRT	0.66	5/75	0.30	5/74	
AC x SC	PCR	0.07	10/75	0.07	10/75	
	MRT	1.12	10/75	1.18	10/74	

(table continues)

Independent Variable	Dependent Variable	Univariate F	Df	Step-Down F	Df	Alpha ^a
BC	PCR	2.64***	20/300	2.64***	20/300	
	MRT	1.57	20/300	1.17	20/299	
BC x SC	PCR	0.86	40/300	0.86	40/300	
	MRT	0.85	40/300	0.91	40/299	
ABC	PCR	0.70	20/300	0.70	20/300	
	MRT	0.91	20/300	0.80	20/299	
ABC x SC	PCR	0.54	40/300	0.54	40/300	
	MRT	1.13	40/300	1.19	40/299	

Note. These analyses were performed on the mean data of all observers in the three conditions and averaged over crossed and uncrossed disparity responses only. The mean accuracy data (i.e., PCR) were converted to corresponding values of d' prior to being subjected to the analyses.

^aAlpha = .025 for each effect being tested.

All values have been rounded to the nearest two decimal places.

SC represents stimulus condition. A, B, and C represent disparity direction, disparity magnitude, and pulse duration, respectively.

PCR = Percent correct responses; MRT = mean reaction time.

* $p < .05$. ** $p < .025$. *** $p < .001$.

Discussion

The interpretation of the results of this study requires some qualification. Specifically, since fixation disparity was not controlled or measured, and given that fixation disparities are known to occur in the range of disparity magnitudes that were used (Ogle, 1950), there is a difficulty of knowing precisely for any given trial whether the disparity pulse was "absolutely" crossed or uncrossed or only "relatively" crossed or uncrossed. That is, one cannot be certain that observers were always precisely converged on the fixation plane prior to the initiation of a trial. Consequently, for any given trial, both the target and the background may have been slightly in front of or behind the plane of fixation when the target disparities were presented in the uncrossed or crossed direction, respectively. Although fixation disparities have generally been found to decrease with reductions in exposure duration (e.g., Schor, 1979), and were hopefully minimized by suitable alignment of the stimuli in this study, their presence cannot be entirely ruled out. Therefore, the present results are discussed in terms of the relative direction of the disparity pulses rather than in terms of absolute crossed and uncrossed disparities per se.

The overall findings reported in this study are generally consistent with previous results, and extend them in a number of ways. First, in agreement with past experiments, the results revealed the existence of a large and consistent difference between the accuracy of depth discrimination performance for crossed and uncrossed disparity

information (e.g., Grabowska, 1983; Harwerth & Boltz, 1979a, 1979b; Lasley et al., 1984). In fact, 17 of the 18 observers who were tested discriminated disparity pulses more accurately when they were presented in the crossed direction than when they were presented in the uncrossed direction (binomial test, $p = .0002$, two-tailed). A similar but less consistent difference in performance was also observed for the MRT data; 13 out of the 18 observers responded more rapidly to pulses containing crossed disparities than they did to pulses containing uncrossed disparities (binomial test, $p = .0964$, two-tailed), and this pattern of results was observed over the full range of disparity magnitudes and pulse durations tested. As such, these findings are consistent with those reported by Alexander (1979/1981).

Second, with the exception of the results obtained in Condition RDS, depth discrimination performance, both in terms of accuracy and speed, improved with increases in the amount of disparity for both crossed and uncrossed directions. The results are thus in general agreement with those reported by Grabowska (1983), Harwerth and Boltz (1979a, 1979b) and Uttal et al. (1975). Despite this improvement with increasing disparity, however, the data continued to show a consistent difference between the level of performance for crossed and uncrossed disparities, both for PCR and MRT responses.

The data of the present study also demonstrated that overall depth discrimination performance declined as a function of decreasing disparity pulse duration when both dependent measures were considered simultaneously, and when the data for crossed and uncrossed disparities were combined. (This main effect was not observed in Condition RDS).

When each dependent measure was considered separately; however, only the mean accuracy data were found to vary in this manner for each stimulus condition. Furthermore, when the data of the two disparity directions were examined separately, only the level of performance for uncrossed disparities varied with respect to manipulations in disparity pulse duration. Tentatively, these findings suggest that although pulsing disparity information for various durations appears to have a similar effect on the accuracy of depth discrimination performance as varying stimulus exposure duration, this effect is different for crossed and uncrossed disparities. This unique effect, however, may be due to the fact that the mechanisms mediating the processing of disparities in the crossed direction may be sensitive to temporal manipulations, but at temporal intervals not used in the present study.

In each condition, the overall level of accuracy was highest when disparities were pulsed for an "infinite" duration and lowest when they were pulsed for the shortest duration (33 ms), indicating that observers benefited from prolonged exposure time. No such advantage, however, was observed for the MRT data in any condition, suggesting that this index of performance was largely unaffected by manipulations of this temporal parameter. Nevertheless, significant differences in MRT performance between crossed and uncrossed disparities were still observed. The only exception to these findings was found in Condition RDS.

It is also interesting to note that neither mean accuracy nor MRT performance for discriminating disparity pulses in the crossed direction were significantly different from performance for discriminating left or right target displacements in either condition where such performance was

assessed. This suggests that depth discrimination performance for pulses containing crossed disparities was as accurate and as immediate as performance for discriminating simple lateral shifts of the target on the plane of fixation. Observers' performance for discriminating pulses containing uncrossed disparities, on the other hand, was always poorer than their performance for discriminating left or right displacements of the central target, both with respect to accuracy and speed.

In both Conditions TDL and RTL, the mean level of performance for discriminating left and right target displacements did not differ for either of these directions, indicating that observers consistently and reliably perceived these shifts at or near the plane of fixation. This finding is consistent with one reported by Beverley and Regan (1974), and suggests that the asymmetry in performance that was observed between pulses with crossed and uncrossed disparities could not be attributed to monocularly defined directional cues.

No consistent improvements in performance with practice were observed at any time during the course of the study for most observers, neither in terms of accuracy nor speed. The lack of improvement with practice is probably attributable to the practice trials that preceded every test session. Although there have been reports of the existence of a stereoscopic learning effect, (i.e., a decreased latency to resolve depth in RDS) with practice (e.g., Frisby & Clatworthy, 1975; MacCracken & Hayes, 1976; MacCracken, Bourne, & Hayes, 1977), the evidence has come from studies using relatively large-disparity RDS of varying complexity and a very small number of trial presentations. For instance, Frisby and Clatworthy (1975) found a progressive reduction in the latency to

perceive stereoscopic depth in a complex RDS (i.e., a stereogram depicting a spiral staircase) when the same stereogram was presented a number of times to naive observers within a single session. Not surprisingly, these investigators found that subsequent presentations produced substantially less improvement. MacCracken and Hayes (1976) also reported the presence of a similar stereoscopic learning effect across five trials when the same RDS was presented to a naive observer in a single session. Finally, Chung and Berbaum (1984) found evidence of a reduction in RT with practice but no evidence of an accompanying improvement in the accuracy of depth discrimination performance. This led them to question what was really being learned. Furthermore, their finding of a practice effect for RT but none for accuracy, casts doubt on the validity and usefulness of using RT measures to infer learning-like effects in stereopsis with practice.

In this study, the large number of practice trials and the use of small disparities, are the most likely factors that contributed to the stable and reliable performance levels. A close examination of the data obtained during the practice trials did reveal, however, that observers improved initially. This is neither surprising nor interesting, given that all of the observers were initially unfamiliar with the experimental task and naive with respect to the types of stereoscopic stimuli being presented.

Another noteworthy aspect of the data in this study concerns the finding that most of the parametric manipulations performed on the stimuli had a pronounced effect on the mean accuracy with which depth discriminations were made, but considerably less effect on the speed with

which depth was resolved in the various stimulus conditions. For example, although a significant univariate main effect of disparity pulse duration was found for the PCR data in both Conditions TDL and RTL, the presence of this main effect was not observed in the MRT data in either of these conditions. Similarly, the mean data in Condition RDS revealed the presence of a significant multivariate main effect of disparity direction when both dependent measures were analyzed simultaneously, but subsequent univariate analyses showed this main effect to be present only for the mean accuracy data. In other words, most observers discriminated disparity pulses more accurately in RDS when the pulses were directed toward them than when they were directed away from them. This pattern of results, however, was not observed for the MRT data. Furthermore, differences in the overall levels of performance for crossed and uncrossed disparities with respect to manipulations of disparity magnitude and pulse duration were observed mostly for the accuracy data. Finally, the results of the step-down analysis performed on the combined mean data from the three stimulus conditions, indicated that the accuracy data made a significantly greater contribution to the observed effects in the present study than the MRT data. Taken together, these findings tentatively suggest that RT performance may be less sensitive or susceptible to direct disparity manipulations than accuracy of performance. The lack of such latency effects, on the other hand, may also be due to possible baseline differences in RT performance, which may have existed for the observers tested in this study.

In their study, Chung and Berbaum (1984, Experiment 3) reported that the addition of monocular contours that delineated the disparate target

in static RDS interfered with the resolution of depth in these stereograms when both were presented at the same time. That is, observers required a significantly longer time to respond to RDS containing monocularly juxtaposed contours of the target than they did to RDS alone. Previously, Saye and Frisby (1975) also demonstrated that the introduction of monocular features could interfere with the speed of resolving depth in RDS, but they noted that such interference effects were found only when they were dissimilar to the disparate region or were presented in large-disparity RDS.

In the present study, no detrimental effects of monocular contour information were observed on the mean latency data in Condition RTL, neither for the crossed nor the uncrossed disparity direction, and as such, these findings are consistent with those of Saye and Frisby (1975) and Saye (1976). Not only did the presence of monocular outlines of the central square not seem to interfere with the amount of time observers required to make their depth responses to the RDS, but the addition of such information actually led to more accurate discrimination performance in Condition RTL, as compared to the RDS condition where such information was absent. The finding of a significant improvement in the accuracy of depth discriminations when monocular contours were added to the disparate target, is thus in agreement with a similar finding reported by Richards (1977), but conflicts with the results of Chung and Berbaum (1984).

What are the possible reasons for the discrepancies in the results? One potential explanation may be related to the existence of methodological differences between this study and that of Chung and Berbaum. For instance, the stimuli in their study were continuously

exposed until observers made a response, whereas in the present study, the durations for which the stimuli were available to the observers were systematically varied and controlled. It is possible that in their study, the effect of continuous viewing caused observers to become distracted by the presence of the monocular contours that enclosed the disparate target. The fact that the outlined targets were pulsed once in this study rather than exposed continuously as in their study, may have prevented this occurrence. It is not immediately apparent whether there are other reasons that might account for the observed differences.

On a different note, it might be argued that the use of monocular outlines of the central target in Condition RTL that always coincided with the direction of the disparity pulses may constitute a possible artifact in this study. In other words, the possibility exists that some observers may have responded to the direction of disparity pulses in this stimulus condition that were actually based on the depth associated with the monocular contours, and not with the random-dot portion of the stereograms. On this point, Chung and Berbaum (1984) recently found that whether a monocular contour was congruent or incongruent with the perceived depth of the RDS target, made little or no difference on the accuracy or speed with which depth was resolved in these stimuli. The finding in this study that there were no significant differences between the overall results of Conditions TDL and RTL suggests, however, that some observers may have based their depth judgments on the presence of the monocular outline of the target. That is, when the monocular outline of the target was present, it may have allowed observers to quickly direct their search near it in depth.

Classical line stereograms and stereograms containing some monocular cues have generally been found to be solved more quickly than RDS (e.g., Julesz et al., 1976; Staller et al., 1975). In this study, no significant differences were noted among observers' mean latency performance for discriminating the direction of the disparity pulses in the different types of stereograms. What is the source of this negative finding? The most likely reason for the lack of a significant difference in MRT performance between Conditions TDL and RTL, and Condition RDS, may be due to the presence of large amounts of variability seen in these data. The presence of a great deal of variability would inevitably make it less likely to find significant differences. Furthermore, the level of latency performance varied considerably from one observer to the next. An examination of observers' MRT data in each condition, presented in Appendix D, Tables D-1 to D-18, would seem to support these suggestions.

The most unexpected finding to emerge from this study, and one that deserves special consideration, concerns the existence of the different results obtained for Condition RDS as compared to the other two conditions. In this condition, no significant multivariate main effects of disparity magnitude or disparity pulse duration were found, and overall depth discrimination performance was substantially poorer than in both conditions containing monocular cues. Yet, the main effect of disparity direction was statistically reliable and robust for the mean accuracy data. The presence of a main effect for direction implies that this spatial parameter affected observers' accuracy for discriminating disparity pulses, and indeed, their discrimination performance was found to be significantly better for disparity pulses in the crossed direction

than for those in the uncrossed direction. The lack of magnitude and duration main effects suggests that once direction information had been extracted, there may not have been sufficient time left within the duration of the brief disparity pulses to extract information about magnitude and duration.

The major finding of a crossed-uncrossed asymmetry in performance for RDS is in agreement with previous findings. The lack of magnitude- and duration-dependent effects on performance, however, is not. For example, Harwerth and Boltz (1979a, 1979b) used disparity steps of 6' of arc in static RDS, and found significant main effects of disparity and duration for these stimuli. Similarly, Grabowska (1983) also used disparity steps of 6' of arc in static RDS displays, and reported that the accuracy with which these stimuli were detected improved as a function of disparity, although she did note that the function relating this variable to discrimination performance was not monotonic. Uttal et al. (1975) varied disparities between 5.60' (crossed) and 5.60' (uncrossed) in 1.12' steps in dynamic RDS, and still observed the presence of magnitude and duration effects. The findings of these studies thus suggest that the size or magnitude of the disparity step cannot account for the differences in the results. It appears more likely that the differences may be due to the manner in which the duration of disparity information was manipulated in this study, given that previous studies used flashed presentations and the present study used pulsed disparity presentations.

There are several other observations from this study that may be related directly to this methodological difference. For example,

although most observers' pooled performance levels (crossed and uncrossed) in Condition RDS were significantly above chance with a disparity pulse duration of 50 ms or more, 4 of the 6 observers were nevertheless able to discriminate pulses containing crossed disparities with a pulse duration of 33 ms (i.e., the briefest pulse duration used in this study), all $z_s > 2.71$, $p < .05$, two-tailed. In addition, one observer discriminated disparity pulses in the uncrossed direction above chance with a pulse duration of 33 ms, $z = 4.13$, $p < .001$, two-tailed (Observer 4). Eight out of the 12 observers who participated in the other two stimulus conditions were able to identify the direction of target pulses containing crossed and uncrossed disparities above chance at the briefest pulse duration, all $z_s > 3.38$, $p < .01$, two-tailed. These findings lead to the suggestion that previous estimates of the time required to process disparity information in stereopsis may be inflated.

It is generally accepted, for instance, that human observers require approximately 50 ms to perceive depth in RDS (e.g., Julesz, 1964; Uttal et al., 1975). This value, however, is based on results obtained with flashed presentations of these stereoscopic stimuli. Flashing disparity information in RDS involves the brief simultaneous presentation of a disparate central region and its accompanying surround. As such, this mode of presentation represents a situation in which the total processing time required to resolve depth in these stereograms is measured rather than the time required to process disparity information per se. Because the two retinal images are not initially registered, the image in each eye must first be fused at the time of presentation or shortly thereafter, and then encoded to extract the depth information. Pulsed

presentations, on the other hand, presumably do not require this two-stage process because the images are already initially fused. All that they require is that the disparity contained in the stereograms be extracted. Therefore, the finding in the present study that some observers were able to correctly perceive the direction of disparity pulses in RDS with a pulse duration as brief as 33 ms, suggests that this mode of presentation may reflect the "true" time required for the extraction of binocular disparity information in RDS more accurately than flashed presentations.

Whether or not the resolution of depth in RDS in fact requires two different stages, with each stage requiring a different amount of processing time, remains an empirical question. The idea that stereopsis may involve at least two basic steps, namely, image registration and disparity extraction, however, forms a central part of Marr and Poggio's (1979) computational theory of human stereopsis. Unfortunately, their model does not address the temporal processing requirements of each step.

On the basis of such a model and given the findings of this study, one possible experiment that might be proposed could be to compare performance in static and dynamic RDS using both flashed and pulsed presentation modes. One hypothesis that could be tested is that observers should be able to perform better with pulsed presentations than with flashed presentations of the same duration. Furthermore, if Marr and Poggio's (1979) proposal that stereopsis requires two basic steps is correct, a systematic comparison of these two different modes of presentation might be used to assess the minimum time required to extract disparity information in RDS. Alternatively, the differences between

flashed and pulsed presentations of the same stimulus might be used to estimate the time required for sensory fusion. In any event, future research should carefully explore these two modes of presentation. The existence of fundamental differences between flashed and pulsed presentations may ultimately lead to possibly significant insights about the encoding of disparity information in stereopsis.

Interestingly, the overall level of performance for discriminating disparity pulses in the crossed direction was consistently found not to vary as a function of pulse duration in the present study, neither in terms of overall accuracy nor mean latency. In each condition, the psychophysical functions relating overall performance to this variable remained relatively flat with respect to increases in disparity pulse duration. This finding suggests that the extraction of such information may take place very early in stereoscopic visual processing. Furthermore, it also suggests that the extraction of disparity information in the crossed direction may be very rapid, requiring little additional time once sensory fusion has taken place. This finding, however, may be peculiar to the paradigm and stimulus configurations used in the present study. Nevertheless, it is an interesting result that needs to be studied in much greater detail in future experiments.

Finally, several of the observers who were tested in the RDS condition remarked that when disparity pulses were presented in these stereograms, they sometimes appeared as slight horizontal movements rather than as clearly perceivable, discrete disparity jumps. This might possibly help explain why depth discrimination performance in Condition RDS was poorer than originally expected. On the basis of these personal

observations, it might be worthwhile to replicate this study with dynamic RDS. Perhaps, the continuously dynamic motion of the dots in such displays might be effective in masking the apparent motion of the target, and therefore result in generally better overall depth discrimination performance.

In conclusion, the findings of this study provide new empirical data concerning the spatio-temporal processing of crossed and uncrossed disparity information in human stereopsis. There are, however, several questions that remain unanswered. The first concerns the question of fixation disparity. Since fixation disparity was not controlled or measured in this study, this potential artifact makes it difficult to discuss the results in terms of "absolute" crossed and uncrossed disparities. A related question concerns the range of disparity magnitudes used in this study. Given that fixation disparities are generally on the order of $\pm 5'$ of arc (e.g., Ogle, 1950), future experiments should make it a point to use a larger range of disparities. More importantly, fixation disparity should be measured, and if not possible, properly controlled for. This would allow much stronger statements to be made about the manner in which crossed and uncrossed disparity information may be processed by the visual system.

Conclusion

Taken together, the results of the present study suggest that the human visual system is differentially sensitive to the direction of binocular disparity information when this information is presented in the

form of brief pulses. Specifically, human observers appear to be more sensitive to disparity information in the crossed direction than to disparity information in the uncrossed direction. In addition, this difference in performance appears to be a fundamental one, given that it can be observed with both the presence and absence of monocular outlines that enclose a disparate target. As such, the results are consistent with the idea, first proposed by Richards (1970, 1971a), that there exist at least two stereoscopic mechanisms in the visual system--one mechanism that is selectively tuned to disparity information in the crossed direction, and another that is selectively tuned to disparity information in the uncrossed direction.

In this study, pulses that contained crossed disparities were discriminated significantly better than those that contained uncrossed disparities, both in terms of the accuracy of performance and speed of resolution. Specifically, disparities that were pulsed toward the observer were discriminated with consistently greater accuracy and speed than those pulsed away from the observer. Furthermore, this asymmetry in depth discrimination performance was observed across an entire range of small disparities and over a number of brief pulse durations.

What is the origin of this crossed-uncrossed asymmetry, and what possible value can it have in everyday life? There is no doubt that disparity relationships between images convey important information for spatial vision. On ecological grounds, one might speculate that an object that is perceived in front of another and closer to an observer might have a greater saliency or primacy than one that lies in a more remote region of the visual world. Accordingly, an object in the natural

environment, say, a predator or prey, that is seen first (either with respect to space or time) would most likely be given the greatest amount of attention and receive the most immediate response, thereby ensuring its survival and that of the species as a whole. The visual system's natural bias for a stereoscopically viewed object lying in front of the plane of fixation (i.e., in the crossed disparity direction) may therefore play an important survival role in the detection of stimuli (e.g., prey or predators), particularly in situations where they elude immediate detection or are monocularly camouflaged, and thus require stereoscopic vision.

Another line of reasoning that might account in part for some of the observed superiority of crossed over uncrossed performance, may be based on geometrical considerations. Recent work by Fox and his colleagues (Cormack & Fox, 1985, in press; Fox, Cormack, & Patterson, 1985) has begun to show that on geometrical grounds, there is a inherent difference between crossed and uncrossed disparity. For instance, for targets containing crossed disparities, the magnitude of perceived depth can never exceed the distance between the observer and the fixation plane, and it increases linearly as a function of viewing distance, as predicted from the geometry of stereopsis. For identical targets containing uncrossed disparities, however, the magnitude of perceived depth is boundless, and it increases as a positively accelerating function of viewing distance. In fact, the depth interval for uncrossed disparities becomes asymptotic or infinite with relatively modest increases in viewing distance or retinal disparity. These demonstrations indicate that manipulations of crossed and uncrossed disparities can produce quite

different perceptual results, particularly in cases where fixation distance or disparity are sufficiently large. In such cases, the depth intervals calculated for crossed disparities follow the rules of geometry, whereas those computed for uncrossed disparities show gross departures from the geometry underlying stereopsis.

Endnotes

¹Although there is some support for Richards' (1970) original estimate of the incidence and distribution of stereosanomalies in the general population (e.g., Herring & Bechtoldt, 1981; Jones, 1977), several recent studies have raised doubts about the accuracy of his estimate (e.g., Francis, Fox, & Patterson, 1984; Patterson & Fox, 1984). The principal finding of these studies is that the detection of stereosanomalies is highly dependent on the method used to assess them, and particularly on the stimulus exposure durations used. These studies have shown that the majority of individuals classified as being stereosanomalous under brief viewing conditions, can respond quite normally when presented with the same stimuli under continuous viewing conditions. In addition, Newhouse and Uttal (1982) have suggested that the previously reported high incidence of such impairments in stereoscopic vision may also be due to other factors, such as strategy or sequence effects.

²When $p = .5$, the standard normal distribution provides a good approximation to the binomial distribution. When $p \neq .5$, however, the binomial distribution is asymmetric. Nevertheless, if the sample size (N) is sufficiently large, the asymmetry will be small and the normal-curve approximation can be used. As a general rule, most statisticians recommend that Np or Nq be 5 or greater if normal probabilities are used to approximate binomial probabilities. A better

approximation is obtained if the products Np or Nq are ≥ 10 . Indeed, if N is large enough, the normal distribution can always be used to approximate the binomial distribution, irrespective of the value of p (Hays & Winkler, 1971).

It is clear that these criteria were met in this study, and therefore, the use of the normal-curve approximation was theoretically justified.

The Type I error rate, alpha, for a step-down analysis is based on the error rate for testing each dependent variable in succession according to some a priori ordering. The overall level of significance can be found by considering one minus the product of $(1 - \alpha(i))$'s where $\alpha(i)$ is the level of significance for test i . Symbolically, this can be expressed as:

$$\alpha = 1 - \prod_{i=1}^p (1 - \alpha(i)) \quad (1)$$

where \prod represents the product over p dependent variables (Barcikowski, 1983).

This computational procedure thus allows one to set each alpha at the desired level. In the present study, the individual alphas were set at the same level (.025) for each dependent variable since there were only two such variables. This resulted in an overall alpha level of .049375.

References

- Alexander, J. A. (1981). Temporal and spatial factors in the perceptual response to random pattern stereograms (Doctoral dissertation, University of New South Wales, 1979). Dissertation Abstracts International, 41, 2546B-2547B.
- Barcikowski, R. S. (1983). Step-down analysis. In R. S. Barcikowski (Ed.), Computer packages and research design. Vol 1. BMDP (pp. 747-748). Lanham, MD: University Press of America.
- Barlow, H. B., Blakemore, C., & Pettigrew, J. D. (1967). The neural mechanisms of binocular depth discrimination. Journal of Physiology, 193, 327-342.
- Beverley, K. I., & Regan, D. (1974). Visual sensitivity to disparity pulses: Evidence for directional selectivity. Vision Research, 14, 357-361.
- Birch, E. E., Gwiazda, J., & Held, R. (1982). Stereoacuity development for crossed and uncrossed disparities in human infants. Vision Research, 22, 507-513.
- Birch, E. E., Gwiazda, J., & Held, R. (1983). The development of vergence does not account for the onset of stereopsis. Perception, 12, 331-336.
- Bishop, P. O. (1974). Stereopsis and fusion. Transactions of the Ophthalmological Society of New Zealand, 26, 17-27.
- Bishop, P. O. (1981). Binocular vision. In R. A. Moses (Ed.), Adler's physiology of the eye: Clinical applications (7th ed., pp. 575-649).

St. Louis, MO: C. V. Mosby.

- Bishop, P. O., & Henry, G. H. (1971). Spatial vision. Annual Review of Psychology, 22, 119-160.
- Blakemore, C., & Hague, B. (1972). Evidence for disparity detecting neurons in the human visual system. Journal of Physiology, 225, 437-455.
- Bough, E. W. (1970). Stereoscopic vision in the macaque monkey: A behavioral demonstration. Nature, 225, 42-43.
- Bouldin, D. W. (1976). Visual evoked cortical potentials elicited by dynamic random-dot stereograms. Dissertation Abstracts International, 36, 3516B. (University Microfilms No. 76-92,172)
- Breitmeyer, B., Julesz, B., & Kropfl, W. (1975). Dynamic random-dot stereograms reveal up-down anisotropy and left-right isotropy between cortical hemifields. Science, 187, 269-270.
- Chung, C. S. & Berbaum, K. (1984). Form and depth in global stereopsis. Journal of Experimental Psychology: Human Perception and Performance, 10, 258-275.
- Clarke, P. G. H., Donaldson, I. M. L., & Whitteridge, D. (1976). Binocular visual mechanisms in cortical areas I and II of the sheep. Journal of Physiology, 256, 509-526.
- Collett, T. (1977). Stereopsis in the toad. Nature, 267, 349-351.
- Cormack, R., & Fox, R. (1985). The computation of retinal disparity. Perception & Psychophysics, 37, 176-178.
- Cormack, R., & Fox, R. (in press). The computation of disparity and depth in stereograms. Perception & Psychophysics.
- Cowey, A., & Porter, J. (1979). Brain damage and global stereopsis.

Proceedings of the Royal Society of London, 204B, 399-407.

- Cowey, A., Parkinson, A. M., & Warnick, L. (1975). Global stereopsis in rhesus monkeys. Quarterly Journal of Experimental Psychology, 27, 93-109.
- Dixon, W. J. (Ed.). (1981). BMDP statistical software. Berkeley, CA: University of California Press.
- Ferster, D. A. (1981). A comparison of binocular depth mechanisms in areas 17 and 18 of the cat visual cortex. Journal of Physiology, 311, 623-655.
- Fischer, B., & Krüger, J. (1979). Disparity tuning and binocularity of single neurons in cat visual cortex. Experimental Brain Research, 35, 1-8.
- Fischer, B., & Poggio, G. F. (1979). Depth sensitivity of binocular neurons of behaving monkeys. Proceedings of the Royal Society of London, 204B, 409-414.
- Foley, J. M., Applebaum, T. H., & Richards, W. (1975). Stereopsis with large disparities: Discrimination and depth magnitude. Vision Research, 15, 417-421.
- Fox, R. (1981). Stereopsis in animals and human infants: A review of behavioral investigations. In R. N. Aslin, J. R. Alberts, & M. R. Petersen (Eds.), Development of perception: Vol. 2. The visual system (pp. 335-381). New York: Academic Press.
- Fox, R., & Blake, R. (1971). Stereoscopic vision in the cat. Nature, 233, 55-56.
- Fox, R., Cormack, R., & Patterson, R. (1985, May). Discrimination of stereoscopic targets at "infinite" depth intervals. Presented at the

- annual meeting of the Association for Research in Vision and Ophthalmology, Sarasota, FL.
- Fox, R., Lehmkuhle, S. W., & Bush, R. C. (1977). Stereopsis in the falcon. Science, 197, 79-81.
- Francis, E. L., Fox, R., & Patterson, R. (1984, May). Stereoanomaly: Dependence on the method of testing. Presented at the annual meeting of the Association for Research in Vision and Ophthalmology, Sarasota, FL.
- Frisby, J. P. & Clatworthy, J. L. (1975). Learning to see complex random-dot stereograms. Perception, 4, 173-178.
- Grabowska, A. (1983). Lateral differences in the detection of stereoscopic depth. Neuropsychologia, 21, 249-257.
- Grimson, W. E. L. (1981a). A computer implementation of a theory of human stereo vision. Philosophical Transactions of the Royal Society of London, 292B, 217-253.
- Grimson, W. E. L. (1981b). From images to surfaces. Cambridge, MA: The MIT Press.
- Gulick, W. L. & Lawson, R. B. (1976). Human stereopsis. New York: Oxford University Press.
- Hacker, M. J., & Ratcliff, R. (1979). A revised table of d' for M-alternative forced choice. Perception & Psychophysics, 26, 168-170.
- Harwerth, R. S., & Boltz, R. L. (1979a). Behavioral measures of stereopsis in monkeys using random dot stereograms. Physiology & Behavior, 22, 229-234.
- Harwerth, R. S., & Boltz, R. L. (1979b). Stereopsis in monkeys using

- random dot stereograms: The effect of viewing duration. Vision Research, 19, 985-991.
- Harwerth, R. S., & Rawlings, S. C. (1977). Viewing time and stereoscopic threshold with random-dot stereograms. American Journal of Optometry & Physiological Optics, 54, 452-457.
- Hays, W. L., & Winkler, R. L. (1971). Statistics: Probability, inference, and decision. New York: Holt, Rinehart, & Winston.
- Held, R., Birch, E., & Gwiazda, J. (1980). Stereoacuity of human infants. Proceedings of the National Academy of Sciences (USA), 77, 5572-5574.
- Herring, R. D., & Bechtoldt, H. P. (1981). Categorical perception of stereoscopic stimuli. Perception & Psychophysics, 29, 129-137.
- Hubel, D. H., & Wiesel, T. N. (1970). Cells sensitive to binocular depth in area 18 of the macaque monkey cortex. Nature, 225, 41-42.
- Jones, R. (1977). Anomalies of disparity detection in the human visual system. Journal of Physiology, 262, 621-640.
- Joshua, D. E., & Bishop, P. O. (1970). Binocular single vision and depth discrimination. Receptive field disparities for central and peripheral vision and binocular interaction on peripheral single units in cat striate cortex. Experimental Brain Research, 10, 389-416.
- Julesz, B. (1960). Binocular depth perception of computer-generated patterns. Bell System Technical Journal, 39, 1125-1162.
- Julesz, B. (1964). Binocular depth perception without familiarity cues. Science, 145, 356-362.
- Julesz, B. (1971). Foundations of cyclopean perception. Chicago: The

University of Chicago Press.

- Julesz, B. (1978). Global stereopsis: Cooperative phenomena in stereoscopic depth perception. In R. Held, H. W. Leibowitz, & H. L. Teuber (Eds.), Handbook of sensory physiology: Vol. 7. Perception (pp. 215-256). Berlin: Springer-Verlag.
- Julesz, B., & Chang, J. -J. (1976). Interaction between pools of binocular disparity detectors tuned to different disparities. Biological Cybernetics, 22, 107-119.
- Julesz, B., & Schumer, R. A. (1981). Early visual perception. Annual Review of Psychology, 32, 575-627.
- Julesz, B., & Spivack, G. J. (1967). Stereopsis based on vernier acuity cues alone. Science, 157, 563-565.
- Julesz, B., Breitmeyer, B., & Kropfl, W. (1976). Binocular-disparity-dependent upper-lower hemifield anisotropy and left-right hemifield isotropy as revealed by dynamic random-dot stereograms. Perception, 5, 129-141.
- Kaufman, L. (1964). On the nature of binocular disparity. American Journal of Psychology, 77, 398-401.
- Lasley, D. J. (1985). Discrimination of crossed and uncrossed disparities. Journal of the Optical Society of America A, 2, 399-403.
- Lasley, D. J., Rivlin, J., Rich, L., & Flynn, J. T. (1984). Stereo-discrimination between diplopic images in clinically normal observers. Investigative Ophthalmology & Visual Science, 25, 1316-1320.
- Lehmkuhle, S., & Fox, R. (1977, May). Global stereopsis in the cat.

Presented at the annual meeting of the Association for Research in Vision and Ophthalmology, Sarasota, FL.

- MacCracken, P. J., & Hayes, W. N. (1976). Experience and latency to achieve stereopsis. Perceptual & Motor Skills, 43, 1227-1231.
- MacCracken, P. J., Bourne, J. A., & Hayes, W. N. (1977). Experience and latency to achieve stereopsis: A replication. Perceptual & Motor Skills, 45, 261-262.
- Marr, D. (1982). Vision. San Francisco: W. H. Freeman.
- Marr, D., & Poggio, T. (1976). Cooperative computation of stereo disparity. Science, 194, 283-287.
- Marr, D., & Poggio, T. (1979). A computational theory of human stereo vision. Proceedings of the Royal Society of London, 204B, 301-328.
- Maunsell, J. H. R., & Van Essen, D. C. (1983). Functional properties of neurons in middle temporal visual area of the macaque monkey: II. Binocular interactions and sensitivity to binocular disparity. Journal of Neurophysiology, 49, 1148-1167.
- Mayhew, J. E. W., & Frisby, J. P. (1979). Convergent disparity discriminations in narrow-band-filtered random-dot stereograms. Vision Research, 19, 63-71.
- Mayhew, J. E. W., & Frisby, J. P. (1980). The computation of binocular edges. Perception, 9, 69-86.
- Mayhew, J. E. W., & Frisby, J. P. (1981). Psychophysical and computational studies towards a theory of human stereopsis. Artificial Intelligence, 17, 349-385.
- Mitchell, D. E. (1966). A review of the concept of "Panum's fusional areas." American Journal of Optometry & Archives of the American

Academy of Optometry, 43, 387-391.

Mitchell, D. E., & Baker, A. G. (1973). Stereoscopic aftereffects: Evidence for disparity-specific neurones in the human visual system. Vision Research, 13, 2273-2288.

Newhouse, M., & Uttal, W. R. (1982). Distribution of stereoanomalies in the general population. Bulletin of the Psychonomic Society, 20, 48-50.

Nikara, T., Bishop, P. O., & Pettigrew, J. D. (1968). Analysis of retinal correspondence by studying receptive fields of binocular single units in cat striate cortex. Experimental Brain Research, 6, 353-372.

Norcia, A. M., & Stevenson, S. B. (1982, May). Temporal modulation transfer functions for changing disparities in global stereopsis. Presented at the annual meeting of the Association for Research in Vision and Ophthalmology, Sarasota, FL.

Ogle, K. N. (1950). Researches in binocular vision. Philadelphia: W. B. Saunders.

Ogle, K. N. (1952). On the limits of stereoscopic vision. Journal of Experimental Psychology, 44, 253-259.

Ogle, K. N. (1959). Theory of stereoscopic vision. In S. Koch (Ed.) Psychology: A study of a science: Vol. 1 (pp. 362-394). New York: McGraw-Hill.

Packwood, J., & Gordon, B. (1975). Stereopsis in normal domestic cat, Siamese cat, and cat with alternating occlusion. Journal of Neurophysiology, 38, 1485-1499.

Patterson, R., & Fox, R. (1984). The effect of testing method on

- stereoanomaly. Vision Research, 24, 403-408.
- Pettigrew, J. D. (1973). Binocular neurones which signal change of disparity in area 18 of the cat visual cortex. Nature, 241, 123-124.
- Pettigrew, J. D., & Konishi, M. (1976). Neurons selective for orientation and binocular disparity in the visual Wulst of the barn owl (*Tyto alba*). Science, 193, 675-678.
- Pettigrew, J. D., Nikara, T., & Bishop, P. O. (1968). Binocular interaction of single units in cat striate cortex: Simultaneous stimulation by single moving slits with receptive fields in correspondence. Experimental Brain Research, 6, 391-410.
- Poggio, G. F. (1980). Neurons sensitive to dynamic random-dot stereograms in areas 17 and 18 of rhesus monkey cortex. (From Society of Neuroscience Abstracts, 1980, 6, Abstract No. 230.12)
- Poggio, G. F. (1981). Cortical mechanisms of binocular vision in the rhesus monkey. In O. Pompeiano & C. Ajmone Marsan (Eds.), Brain mechanisms and perceptual awareness (pp. 53-66). New York: Raven Press.
- Poggio, G. F. (1984). Processing of stereoscopic information in primate visual cortex. In G. M. Edelman, W. E. Gall, & W. M. Cowan (Eds.), Dynamic aspects of neocortical function (pp. 613-635). New York: John Wiley & Sons.
- Poggio, G. F., & Fischer, B. (1977). Binocular interaction and depth sensitivity in striate and prestriate cortex of behaving rhesus monkey. Journal of Neurophysiology, 40, 1392-1405.
- Poggio, G. F., & Poggio, T. (1984). The analysis of stereopsis. Annual Review of Neuroscience, 7, 379-412.

- Poggio, G. F., & Talbot, W. H. (1981). Mechanisms of static and dynamic stereopsis in foveal cortex of the rhesus monkey. Journal of Physiology, 315, 469-492.
- Poggio, G. F., Motter, B. C., Squatrito, S., & Trotter, Y. (1985). Responses of neurons in visual cortex (V1 and V2) of the alert macaque to dynamic random-dot stereograms. Vision Research, 25, 397-406.
- Poggio, T. (1984). Vision by man and machine. Scientific American, 250, 106-116.
- Prazdny, K. (1985). Detection of binocular disparities. Biological Cybernetics, 52, 93-99.
- Regan, D., & Beverley, K. I. (1973). Electrophysiological evidence for the existence of neurones sensitive to direction of depth movement. Nature, 246, 504-506.
- Regan, D., & Spekreijse, H. (1970). Electrophysiological correlates of binocular depth perception in man. Nature, 225, 92-94.
- Reuss, J. L. (1981). Human stereopsis: Detection and development. Dissertation Abstracts International, 42, 1961B. (University Microfilms No. 81-24,989)
- Richards, W. (1970). Stereopsis and stereoblindness. Experimental Brain Research, 10, 380-388.
- Richards, W. (1971a). Anomalous stereoscopic depth perception. Journal of the Optical Society of America, 61, 410-414.
- Richards, W. (1971b). Independence of Panum's near and far limits. American Journal of Optometry & Archives of the American Academy of Optometry, 48, 103-109.

- Richards, W. (1971c). Size-distance transformations. In O. -J. Grüsser & R. Klinke (Eds.), Zeichenerkennung durch biologische und technische Systeme [Pattern recognition in biological and technical systems] (pp. 276-287). Berlin: Springer-Verlag.
- Richards, W. (1972b). Stereoperimetry: New technique for analyzing visual function. Journal of the Optical Society of America, 62, 715.
- Richards, W. (1973). Reversal in stereo discrimination by contrast reversal. American Journal of Optometry & Archives of the American Academy of Optometry, 50, 853-862.
- Richards, W. (1977). Stereopsis with and without monocular contours. Vision Research, 17, 967-969.
- Richards, W., & Foley, J. M. (1971). Interhemispheric processing of binocular disparity. Journal of the Optical Society of America, 61, 419-421.
- Richards, W., & Kaye, M. (1974). Local versus global stereopsis: Two mechanisms? Vision Research, 14, 1345-1347.
- Richards, W., & Regan, D. (1973). A stereo field map with implications for disparity processing. Investigative Ophthalmology, 12, 904-909.
- Roy, J., & Bargmann, R. E. (1958). Tests of multiple independence and the associated confidence bounds. Annals of Mathematical Statistics, 29, 491-503.
- Sarmiento, R. F. (1975). The stereoacuity of macaque monkey. Vision Research, 15, 493-498.
- Saye, A. (1976). Facilitation of stereopsis from a large disparity random-dot stereogram by various monocular features: Further findings (A shorter note). Perception, 5, 461-465.

- Saye, A., & Frisby, J. P. (1975). The role of monocularly conspicuous features in facilitating stereopsis from random-dot stereograms. Perception, 4, 159-171.
- Schor, C. M. (1979). The influence of rapid prism adaptation upon fixation disparity. Vision Research, 19, 757-765.
- Schor, C. M., & Wood, I. (1983). Disparity range for local stereopsis as a function of luminance spatial frequency. Vision Research, 23, 1649-1654.
- Schumer, R. A., & Julesz, B. (1984). Binocular disparity modulation sensitivity to disparities offset from the plane of fixation. Vision Research, 24, 533-542.
- Shipley, T., Garfinkel, R., & Van Houten, P. (1984). Interhemispherical comparisons in the processing of contour and random texture sinewave stereograms. Documenta Ophthalmologica, 58, 269-305.
- Staller, J. D., Lappin, J. S., & Fox, R. (1980). Stimulus uncertainty does not impair stereopsis. Perception & Psychophysics, 27, 361-367.
- Sugie, N., & Suwa, M., (1977). A scheme for binocular depth perception suggested by neurophysiological evidence. Biological Cybernetics, 26, 1-15.
- Tyler, C. W., & Julesz, B. (1980). On the depth of the cyclopean retina. Experimental Brain Research, 40, 196-202.
- Uttal, W. R., Fitzgerald, J., & Eskin, T. E. (1975). Parameters of tachistoscopic stereopsis. Vision Research, 15, 705-712.
- von der Heydt, R., Adorjani, C. S., Hännly, P., & Baumgartner, G. (1978). Disparity sensitivity and receptive field incongruity of units in the cat striate cortex. Experimental Brain Research, 31, 523-545.

Wheatstone, C. (1838). Contributions to the physiology of vision - Part the first. On some remarkable, and hitherto unobserved, phenomena of binocular vision. Philosophical Transactions of the Royal Society, 128, 371-394.

Woo, G. C. S. (1974). Temporal tolerance of the foveal size of Panum's area. Vision Research, 14, 633-635.

Woo, G. C. S., & Sillanpaa, V. (1979). Absolute stereoscopic thresholds as measured by crossed and uncrossed disparities. American Journal of Optometry & Physiological Optics, 56, 350-355.

Appendix A

Detailed Univariate-Multivariate Analysis
of Variance Source Tables

Table A-1

Detailed Univariate-Multivariate Analysis of VarianceSource Table for Condition TDL

Source	Wilks' Lambda	SS	Df	MS	F
A	0.243530		6 28		4.79**
(PCR)		136482.88	3	45494.29	7.70**
ERROR		88672.33	15	5911.49	
(MRT)		7714472.69	3	2571490.90	5.23*
ERROR		7381812.89	15	492120.86	
B	0.085182		8 38		11.52***
(PCR)		31618.40	4	7940.60	46.57***
ERROR		3394.98	20	169.75	
(MRT)		2016703.29	4	504175.82	10.92***
ERROR		923568.97	20	46178.45	
C	0.228366		10 48		5.24***
(PCR)		15965.59	5	3913.12	12.01***
ERROR		6646.70	25	265.87	
(MRT)		171994.74	5	34398.95	1.58
ERROR		545683.66	25	21827.35	
AB	0.565901		24 118		1.62*
(PCR)		3797.15	12	316.43	1.02
ERROR		18536.18	60	308.94	
(MRT)		715092.68	12	59591.06	2.98**
ERROR		1199126.13	60	19985.44	
AC	0.642759		30 148		1.22
(PCR)		10138.99	15	675.93	1.34
ERROR		37894.55	75	505.26	
(MRT)		189626.99	15	12641.80	1.04
ERROR		909039.31	75	12120.52	
BC	0.586424		40 198		1.51*
(PCR)		5064.10	20	253.20	2.70***
ERROR		9385.07	100	93.85	
(MRT)		225244.16	20	11262.21	0.98
ERROR		1152358.07	100	11523.58	

(table continues)

Source	Wilks' Lambda	SS	Df	MS	F
ABC	0.628572		120 598		1.30*
(PCR)		6407.01	60	106.78	1.34
ERROR		23877.15	300	79.59	
(MRT)		954797.90	60	15913.30	1.53*
ERROR		3112741.40	300	10375.80	

Note. This table and the other tables in this appendix were prepared from the output listings provided by BMDP4V. Additional tests available from the output of this program, such as conservative tests for the within factors (e.g., Greenhouse-Geisser Adjusted Dfs, Huynh-Feldt Adjusted Dfs) have been omitted for the sake of clarity. All values have been rounded to the nearest two decimal places. A represents disparity direction. B and C represent disparity magnitude and pulse duration, respectively. PCR = percent correct responses; MRT = mean reaction time.

*p < .05. **p < .005. ***p < .001.

Table A-2

Detailed Univariate-Multivariate Analysis of VarianceSource Table for Condition RDS

Source	Wilks' Lambda	SS	Df	MS	F
A	0.017056		2 4		13.31**
(PCR)		65098.00	1	65098.00	30.86***
ERROR		10546.85	5	2109.37	
(MRT)		269089.58	1	269089.58	4.34
ERROR		309804.58	5	61960.92	
B	0.779415		8 38		0.63
(PCR)		719.77	4	179.94	0.58
ERROR		6165.77	20	308.29	
(MRT)		129845.42	4	32461.36	0.72
ERROR		898494.28	20	44924.71	
C	0.505258		10 48		1.95
(PCR)		5677.23	5	1135.45	3.39**
ERROR		8378.76	25	335.15	
(MRT)		282078.85	5	56415.71	1.28
ERROR		1100968.59	25	44038.74	
AB	0.811153		8 38		0.52
(PCR)		2085.18	4	521.29	0.86
ERROR		12137.56	20	606.88	
(MRT)		58247.83	4	14561.96	0.74
ERROR		395275.33	20	19763.77	
AC	0.664643		10 48		1.09
(PCR)		6258.25	5	1251.65	0.75
ERROR		41669.60	25	1666.78	
(MRT)		460719.02	5	92143.80	2.37
ERROR		971601.78	25	38864.07	
BC	0.797709		40 198		0.59
(PCR)		2818.90	20	140.95	1.68
ERROR		8413.37	100	84.13	
(MRT)		403441.44	20	20172.07	1.37
ERROR		1467531.17	100	14675.31	

(table continues)

Source	Wilks' Lambda	SS	DF	MS	F
ABC	0.820264 *		40 198		0.52
(PCR)		1391.82	20	69.59	0.48
ERROR		14537.24	100	145.37	
(MRT)		341215.59	20	17060.78	1.04
ERROR		1635664.67	100	16356.64	

Note. All values have been rounded to the nearest two decimal places.

A represents disparity direction. B and C represent disparity magnitude and pulse duration, respectively. PCR = percent correct responses; MRT = mean reaction time.

*p < .05. **p < .025. ***p < .005.

Table A-3

Detailed Univariate-Multivariate Analysis of VarianceSource Table for Condition RTL

Source	Wilks' Lambda	SS	Df	MS	F
A	0.107785		6 28		9.55****
(PCR)		243254.39	3	81084.80	13.14****
ERROR		92555.96	15	6170.40	
(MRT)		16350920.35	3	5450306.78	6.76***
ERROR		12089614.39	15	805974.29	
B	0.302708		8 38		3.88***
(PCR)		7034.91	4	1758.73	4.30*
ERROR		8177.96	20	408.90	
(MRT)		2309262.29	4	577315.57	3.46*
ERROR		3335027.21	20	166751.36	
C	0.056952		10 48		15.31****
(PCR)		17393.84	5	3478.77	28.04****
ERROR		3101.70	25	124.07	
(MRT)		688583.92	5	137716.78	2.38
ERROR		1447447.05	25	57897.88	
AB	0.513909		24 118		1.94**
(PCR)		5866.67	12	488.89	2.15*
ERROR		13638.93	60	227.32	
(MRT)		1692713.30	12	141059.44	0.86
ERROR		9873238.53	60	164553.98	
AC	0.489162		30 148		2.12****
(PCR)		12238.97	15	815.93	2.33**
ERROR		26220.33	75	349.60	
(MRT)		747665.01	15	49844.33	1.39
ERROR		2699082.96	75	35987.77	
BC	0.729529		40 198		0.85
(PCR)		1640.29	20	82.01	1.00
ERROR		8213.54	100	82.14	
(MRT)		1115319.85	20	55765.99	1.29
ERROR		4320565.06	100	43205.65	

(table continues)

Source	Wilks' Lambda	SS	Df	MS	F
ABC	0.724304		120 598		0.87
(PCR)		4932.60	60	82.21	0.89
ERROR		27627.90	300	92.09	
(MRT)		2672331.17	60	44538.85	0.89
ERROR		14984430.72	300	49948.10	

Note. All values have been rounded to the nearest two decimal places.

A represents disparity direction. B and C represent disparity magnitude and pulse duration, respectively. PCR = percent correct responses; MRT = mean reaction time.

* $p < .05$. ** $p < .01$. *** $p < .005$. **** $p < .001$.

Table A-4

Detailed Univariate-Multivariate Analysis of VarianceSource Table for All Three Stimulus Conditions

Source	Wilks' Lambda	SS	Df	MS	F
SC	0.384053		4 28		4.30***
(PCR)		448.42	2	224.21	5.55**
ERROR		606.45	15	40.43	
(MRT)		969724.69	2	484862.35	0.13
ERROR		57678331.51	15	3845222.10	
A	0.077512		2 14		18.14****
(PCR)		483.04	1	483.04	44.20****
ERROR		163.93	15	10.93	
(MRT)		13851371.94	1	13851371.94	20.23****
ERROR		10269269.43	15	684617.96	
A x SC	0.589787		4 28		2.11
(PCR)		33.71	2	16.86	1.54
ERROR		163.93	15	10.93	
(MRT)		4403754.99	2	2201877.50	3.22
ERROR		10269269.43	15	684617.96	
B	0.475010		8 118		6.65****
(PCR)		47.80	4	11.95	12.98****
ERROR		55.23	60	0.92	
(MRT)		3740783.93	4	935195.98	5.60****
ERROR		10012732.25	60	166878.87	
B x SC	0.482816		16 118		3.24****
(PCR)		47.16	8	5.89	6.40****
ERROR		55.23	60	0.92	
(MRT)		1848370.49	8	231046.31	1.38
ERROR		10012732.25	60	166878.87	
C	0.684225		10 148		3.09***
(PCR)		23.19	5	4.64	6.08****
ERROR		57.25	75	0.76	
(MRT)		282020.29	5	56404.06	1.12
ERROR		3763948.07	75	50185.97	

(table continues)

Source	Wilks' Lambda	SS	Df	MS	F
C x SC	0.752937		20 148		1.13
(PCR)		8.25	10	0.83	1.08
ERROR		57.25	75	0.76	
(MRT)		784481.89	10	78448.19	1.56
ERROR		3763948.07	75	50185.97	
AB	0.928735		8 118		0.56
(PCR)		3.91	4	0.98	0.99
ERROR		59.24	60	0.99	
(MRT)		277586.92	4	69396.72	0.74
ERROR		5622818.01	60	93713.63	
AB x SC	0.860619		16 118		0.57
(PCR)		4.59	8	0.57	0.58
ERROR		59.24	60	0.99	
(MRT)		523363.79	8	65420.35	0.70
ERROR		5622818.01	60	93713.63	
AC	0.730895		10 148		2.51***
(PCR)		31.65	5	6.33	2.58*
ERROR		189.90	75	2.45	
(MRT)		128668.17	5	25733.63	0.66
ERROR		2937596.22	75	39167.95	
AC x SC	0.758536		20 148		1.10
(PCR)		1.82	10	0.18	0.07
ERROR		189.90	75	2.45	
(MRT)		440396.49	10	44039.65	1.12
ERROR		2937596.22	75	39167.95	
BC	0.821873		40 598		1.54*
(PCR)		12.94	20	0.65	2.64***
ERROR		73.45	300	0.24	
(MRT)		1301754.91	20	65087.75	1.57
ERROR		12460804.70	300	41536.02	
BC x SC	0.750181		80 598		1.16
(PCR)		8.46	40	0.21	0.86
ERROR		73.45	300	0.24	
(MRT)		1412718.27	40	35317.96	0.85
ERROR		12460804.70	300	41536.02	

(table continues)

Source	Wilks' Lambda	SS	Df	MS	F
ABC	0.866324		40 598		1.11
(PCR)		4.34	20	0.22	0.70
ERROR		92.57	300	0.31	
(MRT)		673949.40	20	33697.47	0.91
ERROR		11156395.16	300	37187.98	
ABC x SC	0.837462		80 598		0.69
(PCR)		6.71	40	0.17	0.54
ERROR		92.57	300	0.31	
(MRT)		1673596.41	40	41839.91	1.13
ERROR		11156395.16	300	37187.98	

Note. This analysis was performed on the mean data of all observers in the three conditions, and averaged over crossed and uncrossed disparity responses only. The mean accuracy data (i.e., PCR) were converted to corresponding values of d' prior to being subjected to the analysis.

All values have been rounded to the nearest two decimal places.

SC represents stimulus condition. A, B, and C represent disparity direction, disparity magnitude, and pulse duration, respectively.

PCR = percent correct responses; MRT = mean reaction time.

* $p < .05$. ** $p < .025$. *** $p < .01$. **** $p < .001$.

Appendix B**Step-Down Analysis of Each Main Effect and Interaction**
Tested for the Two Dependent Variables

Table B-1

Step-Down Analysis of Each Main Effect and Interaction
Tested for the Two Dependent Variables

Variate	Hypothesis MS	Error MS	Step-Down F	Hypothesis Df	Error Df
SC					
PCR	224.21	40.43	5.55**	2	15
MRT	2489065.67	2341459.20	1.06	2	14
A					
PCR	483.04	10.93	44.20***	1	15
MRT	2541.02	370882.78	0.01	1	14
A x SC					
PCR	16.86	10.93	1.54	2	15
MRT	1326701.07	370882.78	3.58	2	14
B					
PCR	11.95	0.92	12.98***	4	60
MRT	421815.78	166741.29	2.53*	4	59
B x SC					
PCR	5.89	0.92	6.40***	8	60
MRT	135383.76	166741.29	0.81	8	59
C					
PCR	4.64	0.76	6.08***	5	75
MRT	63095.70	47497.86	1.33	5	74
C x SC					
PCR	0.83	0.76	1.08	10	75
MRT	80123.00	47497.86	1.69	10	74
AB					
PCR	0.98	0.99	0.99	4	60
MRT	75885.70	94184.82	0.81	4	59
AB x SC					
PCR	0.57	0.99	0.58	8	60
MRT	54044.40	94184.82	0.57	8	59

(table continues)

Variate	Hypothesis MS	Error MS	Step-Down F	Hypothesis Df	Error Df
AC					
PCR	6.33	2.45	2.58*	5	75
MRT	11277.30	37151.10	0.30	5	74
AC x SC					
PCR	0.18	2.45	0.07	10	75
MRT	43838.30	37151.10	1.18	10	74
BC					
PCR	0.65	0.24	2.64***	20	300
MRT	94207.50	80796.53	1.17	20	299
BC x SC					
PCR	0.21	0.24	0.86	40	300
MRT	73687.05	80796.53	0.91	40	299
ABC					
PCR	0.22	0.31	0.70	20	300
MRT	87498.74	109845.25	0.80	20	299
ABC x SC					
PCR	0.17	0.31	0.54	40	300
MRT	130614.06	109845.25	1.19	40	299

Note. This analysis was performed on the mean data of all observers in the three conditions and averaged over crossed and uncrossed disparity responses only. The mean accuracy data (PCR) were converted to corresponding values of d' prior to being subjected to the analysis.

All values have been rounded to the nearest two decimal places.

A represents disparity direction. B and C represent disparity magnitude and pulse duration, respectively. PCR = percent correct responses; MRT = mean reaction time.

* $p < .05$. ** $p < .025$. *** $p < .001$.

Appendix C

Combined Mean Data of All Observers
as a Function of Stimulus Condition

Table C-1

Combined Mean Data of All Observers in Condition TDL

Independent Variable		Dependent Variable			
		PCR		MRT (ms)	
Direction	Crossed	83.11	(5.35)	656.95	(60.58)
	Uncrossed	57.19	(10.17)	918.62	(132.65)
	Left	92.00	(4.31)	694.30	(43.30)
	Right	89.22	(3.37)	705.22	(57.86)
Disparity (min)	1.56	67.92	(3.59)	820.92	(72.93)
	3.12	79.38	(3.61)	744.92	(58.29)
	4.68	83.58	(3.88)	699.57	(54.78)
	6.24	85.24	(4.16)	706.47	(64.01)
	7.80	85.72	(3.82)	671.65	(52.18)
Pulse Duration (ms)	33	71.17	(3.92)	755.58	(64.80)
	50	78.17	(3.86)	733.75	(56.78)
	67	80.96	(3.92)	731.95	(63.31)
	83	82.42	(4.21)	730.38	(63.27)
	100	84.04	(4.04)	714.28	(54.86)
	IPD	85.54	(3.59)	707.16	(56.57)

Note. Values inside the parentheses represent the 95% confidence intervals of the means. The data for each variable were averaged across all the other variables and across all observers.

PCR = percent correct responses; MRT = mean reaction time;

IPD = "infinite" pulse duration.

Table C-2

Combined Mean Data of All Observers in Condition RDS

Independent Variable		Dependent Variable	
		PCR	MRT (ms)
Direction	Crossed	70.19 (7.21)	722.40 (74.93)
	Uncrossed	43.22 (8.08)	781.10 (80.12)
Disparity _z (min)	1.56	58.77 (5.14)	769.60 (90.96)
	3.12	56.83 (7.49)	718.70 (75.71)
	4.68	56.31 (5.51)	734.20 (75.15)
	6.24	54.53 (5.59)	752.70 (80.81)
	7.80	57.09 (4.88)	761.60 (77.54)
Pulse Duration (ms)	33	52.19 (3.90)	751.50 (86.24)
	50	55.08 (6.51)	705.30 (65.78)
	67	54.30 (6.02)	724.50 (74.03)
	83	57.20 (5.66)	749.10 (75.99)
	100	56.80 (4.76)	753.00 (76.40)
	IPD	64.64 (13.62)	793.60 (104.31)

Note. Values inside the parentheses represent the 95% confidence intervals of the means. The data for each variable were averaged across all the other variables and across all observers.

PCR = percent correct responses; MRT = mean reaction time;

IPD = "infinite" pulse duration.

Table C-3

Combined Mean Data of All Observers in Condition RTL

Independent Variable		Dependent Variable			
		PCR		MRT (ms)	
Direction	Crossed	83.17	(11.51)	645.65	(78.91)
	Uncrossed	42.16	(18.42)	1023.48	(103.23)
	Left	84.53	(9.72)	692.38	(76.22)
	Right	86.72	(8.72)	641.36	(59.41)
Disparity (min)	1.56	68.64	(6.53)	803.50	(115.23)
	3.12	73.79	(6.45)	692.80	(72.64)
	4.68	75.76	(6.08)	663.90	(67.99)
	6.24	77.47	(5.47)	698.40	(83.01)
	7.80	75.21	(5.72)	699.90	(70.13)
Pulse Duration (ms)	33	65.46	(5.64)	770.00	(96.63)
	50	69.92	(6.23)	700.50	(79.79)
	67	76.04	(5.57)	695.00	(74.79)
	83	77.04	(6.13)	691.50	(75.87)
	100	76.62	(6.27)	680.60	(69.42)
	IPD	79.79	(5.86)	728.50	(88.38)

Note. Values inside the parentheses represent the 95% confidence intervals of the means. The data for each variable were averaged across all the other variables and across all observers.

PCR = percent correct responses; MRT = mean reaction time;

IPD = "infinite" pulse duration.

Appendix D

Mean Data of Each Observer
as a Function of Stimulus Condition

Table D-1

Mean Data of Observer 1 in Condition TDL

Independent Variable		Dependent Variable			
		PCR	MRT (ms)		
Direction	Crossed	72.17	(5.64)	833.20	(48.43)
	Uncrossed	58.00	(5.92)	931.60	(71.79)
	Left	96.00	(2.37)	678.90	(35.28)
	Right	94.33	(2.86)	640.80	(26.40)
Disparity (min)	1.56	67.71	(6.29)	900.60	(79.56)
	3.12	76.67	(6.27)	830.00	(60.98)
	4.68	82.71	(5.47)	743.50	(49.55)
	6.24	86.04	(5.02)	686.70	(39.04)
	7.80	87.05	(5.00)	622.10	(26.28)
Pulse Duration (ms)	33	74.50	(6.61)	843.00	(60.70)
	50	77.75	(6.35)	763.20	(52.68)
	67	79.50	(6.29)	786.00	(74.46)
	83	84.00	(5.23)	748.20	(59.00)
	100	86.50	(5.47)	750.10	(67.95)
	IPD	78.50	(7.53)	682.60	(41.89)

Note. Values inside the parentheses represent the 95% confidence intervals of the means. The data for each variable were averaged across all the other variables for this observer. PCR = percent correct responses; MRT = mean reaction time; IPD = "infinite" pulse duration.

Table D-2

Mean Data of Observer 2 in Condition TDL

Independent Variable		Dependent Variable			
		PCR		MRT (ms)	
Direction	Crossed	81.00	(3.53)	722.40	(23.05)
	Uncrossed	32.33	(4.12)	988.40	(49.69)
	Left	83.33	(4.51)	747.80	(27.05)
	Right	83.67	(4.29)	805.50	(26.42)
Disparity (min)	1.56	63.96	(5.94)	816.40	(34.77)
	3.12	69.79	(6.19)	836.30	(46.96)
	4.68	73.33	(5.72)	803.90	(33.46)
	6.24	70.83	(6.17)	791.40	(44.75)
	7.80	72.50	(6.10)	778.70	(33.63)
Pulse Duration (ms)	33	60.25	(6.08)	845.00	(53.35)
	50	69.75	(6.35)	775.20	(33.77)
	67	68.00	(6.61)	804.20	(40.10)
	83	71.00	(6.62)	813.60	(43.61)
	100	74.25	(6.62)	801.70	(45.22)
	IPD	77.25	(7.00)	793.30	(38.55)

Note. Values inside the parentheses represent the 95% confidence intervals of the means. The data for each variable were averaged across all the other variables for this observer. PCR = percent correct responses; MRT = mean reaction time; IPD = "infinite" pulse duration.

Table D-3

Mean Data of Observer 3 in Condition TDL

Independent Variable		Dependent Variable			
		PCR		MRT (ms)	
Direction	Crossed	80.00	(4.49)	780.30	(39.59)
	Uncrossed	14.83	(2.74)	1547.00	(124.64)
	Left	96.67	(2.21)	867.00	(26.83)
	Right	85.67	(4.08)	956.30	(43.39)
Disparity (min)	1.56	57.71	(6.62)	1155.00	(90.51)
	3.12	71.25	(6.55)	950.90	(55.68)
	4.68	70.42	(7.15)	909.90	(68.38)
	6.24	73.54	(6.92)	933.40	(87.91)
	7.80	73.54	(7.13)	900.50	(60.78)
Pulse Duration (ms)	33	65.75	(7.33)	1015.00	(83.54)
	50	68.50	(7.35)	996.50	(80.32)
	67	71.75	(7.39)	1002.00	(93.34)
	83	66.75	(7.86)	968.60	(105.72)
	100	69.50	(8.23)	910.60	(56.19)
	IPD	73.50	(7.49)	928.40	(70.42)

Note. Values inside the parentheses represent the 95% confidence intervals of the means. The data for each variable were averaged across all the other variables for this observer. PCR = percent correct responses; MRT = mean reaction time; IPD = "infinite" pulse duration.

Table D-4

Mean Data of Observer 4 in Condition TDL

Independent Variable		Dependent Variable	
		PCR	MRT (ms)
Direction	Crossed	87.67 (3.47)	608.30 (46.49)
	Uncrossed	88.67 (3.16)	645.20 (50.67)
	Left	93.67 (2.98)	601.40 (15.64)
	Right	86.00 (4.82)	551.60 (16.82)
Disparity (min)	1.56	74.79 (5.45)	705.20 (53.35)
	3.12	85.21 (4.80)	614.80 (46.18)
	4.68	93.33 (3.27)	565.60 (22.46)
	6.24	95.83 (2.35)	595.20 (49.76)
	7.80	95.83 (2.55)	536.40 (16.90)
Pulse Duration (ms)	33	75.00 (6.23)	609.80 (42.81)
	50	84.25 (5.15)	612.90 (49.35)
	67	90.25 (4.61)	575.50 (25.54)
	83	93.00 (3.35)	636.00 (72.21)
	100	94.75 (3.14)	595.40 (35.79)
	IPD	96.75 (1.92)	585.50 (29.67)

Note. Values inside the parentheses represent the 95% confidence intervals of the means. The data for each variable were averaged across all the other variables for this observer. PCR = percent correct responses; MRT = mean reaction time; IPD = "infinite" pulse duration.

Table D-5

Mean Data of Observer 5 in Condition TDL

Independent Variable		Dependent Variable			
		PCR		MRT (ms)	
Direction	Crossed	89.83	(2.78)	483.60	(14.43)
	Uncrossed	68.67	(4.80)	736.10	(19.33)
	Left	89.00	(3.80)	616.80	(19.97)
	Right	91.33	(3.43)	623.10	(15.33)
Disparity (min)	1.56	70.83	(6.12)	667.70	(29.32)
	3.12	83.54	(4.27)	636.60	(22.99)
	4.68	87.71	(3.88)	587.10	(21.29)
	6.24	89.79	(3.65)	610.80	(26.93)
	7.80	91.67	(3.19)	570.20	(22.29)
Pulse Duration (ms)	33	67.50	(6.84)	618.20	(31.67)
	50	82.50	(5.23)	659.30	(34.08)
	67	87.50	(3.98)	608.60	(27.20)
	83	87.75	(4.55)	601.30	(23.83)
	100	88.00	(3.84)	598.50	(20.97)
	IPD	95.00	(2.61)	595.70	(25.70)

Note. Values inside the parentheses represent the 95% confidence intervals of the means. The data for each variable were averaged across all the other variables for this observer. PCR = percent correct responses; MRT = mean reaction time; IPD = "infinite" pulse duration.

Table D-6

Mean Data of Observer G in Condition TDL

Independent Variable		Dependent Variable	
		PCR	MRT (ms)
Direction	Crossed	88.00 (2.80)	513.90 (19.89)
	Uncrossed	80.67 (3.96)	663.40 (50.12)
	Left	93.33 (3.29)	653.90 (29.13)
	Right	94.33 (2.70)	654.00 (24.83)
Disparity (min)	1.56	72.50 (5.51)	680.60 (42.65)
	3.12	89.79 (3.35)	636.50 (61.92)
	4.68	93.96 (2.39)	587.40 (31.56)
	6.24	95.42 (2.10)	621.30 (35.14)
	7.80	93.75 (2.61)	582.00 (18.66)
Pulse Duration (ms)	33	84.00 (5.10)	602.50 (31.14)
	50	86.25 (5.04)	595.40 (27.75)
	67	88.75 (4.02)	615.40 (35.83)
	83	92.00 (3.10)	614.60 (41.73)
	100	91.25 (3.65)	638.40 (76.36)
	IPD	92.25 (2.94)	657.40 (35.97)

Note. Values inside the parentheses represent the 95% confidence intervals of the means. The data for each variable were averaged across all the other variables for this observer. PCR = percent correct responses; MRT = mean reaction time; IPD = "infinite" pulse duration.

Table D-7

Mean Data of Observer 1 in Condition RDS

Independent Variable		Dependent Variable	
		PCR	MRT (ms)
Direction	Crossed	76.66 (3.14)	910.60 (43.94)
	Uncrossed	61.89 (4.27)	901.90 (32.54)
Disparity (min)	1.56	63.88 (5.88)	993.60 (74.54)
	3.12	70.00 (5.43)	866.40 (42.69)
	4.68	66.94 (6.04)	919.40 (56.35)
	6.24	66.94 (7.55)	875.30 (59.86)
	7.80	78.61 (5.39)	875.40 (63.25)
Pulse Duration (ms)	33	55.66 (7.33)	851.30 (45.22)
	50	70.33 (7.80)	835.50 (46.30)
	67	66.66 (6.19)	859.30 (38.53)
	83	70.33 (5.39)	884.80 (53.78)
	100	68.32 (5.76)	890.60 (49.90)
	IPD	84.33 (6.68)	1119.00 (109.74)

Note. Values inside the parentheses represent the 95% confidence intervals of the means. The data for each variable were averaged across all the other variables for this observer. PCR = percent correct responses; MRT = mean reaction time; IPD = "infinite" pulse duration.

Table D-8

Mean Data of Observer 2 in Condition RDS

Independent Variable		Dependent Variable			
		PCR		MRT (ms)	
Direction	Crossed	68.16	(4.27)	753.40	(38.32)
	Uncrossed	41.55	(4.98)	887.00	(51.12)
Disparity (min)	1.56	59.95	(6.78)	886.20	(85.06)
	3.12	61.10	(9.73)	800.50	(71.23)
	4.68	48.29	(8.17)	749.00	(46.20)
	6.24	50.25	(8.62)	764.90	(48.98)
	7.80	54.69	(6.72)	869.60	(74.32)
Pulse Duration (ms)	33	56.29	(8.54)	844.90	(105.47)
	50	50.64	(8.51)	743.60	(50.53)
	67	51.64	(7.64)	817.80	(59.98)
	83	50.64	(8.49)	880.00	(86.20)
	100	53.63	(7.37)	829.20	(75.83)
	IPD	66.30	(10.98)	774.40	(49.25)

Note. Values inside the parentheses represent the 95% confidence intervals of the means. The data for each variable were averaged across all the other variables for this observer. PCR = percent correct responses; MRT = mean reaction time; IPD = "infinite" pulse duration.

Table D-9

Mean Data of Observer 3 in Condition RDS

Independent Variable		Dependent Variable	
		PCR	MRT (ms)
Direction	Crossed	83.78 (2.98)	775.40 (63.94)
	Uncrossed	39.66 (5.10)	833.80 (40.06)
Disparity (min)	1.56	63.89 (9.33)	718.80 (39.77)
	3.12	61.94 (8.51)	686.90 (30.05)
	4.68	62.22 (8.70)	810.20 (64.25)
	6.24	56.66 (8.76)	937.90 (150.74)
	7.80	63.89 (7.94)	855.10 (84.89)
Pulse Duration (ms)	33	56.00 (10.80)	716.80 (50.57)
	50	57.33 (9.84)	760.90 (65.60)
	67	55.33 (9.68)	751.00 (37.48)
	83	59.66 (8.92)	769.50 (52.90)
	100	57.66 (7.82)	816.60 (61.68)
	IPD	83.33 (7.02)	976.20 (124.01)

Note. Values inside the parentheses represent the 95% confidence intervals of the means. The data for each variable were averaged across all the other variables for this observer. PCR = percent correct responses; MRT = mean reaction time; IPD = "infinite" pulse duration.

Table D-10

Mean Data of Observer 4 in Condition RDS

Independent Variable		Dependent Variable			
		PCR		MRT (ms)	
Direction	Crossed	64.13	(4.06)	626.80	(65.11)
	Uncrossed	44.37	(4.23)	682.60	(26.91)
Disparity (min)	1.56	55.20	(5.80)	694.90	(78.58)
	3.12	54.37	(7.15)	626.20	(19.91)
	4.68	53.25	(3.45)	614.50	(19.47)
	6.24	53.25	(3.81)	635.80	(20.77)
	7.80	55.19	(4.01)	696.50	(46.46)
Pulse Duration (ms)	33	52.57	(3.94)	747.60	(45.29)
	50	53.24	(2.85)	630.90	(22.63)
	67	57.92	(3.16)	637.80	(24.18)
	83	54.92	(3.24)	658.70	(22.34)
	100	54.89	(3.93)	641.20	(22.34)
	IPD	51.96	(5.77)	591.90	(23.87)

Note. Values inside the parentheses represent the 95% confidence intervals of the means. The data for each variable were averaged across all the other variables for this observer. PCR = percent correct responses; MRT = mean reaction time; IPD = "infinite" pulse duration.

Table D-11

Mean Data of Observer 5 in Condition RDS

Independent Variable		Dependent Variable	
		PCR	MRT (ms)
Direction	Crossed	69.99 (4.00)	878.10 (38.02)
	Uncrossed	31.55 (4.45)	999.80 (35.63)
Disparity (min)	1.56	62.21 (6.49)	937.70 (69.36)
	3.12	49.16 (6.43)	963.90 (46.06)
	4.68	52.77 (8.51)	945.40 (55.41)
	6.24	46.39 (9.49)	938.70 (56.17)
	7.80	43.30 (9.35)	859.90 (56.94)
Pulse	33	48.99 (8.41)	968.60 (81.77)
Duration (ms)	50	47.66 (8.96)	881.30 (58.56)
	67	45.30 (8.04)	916.90 (69.36)
	83	54.33 (9.33)	934.80 (58.21)
	100	54.33 (9.13)	966.70 (109.96)
	IPD	54.00 (10.41)	914.30 (77.48)

Note. Values inside the parentheses represent the 95% confidence intervals of the means. The data for each variable were averaged across all the other variables for this observer. PCR = percent correct responses; MRT = mean reaction time; IPD = "infinite" pulse duration.

Table D-12

Mean Data of Observer 6 in Condition RDS

Independent Variable		Dependent Variable	
		PCR	MRT (ms)
Direction	Crossed	58.33 (3.39)	389.70 (16.78)
	Uncrossed	40.27 (3.72)	378.40 (17.03)
Disparity (min)	1.56	47.47 (5.37)	385.80 (32.22)
	3.12	44.42 (6.94)	385.60 (34.77)
	4.68	54.40 (5.88)	378.00 (23.87)
	6.24	53.58 (6.17)	376.30 (18.50)
	7.80	46.89 (5.68)	395.40 (23.05)
Pulse Duration (ms)	33	43.65 (6.66)	392.40 (25.87)
	50	51.29 (7.59)	389.40 (39.10)
	67	48.97 (6.43)	369.20 (22.07)
	83	53.31 (6.80)	377.50 (18.01)
	100	51.95 (6.17)	380.90 (23.79)
	IPD	46.94 (6.12)	396.10 (39.08)

Note. Values inside the parentheses represent the 95% confidence intervals of the means. The data for each variable were averaged across all the other variables for this observer. PCR = percent correct responses; MRT = mean reaction time; IPD = "infinite" pulse duration.

Table D-13

Mean Data of Observer 1 in Condition RTL

Independent Variable		Dependent Variable	
		PCR	MRT (ms)
Direction	Crossed	94.50 (2.18)	531.30 (14.99)
	Uncrossed	37.67 (4.96)	898.40 (68.23)
	Left	97.00 (2.12)	528.80 (17.46)
	Right	94.67 (2.65)	525.20 (18.25)
Disparity (min)	1.56	75.42 (6.37)	680.70 (69.56)
	3.12	80.63 (5.96)	587.40 (41.51)
	4.68	81.88 (5.80)	567.80 (32.59)
	6.24	82.92 (5.35)	580.80 (33.75)
	7.80	83.96 (5.02)	586.70 (30.52)
Pulse Duration (ms)	33	74.50 (7.17)	583.40 (32.99)
	50	75.75 (7.11)	592.60 (40.30)
	67	78.00 (6.98)	560.10 (36.77)
	83	83.50 (5.96)	591.00 (37.20)
	100	85.25 (5.49)	612.20 (49.14)
	IPD	88.75 (3.90)	652.00 (71.09)

Note. Values inside the parentheses represent the 95% confidence intervals of the means. The data for each variable were averaged across all the other variables for this observer. PCR = percent correct responses; MRT = mean reaction time; IPD = "infinite" pulse duration.

Table D-14

Mean Data of Observer 2 in Condition RTL

Independent Variable		Dependent Variable			
		PCR	MRT (ms)		
Direction	Crossed	68.83	(3.88)	698.90	(55.76)
	Uncrossed	9.33	(2.72)	897.60	(76.11)
	Left	70.50	(5.27)	637.60	(22.68)
	Right	72.33	(5.37)	699.10	(41.10)
Disparity (min)	1.56	56.04	(6.59)	714.70	(47.47)
	3.12	54.58	(6.78)	671.00	(45.37)
	4.68	56.25	(6.82)	701.20	(62.66)
	6.24	57.29	(6.92)	670.20	(37.40)
	7.80	52.08	(7.27)	747.20	(75.66)
Pulse Duration (ms)	33	46.75	(7.25)	739.30	(65.13)
	50	49.00	(6.86)	705.00	(70.64)
	67	59.75	(7.53)	704.20	(67.95)
	83	56.00	(7.51)	685.20	(50.82)
	100	57.25	(7.66)	705.50	(61.98)
	IPD	62.75	(7.96)	661.90	(39.89)

Note. Values inside the parentheses represent the 95% confidence intervals of the means. The data for each variable were averaged across all the other variables for this observer. PCR = percent correct responses; MRT = mean reaction time; IPD = "infinite" pulse duration.

Table D-15

Mean Data of Observer 3 in Condition RTL

Independent Variable		Dependent Variable	
		PCR	MRT (ms)
Direction	Crossed	65.83 (4.16)	823.30 (50.41)
	Uncrossed	11.17 (3.02)	1718.00 (187.79)
	Left	87.67 (3.70)	751.30 (84.42)
	Right	73.67 (5.63)	714.70 (33.10)
Disparity (min)	1.56	55.21 (7.00)	1071.00 (186.93)
	3.12	60.00 (6.94)	835.70 (87.02)
	4.68	58.33 (7.21)	747.10 (46.96)
	6.24	63.33 (7.06)	852.50 (119.32)
	7.80	61.04 (6.94)	837.20 (132.14)
Pulse Duration (ms)	33	54.25 (7.51)	1072.00 (178.58)
	50	57.00 (7.47)	831.40 (175.09)
	67	63.75 (7.82)	860.50 (131.75)
	83	60.25 (7.82)	781.70 (65.93)
	100	61.00 (7.92)	726.10 (44.43)
	IPD	61.25 (7.64)	934.00 (158.98)

Note. Values inside the parentheses represent the 95% confidence intervals of the means. The data for each variable were averaged across all the other variables for this observer. PCR = percent correct responses; MRT = mean reaction time; IPD = "infinite" pulse duration.

Table D-16

Mean Data of Observer 4 in Condition RTL

Independent Variable		Dependent Variable	
		PCR	MRT (ms)
Direction	Crossed	76.83 (4.35)	907.90 (44.88)
	Uncrossed	22.83 (4.17)	1403.00 (107.74)
	Left	68.33 (5.82)	1050.00 (62.19)
	Right	89.33 (3.55)	801.40 (41.08)
Disparity (min)	1.56	48.13 (6.98)	1138.00 (102.25)
	3.12	58.96 (6.98)	1003.00 (64.54)
	4.68	70.28 (6.45)	931.80 (66.70)
	6.24	74.38 (6.27)	990.20 (88.81)
	7.80	70.00 (6.21)	937.40 (55.64)
Pulse Duration (ms)	33	53.75 (6.84)	1063.00 (85.81)
	50	60.00 (7.17)	989.50 (101.92)
	67	65.50 (7.78)	947.90 (71.91)
	83	70.50 (7.35)	1015.00 (70.78)
	100	65.75 (7.47)	935.40 (67.29)
	IPD	70.50 (7.55)	1013.00 (106.08)

Note. Values inside the parentheses represent the 95% confidence intervals of the means. The data for each variable were averaged across all the other variables for this observer. PCR = percent correct responses; MRT = mean reaction time; IPD = "infinite" pulse duration.

Table D-17

Mean Data of Observer 5 in Condition RTL

Independent Variable		Dependent Variable			
		PCR		MRT (ms)	
Direction	Crossed	95.17	(2.06)	583.60	(26.71)
	Uncrossed	86.33	(3.45)	778.80	(43.04)
	Left	90.00	(3.82)	710.40	(33.61)
	Right	96.67	(2.39)	699.00	(31.85)
Disparity (min)	1.56	85.21	(4.12)	806.40	(47.94)
	3.12	95.42	(2.25)	665.50	(32.73)
	4.68	95.83	(2.49)	638.80	(31.67)
	6.24	93.33	(3.37)	657.90	(36.87)
	7.80	90.42	(4.23)	694.70	(42.77)
Pulse Duration (ms)	33	78.25	(6.17)	744.70	(52.76)
	50	88.00	(4.49)	676.90	(38.22)
	67	94.75	(2.55)	681.70	(45.49)
	83	96.00	(2.18)	662.90	(34.85)
	100	96.50	(1.98)	694.40	(43.02)
	IPD	96.75	(1.27)	698.80	(47.69)

Note. Values inside the parentheses represent the 95% confidence intervals of the means. The data for each variable were averaged across all the other variables for this observer. PCR = percent correct responses; MRT = mean reaction time; IPD = "infinite" pulse duration.

Table D-18

Mean Data of Observer 6 in Condition RTE

Independent Variable		Dependent Variable			
		PCR		MRT (ms)	
Direction	Crossed	97.83	(1.22)	328.90	(4.80)
	Uncrossed	85.67	(3.19)	445.10	(9.11)
	Left	93.67	(2.82)	476.20	(14.41)
	Right	93.67	(2.67)	408.80	(14.48)
Disparity (min)	1.56	91.04	(3.59)	414.90	(12.35)
	3.12	93.13	(2.86)	417.70	(15.39)
	4.68	92.08	(3.04)	404.80	(15.03)
	6.24	93.54	(2.69)	420.80	(16.46)
	7.80	93.75	(2.67)	414.80	(15.46)
Pulse Duration (ms)	33	85.25	(4.72)	423.10	(19.01)
	50	89.75	(3.88)	418.50	(17.29)
	67	94.50	(2.47)	415.50	(19.27)
	83	96.00	(2.47)	410.00	(14.35)
	100	94.00	(2.80)	408.10	(14.80)
	IPD	96.75	(2.16)	412.60	(13.15)

Note. Values inside the parentheses represent the 95% confidence intervals of the means. The data for each variable were averaged across all the other variables for this observer. PCR = percent correct responses; MRT = mean reaction time; IPD = "infinite" pulse duration.