EFFECTS OF DEPTH CUES ON DEPTH JUDGEMENTS USING A FIELD-SEQUENTIAL STEREOSCOPIC CRT DISPLAY

by

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(ABSTRACT)

Current interest in three-dimensional (3-D) information displays has focused on the use of field-sequential CRT techniques to present binocular stereoscopic images. Although it is widely believed that stereopsis provides a potent depth information cue, numerous monocular cues exist which may augment, detract from, or even supplant stereopsis. Unfortunately, few guidelines or well-controlled analyses on the use of depth cues are available to direct engineering implementations of stereoscopic display systems.

This dissertation describes three experiments using 3-D images presented on a Tektronix SGS 620 field-sequential stereoscopic CRT (19-inch diagonal, 120-Hz field rate, passive glasses). In the first experiment, 10 participants with normal vision judged the relative apparent depth ordering of three simple geometric figures (planar circle, square, and triangle). Four sources of depth information (cue types) were factorially combined to construct exemplary images of planar figures in apparent depth: Relative Size (angular subtense decreased with increasing apparent depth); Disparity (binocular disparity varied from crossed to uncrossed with increasing apparent depth); Interposition (closer figures partially occluded ones farther away in apparent depth); and Luminance (luminance decreased with increasing apparent depth). The three monocular cues (Interposition, Size, and Luminance) produced significantly faster depth judgments when used alone; however, when used in combination, Interposition dominated the response time data trends.

Although the Disparity cue received moderately high "perceived effectiveness" ratings, response time measures indicated that it played a minor role in the relative depth judgment task.

The second experiment was conducted to investigate further the subjective value of the various depth cues. Participants rated subjective image quality (quality of depth) rather than making rapid relative depth judgements. As anticipated, the most satisfactory ratings of depth were made for display images which included stereoscopic depth (Disparity), with the very highest ratings given to display images which included all four depth cues. The results of these first two experiments illustrated a task-demand (objective vs. subjective) discrepancy in the utility of stereoscopic depth cues.

The third experiment extended the initial work to include more geometrically complex stimuli in visual search and cursor positioning tasks. In these task environments, stereoscopic disparity and monocular depth cues had an interactive effect on improving visual search times and reducing cursor positioning errors on the depth axis, with the best performance associated with the presence of all depth cues. The complementary nature of these effects was attenuated when depth cue salience was elevated to suprathreshold levels.

Based on the results of this research, recommendations are presented for the display of depth information with the stereoscopic CRT. The importance of this research is underscored by the fact that while technological advances have been made in the field of stereoscopic display, very few usability data exist either from laboratory testing or from the implementation of such displays in operational systems. This research provides information to complete cost/performance benefit analyses for 3-D display designs which could in turn significantly impact industry acceptance of the field-sequential stereoscopic CRT.

ACKNOWLEDGEMENTS

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The degree to which my family influenced my graduate school success is incalculable. It was the faith and encouragement of my brother, sisters, parents, and grandparents which inspired me to undergo the entire process. And my wife, Jana, deserves the most special thanks. Many not-so-romantic evenings were spent working side by side on our dissertations.

This work is dedicated to my grandfather, Frank H. Niemann, who helped me to see the importance of an education and the wisdom of nature.

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GLOSSARY

2-D	Two-dimensional
3-D	Three-dimensional
ANOVA	Analysis of variance
CDTI	Cockpit display of traffic information
CIE	Commission Internationale de L'Eclairage
CRT	Cathode ray tube
DAC	Digital-to-analog converter
DAT	Differential Aptitude Spatial Relations sub-test
EGA	Extended graphics adapter
FLC	Ferroelectric liquid crystal
FLIR	Forward-looking infrared
FOV	Field of view
GLM	General linear model
HMD	Helmet-mounted display
HSD	Horizontal situation display
HUD	Heads-up display
IPD	Interpupillary distance
ISH	Incoherent superposition holography
LC	Liquid crystal
LED	Light emitting diode
MRT	Mental Rotations Test
LCM	Liquid crystal modulator
NOE	Nap of the earth

GLOSSARY (continued)

PLC	Proximity luminance covariance
PLZT	Lead Lanthanum Zirconate Titanate
RDS	Random dot stereogram
TNLC	Twisted nematic liquid crystal
VISIDEP	Visual image depth enhancement by parallax induction

INTRODUCTION

There has been renewed interest in the display of information in three spatial dimensions (3-D) for more accurate interpretation of complex spatial information. In particular, 3-D displays either do or could have significant benefit to tasks such as air traffic control (Williams and Garcia, 1988), portrayal of multidimensional data sets (Jensen and Anderson, 1987; Kirby and Rixon, 1981), military situation awareness (Bridges and Reising, 1987a;1987b), video entertainment (Free, 1988), review of medical imagery (Herman, 1986; Herron, 1977), teleoperation (Crooks, Freedman, and Coan, 1975; Gould, 1964; Robinson, 1984; McClelland, 1988), microscopy (Wixson, Garrett, and Sinak, 1987), photointerpretation (Whiteside, Ellis, and Haskell, 1987; Williams, 1966), flight simulation (Turner, 1986; Turner and Hellbaum, 1986), computer-aided design (Manzoni, Bidoli, and Manzoni, 1984; Uno, 1979), and molecular modelling (Roese and McCleary, 1979). These applications span the use of simple graphic images, complex graphic simulations, video imagery, and hybrid video imagery with graphic overlays.

Recent 3-D display research has focused on the technological development of electronic, field-sequential stereoscopic imaging systems. Such displays typically employ an active liquid-crystal (LC) light valve placed directly over the cathode-ray tube (CRT) screen and require the user to wear a pair of passive, orthogonally polarizing eyeglasses. Using the light valve to set orthogonal polarization angles for alternate image fields, stereo-pair image fields can be presented in a time-sequential manner. A binocular disparity can thus be introduced in the fused image to produce the 3-D effect. The field-sequential stereoscopic display is a promising electronic display technology for the presentation of compelling 3-D images.

As potent as the stereopsis effect is, it is not the only visual cue capable of invoking the sensation of positional displacements in depth. The ability of amblyopes and one-eyed individuals to discriminate depth attests to the fact that other depth cues are available (Alpern, 1982). Monocular cues exist which may augment, detract from, or even supplant stereopsis. The use of such monocular or 2-D visual cues in conventional display systems could represent a viable and perhaps economically attractive alternative to stereoscopic display technology. While it is commonly accepted that monocular cues may add to or interact with binocular cues in normal depth perception (Baker, 1987), few systematic engineering efforts have been made to quantify the utility of stereoscopic and monocular depth cues using the modern field-sequential stereoscopic CRT. Such information will be important to display designers who must maximize the 3-D presentation while minimizing computational expense. The careful addition of monocular depth information may be especially critical to the approximately 10% of the population which is incapable of fully perceiving depth information from stereoscopic displays.

Another critical concern for designers of stereoscopic displays is the establishment of clear empirical guidelines outlining the applications where stereoscopic displays might best impact task performance and subjective image quality. Unfortunately, few guidelines or well-controlled analyses of task parameters are available to direct engineering implementations of modern stereoscopic display systems. Because the cost of a typical high-end electrooptic stereoscopic display is significantly higher than the cost of a comparable 2-D display, it is important to clearly define the expected advantages of integrating stereoscopic display technology into future workstations.

The contents of this dissertation are intended to provide the practical guidelines necessary for a display engineer to evaluate the need, appropriateness, and expected outcomes of using modern stereoscopic display media in a variety of application environments. A background is provided which describes some of the critical perceptual issues involved in the appreciation of 3-D displays, a brief sampling of the many 3-D display applications which have been advanced over the last two centuries, a consideration of user input and 3-D image manipulation techniques (e.g., 3-D cursor control), and a review of comparison research on the relative efficacy of various 3-D information display strategies. Following this background, research objectives are outlined and three experiments are presented which were conducted to address these objectives.

BACKGROUND

Although the retina is a two-dimensional (2-D) array of optical detectors, our visual perception of the world is of three spatial dimensions. When discussing this remarkable visual phenomenon, it is convenient to introduce the concept of *depth cues*. At the heart of this concept is the belief that in the absence of certain sources of depth information, or depth cues, there is a perceptual primacy of flatness. Vlahos (1965) elaborated on this concept by discussing *anti-cues*. He defined an anti-cue as "any phenomenon that denies depth information or provides false information concerning relative distance" (p. 10).

The subject of this dissertation is the veridical perception of depth information and the ways in which depth cues may be constructively used in visual information display. As such, emphasis is placed on visual depth enhancement rather than on the perceptual mismatches which arise from the use of anti-cues. Furthermore, the meaning of the term *depth cue* in this dissertation will be restricted to the physical parameters of visual stimuli which are associated with the perception of an object or scene in 3-D. It is convenient to divide the various depth cues into those which may be appreciated monocularly and those which require binocular vision (Table 1). Monocular cues are occasionally called *pictorial* depth cues, referring to the use of such cues in 2-D artistic renderings.

Monocular Depth Cues

Accommodation. The accommodative power of the eye is expressed in diopters, which is a function of the accommodative far point (the distance from the retina to the farthest point that the eye can resolve when the ciliary body is maximally contracted) and the near point (the distance from the retina to the nearest point that the eye can resolve when

TABLE 1

Monocular and Binocular Depth Cues

Monocular Depth Cues	*Binocular Depth Cues*
Accommodation	Vergence
Interposition	Horizontal Disparity
Linear Perspective	Luminance Disparity
Relative Size	
Texture Gradients	
Elevation	
Shading	
Shadows	
Aerial Perspective	
Luminance Contrast	
Color Purity	
Hue	
Motion Parallax	
Chromostereopsis	

the ciliary body is at rest) (Valius, 1966). The distance between the far point and the near point is equal to the accommodative range. The accommodative power, or accommodative amplitude, is expressed as:

$$A = (1 / \text{Near Point}) - (1 / \text{Far Point}), \qquad (1)$$

where A is the accommodative amplitude in diopters and both distances are measured in meters (Millodot, 1982a).

At close viewing distances, as the ciliary body relaxes to increase the curvature of the lens, shorten the focal length, and consequently bring the object of interest to focus on the retina, feedback is provided as to the focusing distance. The accommodation cue refers to this feedback associated with the contractile state of the ciliary body (Figure 1). While it was originally thought that direct feedback *from* the ciliary body was assimilated by the brain, it is now believed that it is the neural signals sent *to* the ciliary body which provide this depth information (Braunstein, 1976). Beyond viewing distances of approximately 2 m, this proprioceptive cue is very slight (Hodges and McAllister, 1988) because contraction of the ciliary body approaches the maximum and the focal length of the eye approaches optical infinity. The accommodation cue is normally correlated with the binocular proprioceptive cue of vergence.

Interposition. Opaque foreground objects which lie on the same viewing axis as background objects will occlude background objects (Figure 2a). The interposition cue is the driving concern of hidden line algorithms for graphical display software, since experience dictates that foreground lines which are interposed between the observer and the background will occlude the background. The use of such algorithms is important to prevent perceptual anti-cues. Interposition can be a powerful anti-cue when inappropriately

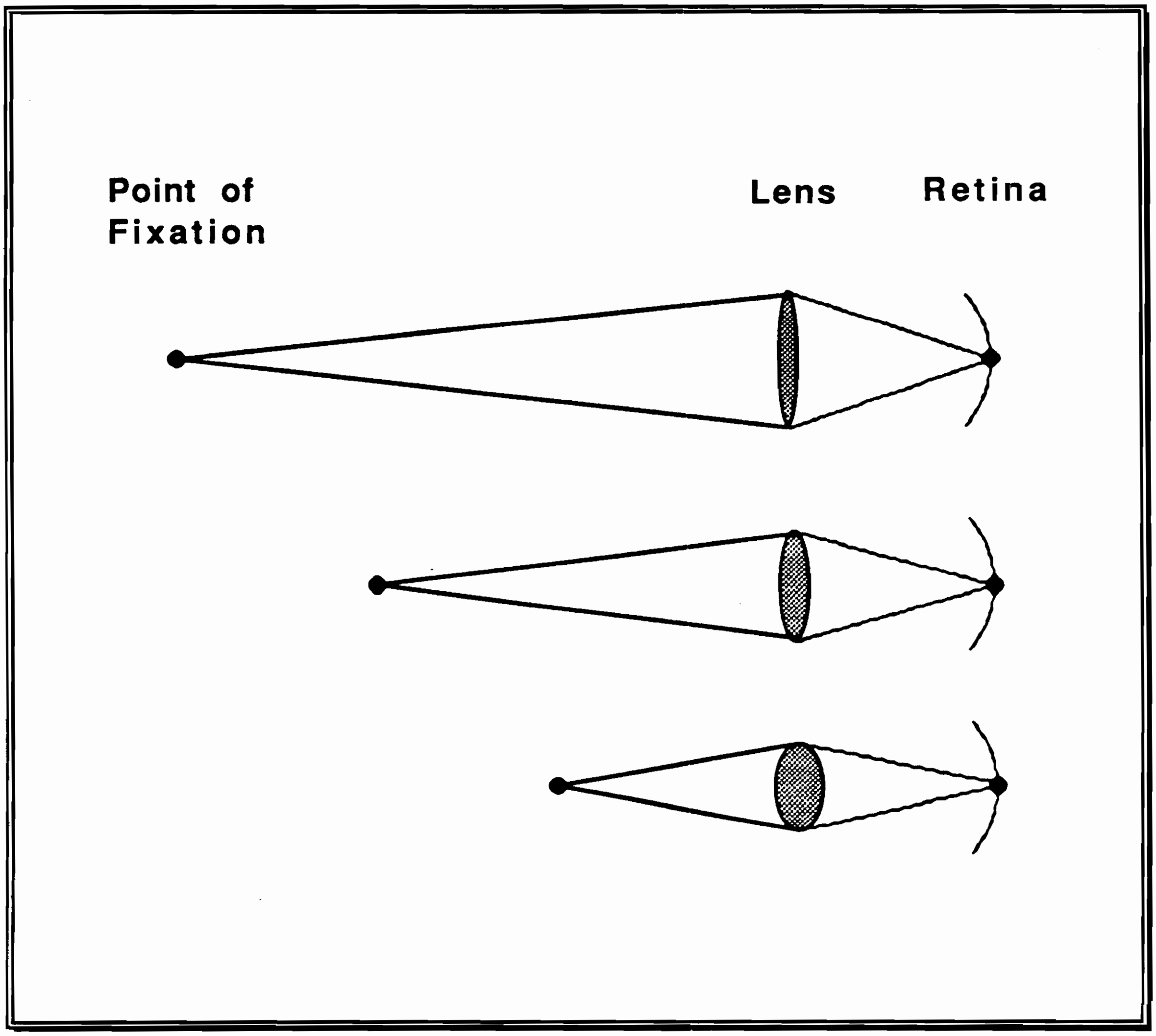


Figure 1. Accommodation of the lens. As the ciliary body relaxes, the lens becomes more rounded and the focal length of the eye becomes shorter.

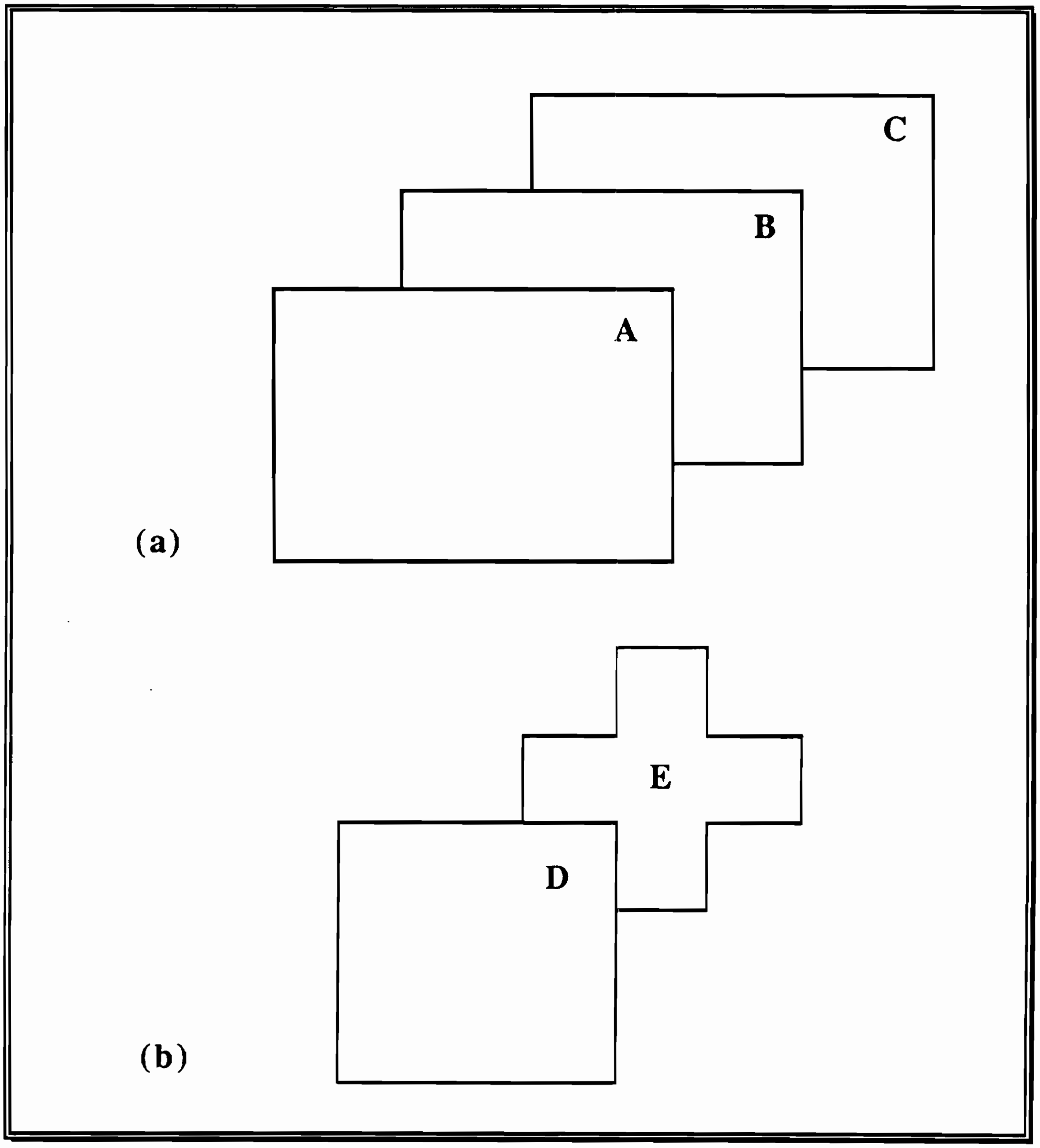


Figure 2. An illustration of interposition. Figures in (a) appear in a clear apparent depth order. Because the complete contour of E is not known, figures in (b) are ambiguous.

present in stereoscopic displays, especially when a stereoscopic image occupies the virtual space in front of the display screen (crossed disparity). If the stereo image is touching the display frame such that the display border appears to occlude the image, the parallax information in the stereoscopic image will be in conflict with the interposition cue (Tolin, 1987).

Another limitation of the interposition cue is the dependence of depth interpretation on clarity or constancy of object contours. For example, the cross and square in Figure 2b have an ambiguous relationship because the observer cannot be sure if the second figure is a cross or an occluded polygon. The effective interpretation of the interposition cue requires that unambiguous contours be present in the scene.

Most contemporary investigations of the interposition cue have concerned kinetic interposition or *kinetic occlusion*, the interposition of dynamic visual elements (Braunstein, Andersen, and Riefer, 1982; Braunstein, Andersen, Rouse, and Tittle, 1986; Rhodes, 1980). While static interposition depends upon the presence of overlapping object contours, kinetic interposition may be perceived using random texture patterns which lack such contours (Rhodes, 1980). Interposition of dynamic texture elements by a continuous edge (*edge occlusion*) provides more compelling relative depth information than interposition of individual texture elements which do not form a continuous edge (*element occlusion*) (Braunstein et al., 1982). The greater potency of edge occlusion was also demonstrated by Braunstein et al. (1986), where edge occlusion which conflicted with stereoscopic disparity severely degraded the accuracy of depth judgements.

Linear perspective. A constant distance between two points will subtend a diminishing visual angle as viewing distance increases (Buffett, 1980; Graham, 1965). Since the size of any given image falling on the retina changes with viewing distance, it is convenient to specify visual dimensions in terms of the visual angle subtended at the retina.

The concept of visual angle is illustrated in Figure 3, where θ_A is the visual angle, S is the spatial extent of the object, and Dv is the distance from the object to the optical center of the eye (Cornsweet, 1970). The angular subtense in degrees may be expressed as:

$$\theta_A = \arctan (S / Dv). \qquad (2)$$

The classic illustration of linear perspective shows the lines of railroad rails converging into the distance. However, aside from the convergence of lines to a horizon, linear perspective encompasses two more specific forms of depth cueing. These are the cues of relative size and texture gradients.

Relative size. One component of linear perspective is relative size. Relative size refers to the apparent depth evoked in a scene by visual forms of different sizes. For example, although the triangles in Figure 4 may be interpreted as having different sizes and the same apparent depth, it is also possible to view them as having the same size but different apparent depths. The relative size effect may be especially potent when the figures in question are similar in shape, since objects of similar shape may be assumed to be of similar size. The relationship between size and apparent distance is captured in Emmert's law, which states that apparent size is proportional to apparent distance (McBurney and Collings, 1984). Gulick and Lawson (1976) have demonstrated Emmert's law in stereoscopic perception. In general, of two objects subtending equal retinal sizes, the object occupying the closer stereoscopic depth plane will be perceived as larger. Similarly, two objects of differing retinal size may appear to be of the same size when occupying appropriately different stereoscopic depth planes.

Emmert's law is modified if familiar forms, such as automobiles, buildings, or people, are viewed. For example, a small child and a skyscraper which subtend equal

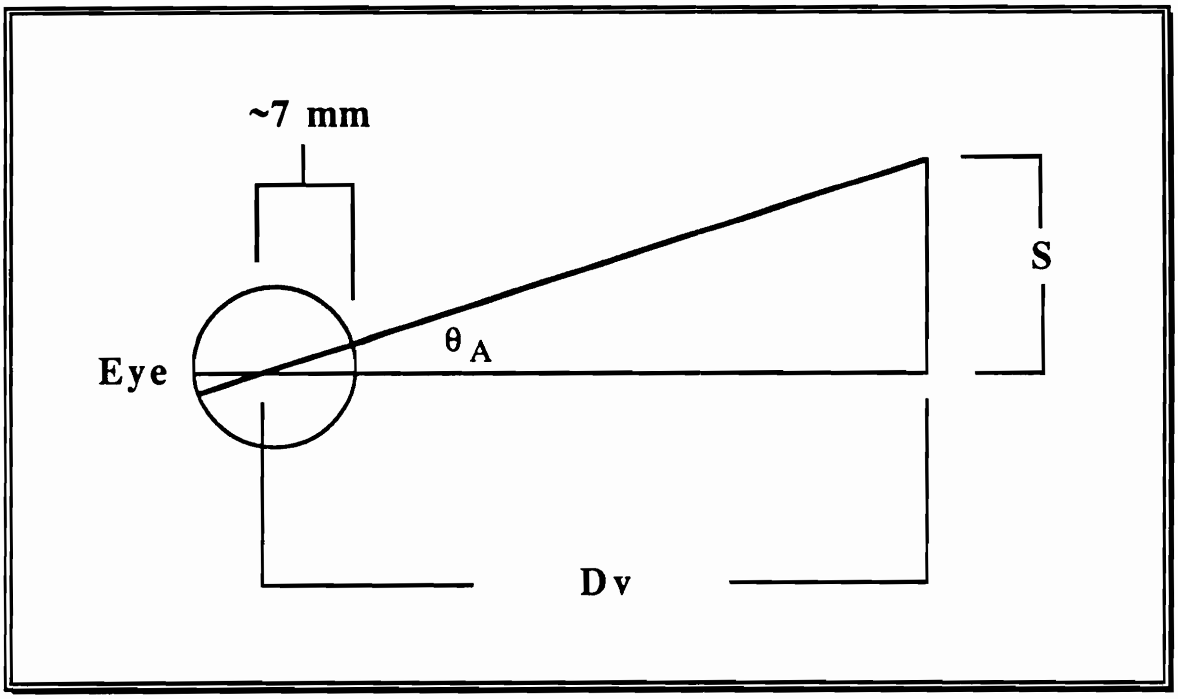


Figure 3. The viewing geometry for the calculation of visual angle. Dv is the viewing distance, S is the extent of the object being viewed, and θ_A is the visual angle in degrees.

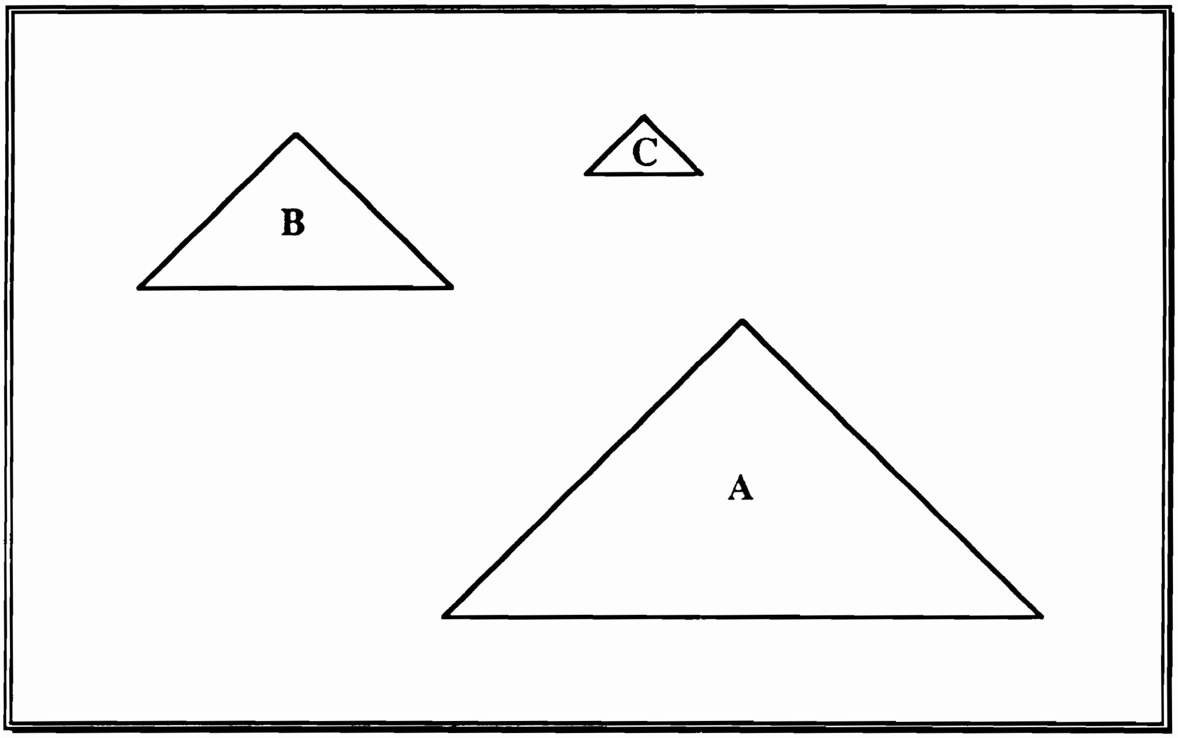


Figure 4. An illustration of relative size. The apparent depth ordering of the figures should be, from closest to farthest, A, B, and C.

retinal angles are not perceived to be equidistant. Because the observer perceives the sizes of the familiar objects to be invariant, the apparent depths of the objects are scaled to the familiar sizes. This is an example of *size constancy*. Relative size is a powerful monocular cue to depth and may overpower lesser cues such as luminance contrast when in conflict (McBurney and Collings, 1984).

Texture gradients. Another depth cue derived from linear perspective is that of texture gradients (Figure 5). Texture gradients occur on the two orthogonal dimensions of texture scale and texture compression, as well as a third dimension of texture density (Cutting, 1984; Cutting and Millard, 1984; Stevens, 1984). Texture scale refers to the width of each texture element perpendicular to the line of sight, while texture compression refers to the flatness or foreshortening along the projection plane (Cutting and Millard, 1984). Texture density (a confounding of scale and compression) is not a reliable measure of distance or surface orientation.

While texture scale is inversely related to distance, texture compression is approximately determined by surface slant (Stevens, 1984). Surface slant is defined as the angle between the surface normal at a given point and the line of sight (Cutting and Millard, 1984). Surfaces which appear curved can be made to appear flat if the texture compression gradient is removed (Todd and Akerstrom, 1987).

Visual texture patterning has been used to improve aircraft carrier landing simulations, where vertical landing velocities are often unacceptably high compared to actual carrier landings. For example, Buckland (1980) measured vertical landing velocities in simulated T-37 carrier landings for 12 instructor pilots. Seven different runways were simulated, including four runways of different sized texturing, a standard Air Force runway, a runway with no markings, and a night-time runway. The runway texturing consisted of grid patterns containing checks of different sizes.

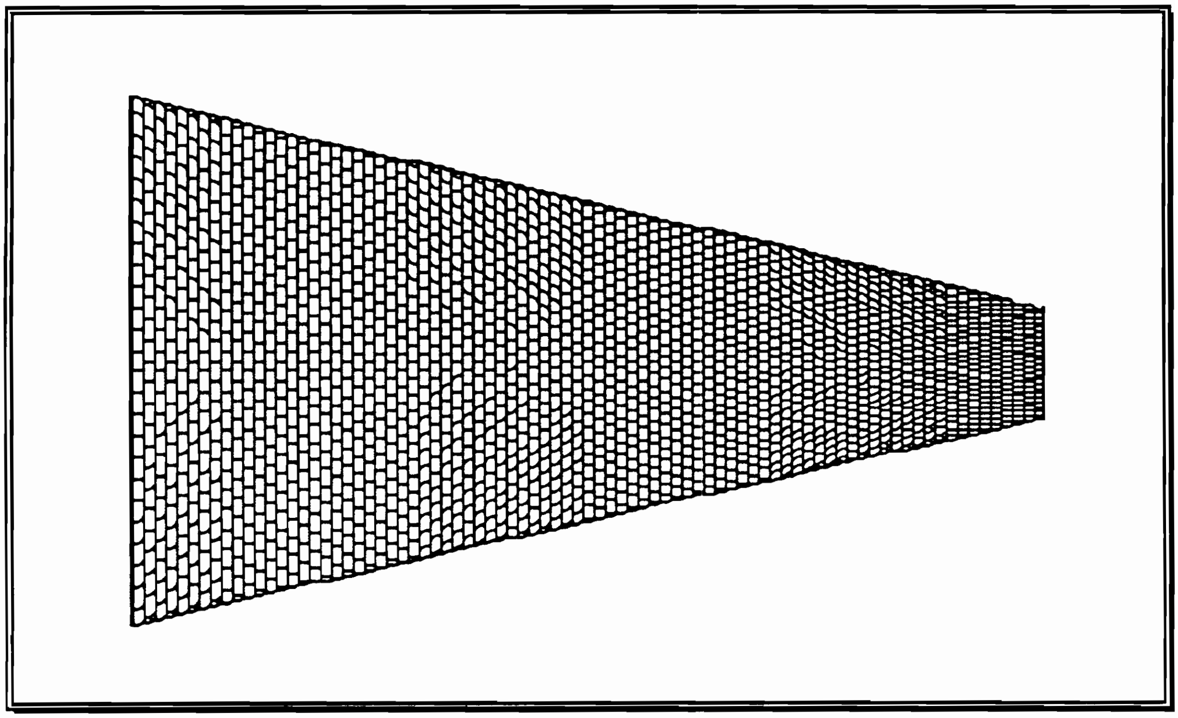


Figure 5. An illustration of linear perspective. The horizontal lines formed by the top and bottom edges of the figure converge toward the horizon. The texture elements within the figure change scale, compression, and density.

Texturing reduced vertical landing velocities (lower velocities are desirable). Mean velocities were highest for the night-time runway, next highest for the empty runway, next highest for the standard runway, and velocities decreased as a function of increased spatial frequency of the texture. Texturing has been used in other flight simulations, also to satisfactory results (Ritchie and Shinn, 1973). It should be noted that simulated landing velocities in Buckland's (1980) study were still significantly greater than acceptable levels for actual landings.

Shading. Shading is generally used graphically to indicate roundedness or angularity of surfaces (McBurney and Collings, 1984) or to resolve ambiguity in figures. As to the relative potency of shading as a depth cue, Todd and Mingolla (1983) concluded that while shading information may be used to estimate the curvature of a cylindrical surface, the use of surface texture is by far the more salient cue to curvature. However, shading algorithms as simple as square-wave luminance patterning are capable of evoking a sense of depth on an otherwise blank and flat field (Bergstrom, Gustafsson, and Putaansuu, 1984).

Shading may be used to influence the subjective interpretation of depth in ambiguous wire-frame figures. An example is seen in Figure 6, where the center object may be interpreted as a 3-D cube in two alternate orientations. If one assumes that the figures are open boxes and that only the outside surfaces are shaded, then the use of shading helps to resolve this ambiguity. For example, point A in Figure 6 should appear to be a corner of the box distant from the observer, while point C should appear to be a close corner. In the middle figure, the position of point B in depth is ambiguous. The geometry of all three figures is identical, with the only difference being the use of shading.

Hemenway and Palmer (1978) used partial shading of Necker-cube figures to create four different stimulus categories. One class of figures consisted only of wire frames

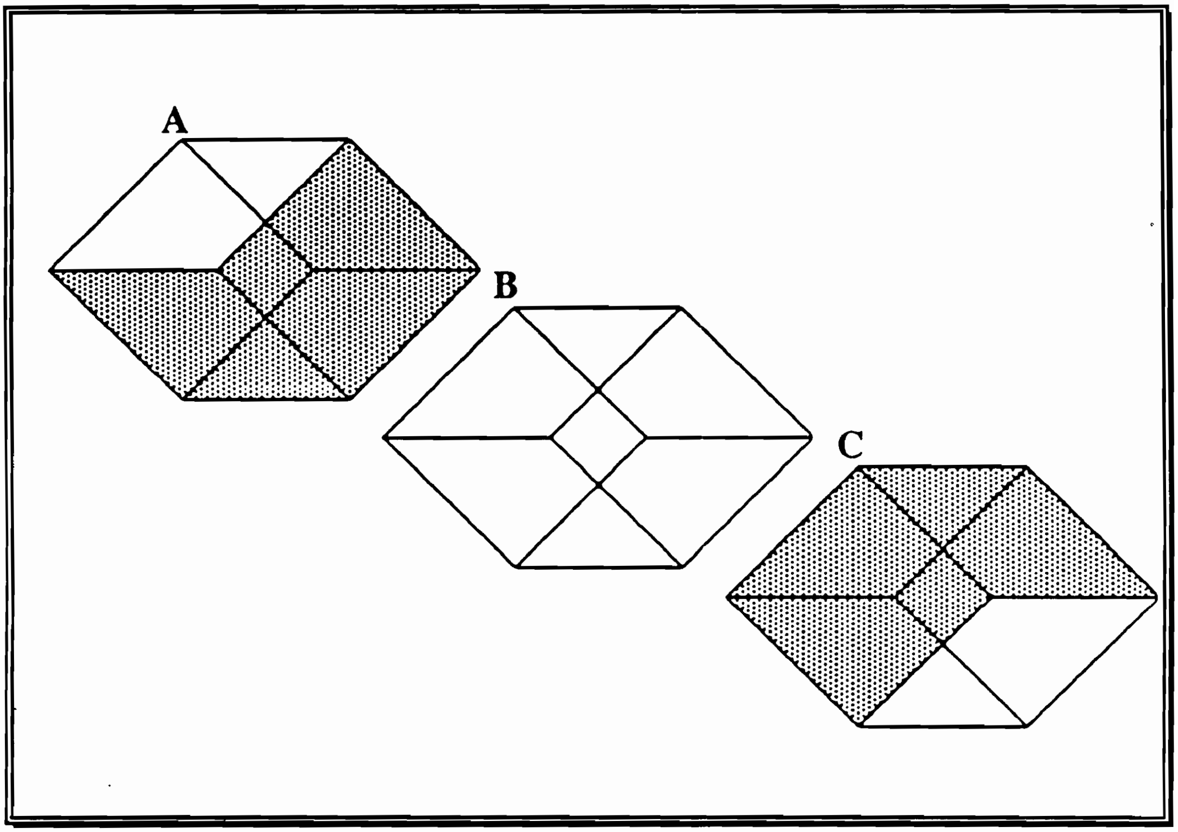


Figure 6. An illustration of shading. The location of point B in depth is ambiguous, while shading in the other two figures suggests that point A is farther and point C is closer.

with no shading. A second class of figures had some sides shaded in a way which was consistent with a 3-D interpretation of the figure. A third group of figures used shading in a manner which was consistent with a 2-D interpretation, while the control group used a random shading scheme. When participants were asked to rate the figures according to the magnitude of the depth experienced in each figure, the order of the rating magnitudes fell in line with the experimental hypotheses. The ratings of greatest apparent depth were given to the figures which incorporated 3-D shading, while the 2-D shading figures received the lowest apparent depth ratings. These results point to the potential potency of figure shading, particularly where properties of the depth dimension may otherwise be ambiguous.

Perhaps the most complete analysis of the derivation of shape from shading was recently completed by Cavanagh and LeClerc (1989). This research project encompassed six different experiments where the psychophysical method of adjustment was used for figure contrast. Figures were presented in which objects differed from backgrounds solely on the basis of shading information. Participants adjusted the luminance contrast between the figures and the background until they were visually separable. In addition to luminance contrast, the cues of hue, motion, stereoscopic depth (anaglyph technique), and texture were used to separate the figures from the backgrounds.

The general conclusion from these experiments was that luminance contrast is the overriding determinant in whether or not 3-D shape is perceived as a result of shading information. Color, motion, stereoscopic disparity, and textural cues were all ineffective individually in evoking the perception of 3-D objects separate from backgrounds if sufficient luminance contrast was not present. Participants were able to perceive 3-D objects provided that adequate figure contrast existed and that a consistent contrast polarity existed at shading borders, even if color, motion, texture, and stereoscopic shading were added which could never occur in natural scenes. Livingstone and Hubel (1988) arrived at the same general conclusion, suggesting that depth information from interposition, relative size, and perspective may be lost in the absence of adequate luminance contrast.

Shadows. Shadows are distinguished from shading in this discussion as being luminance gradients which occur outside of object contours, with the spatial and temporal qualities of the shadow being associated with the characteristics of the object casting the shadow. It is generally accepted that the shapes of shadows may provide 3-D scene information (Figure 7), while a shadow's shape is in turn determined by "the direction of the light source, the shape of the object casting the shadow, and the surface relief on which it falls, as well as the relative positions of the light source, object, and receiving surface" (Cavanagh and LeClerc, 1989, p. 3). Since most natural and artificial illumination comes from above in our environment, reversal of direction of apparent depth in ambiguous figures can easily be achieved by manipulating shadow direction (Okoshi, 1976). Shadow mapping has been used very effectively to enhance 2-D geophysical contour maps (Holroyd, 1986).

Rock, Wheeler, Shallo, and Rotunda (1982) suggested that the addition of attached shadows to wire-frame figures may evoke the perception of a plane resting in depth. While they purportedly removed all other sources of depth information from the visual scenes, their use of shadowing was unfortunately confounded by the use of linear perspective to generate the wire-frame figures. Consequently, their conclusion that cast shadows account for the percept of objects resting on a depth plane is not adequately balanced by a controlled display condition devoid of perspective information.

Elevation relative to the horizon. It is occasionally suggested that the apparent position of an object in depth is influenced by its elevation relative to the horizon in the scene. Given the absence of contrary information, when one object is elevated above

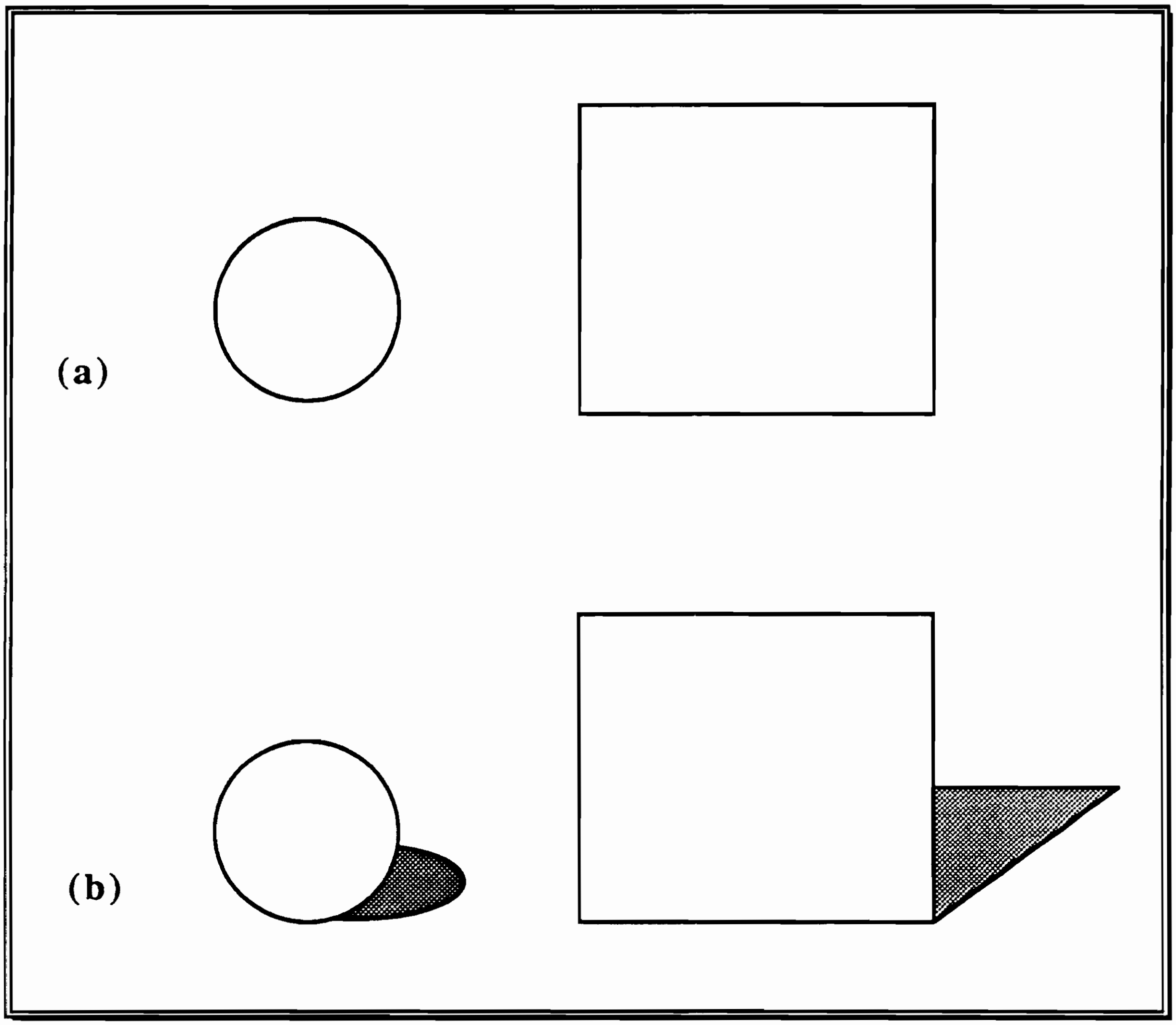


Figure 7. An illustration of shadows. By attaching shadows to the figures in (a), the figures in (b) assume an apparent depth.

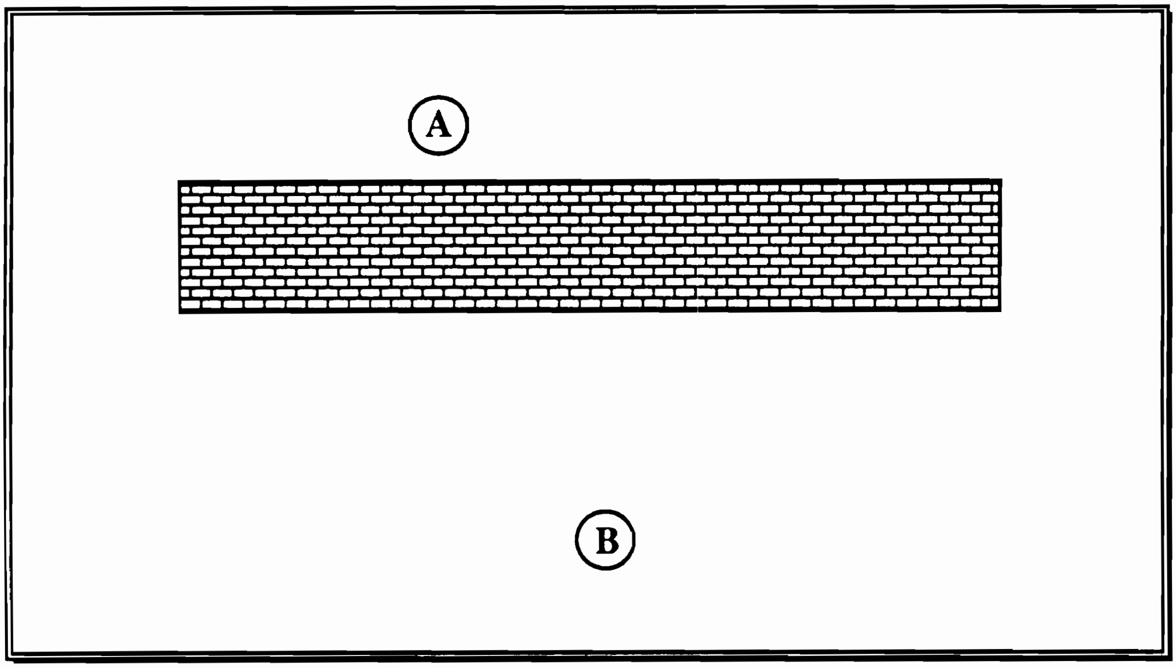


Figure 8. An illustration of elevation relative to the horizon. Point A should appear to be farther in depth than point B.

another object relative to a horizon, the higher object is generally seen as farther away (Mauldin, 1985). For example, if one considers the wall in Figure 8 to serve as an indication of the horizon, the circle A appears to be farther in depth than circle B. A more precise statement of this principle is that objects portrayed as above eye level appear to recede in depth as they *descend* toward the horizon, while objects portrayed as below eye level appear to recede in depth as they *ascend* toward the horizon (McBurney and Collings, 1984). This cue is largely dependent on the scene perspective used and is most effective when the objects of interest are superimposed on backgrounds containing an element of linear perspective such as texture gradients or converging lines (Dember and Warm, 1979). As such, the potency of elevation relative to the horizon as an indication of depth could be considered to be dependent on linear perspective.

Aerial perspective. Aerial perspective is a familiar source of depth information to anyone who has gazed at a distant horizon such as a mountain range or viewed a landscape through the window of an aircraft. This cue is also called *haze* and refers to the loss of luminance contrast and color purity which would normally be present in the scene when viewed from a closer distance. Sharp edges may also appear to blur as a function of distance. These visual effects are primarily due to small particles suspended in the atmosphere.

The aerial perspective cue may be described by at least three quantifiable stimulus properties: luminance contrast, color purity, and spatial frequency content. Distant objects will have less luminance contrast with the background than will closer objects. In addition, a scene viewed from a great distance or altitude will appear to be less saturated (i.e., it will have a lower color purity) and high spatial frequencies may be attenuated by atmospheric haze.

The luminance contrast, or modulation, of an emissive display or any object against its background is quantified as:

$$M = (L_h - L_l) / (L_h + L_l), \qquad (3)$$

where M is the modulation, L_h is the maximum luminance level, and L_l is the minimum luminance level (Cornsweet, 1970). It can be seen from formula (3) that when luminous objects are displayed on a background devoid of any luminous emission or reflectance, the modulation is unity. In such cases, it is more useful to characterize the display by simply describing the luminance of the object.

Egusa (1983) conducted a controlled laboratory study to determine if changes in luminance, color purity, and hue affected perceived depth of colored hemifields. Despite the absence of any other monocular cues to depth, hemifields of the same hue but different color purities were judged to be at different depths, increasingly so with larger differences in color purity. The effect, however, was not entirely consistent with that observed with aerial perspective in naturalistic settings. For example, for red and green stimuli, hemifields which had higher color purity appeared to be nearer. However, for blue stimuli there was a slight tendency for the hemifield with the higher color purity to appear more distant.

When the luminance of the hemifields was changed, the magnitude of the depth estimations reliably increased as a function of luminance contrast. However, the direction of this effect was not reliable, with large individual differences as to whether the brighter hemifield was perceived as closer or farther. Results from previous research have indicated that the direction of this effect is determined by the relative brightness of the background, where the higher luminance object appears nearer only when the background appears darker than both objects (Coules, 1955; Fry, Bridgman, and Ellerbrock, 1949, cited by Egusa, 1983; Takasaki and Kato, 1974, cited by Egusa, 1983).

The change in apparent brightness contrast when used as a depth encoding scheme has been referred to as proximity luminance covariance (PLC), where luminance as a coding dimension covaries with apparent distance or depth (Dosher, Sperling, and Wurst,1986; Schwartz and Sperling, 1983). Dosher et al. (1986) used PLC by varying the luminance of the sides of ambiguous wire-frame perspective cubes, where the luminance of the lines increased in inverse proportion to the viewing distance. The PLC cue was orthogonally combined with stereoscopic disparity, and participants reported their perception of the figure as either a cube or a truncated pyramid. Unfortunately, only four participants were used in this series of experiments, two of which were authors of the paper with foreknowledge of the experimental hypotheses. There were considerable individual differences in response to the different depth cues, but the authors concluded that the effects of the two cues were approximately additive, with stereo being the more potent of the two cues in evoking the perception of the cube. These results contrast with those reported by Schwartz and Sperling (1983), who concluded that PLC could be such a powerful cue in the interpretation of ambiguous figures that not even conflicting stereoscopic information destroyed the PLC effect.

Aerial perspective may be an especially important cue in simulations involving high speed translations in 3-D space. For example, Ritchie and Shinn (1973) found that when a haze simulation was added to a digital flight simulation, more satisfactory feedback seemed to be available to the pilot regarding altitude and velocity judgements. The haze simulation made colors appear less saturated and objects less distinct at greater distances. Patterson and Rinalducci (1984) asked participants to make direct altitude estimations from aerial photographs. The aerial perspective cues were partially removed from one set of photographs by recording the images through polarizing filters. Polarizing filters are frequently used in photography as haze reducers. While all participants underestimated the true altitudes in the photographs, better estimates were provided by participants with flight experience when aerial perspective was present. Participants with no flight experience performed equally well in either condition.

Motion parallax. The sensation of depth in a scene may be enhanced by moving one's head from side to side. This is the depth cue of *motion parallax.* Objects in the foreground show greater lateral displacement on the retina with corresponding head movement than objects in the background, with the velocity of displacement being inversely proportional to the viewing distance (Braunstein, 1986). Rather than deriving depth information from two instantaneous spatial view points, depth is derived by comparing successive viewpoints in time. Consequently, Getty and Huggins (1986) described motion parallax as "the temporal analog of binocular disparity" (p. 323). Although lateral motions perpendicular to the viewing axis in dynamic visual displays are often referred to as motion parallax, it is sometimes preferred to reserve the term *motion parallax* to displacements involving head motion, and to use the term *velocity gradient* in instances where no head motion is involved (Braunstein et al., 1986).

Motion parallax is a very potent monocular depth cue (e.g., Smets, Overbeeke, and Stratman, 1987) and one which requires little perceptual experience to use. For example, the classic visual cliff experiment of E. J. Gibson and Walk (1960) demonstrated that very young organisms (including 6-month-old infants) with a minimal amount of perceptual experience could discriminate depth based on motion parallax.

Motion parallax is conspicuously absent in many stereoscopic presentations. Moving the head to see around a stereoscopic image, the observer perceives the stereoscopic image as following along, with an unnatural distortion in the image. Although this false motion parallax has not been found to degrade stereo performance (Pepper, Cole, Spain, and Sigurdson, 1983) the distortion may adversely affect the subjective sensation of realistic depth. Furthermore, the provision of veridical motion parallax could enhance stereoscopic perception in the way that it has been found to enhance monocular depth cues. For example, Petersik (1979) found that adding motion parallax to a perspective display (i.e., dynamic perspective) facilitated signal perception in the presence of visual noise. A variety of solutions have been proposed for adding veridical motion parallax to stereoscopic displays.

Merritt (1987) discussed the use of a head tracker system which changes the stereoscopic perspective to compensate for head movement. A prototype stereoscope with an infrared head tracking system was demonstrated by Schwartz (1986) and a helmet mounted display (HMD) with an accompanying head tracker has been shown to improve stereoscopic thresholds (Pepper et al., 1983). These techniques may be especially beneficial in promoting the sense of telepresence in remotely piloted vehicles or telemanipulators.

Chromostereopsis. Chromostereoscopic depth perception occurs as a result of chromatic dispersion of the lens in the eye (Millodot, 1982b). Typically, red objects appear to be slightly closer to the observer than blue objects, with green falling somewhere in between. Egusa (1983) found this effect to be most reliable when colored hemifields were compared to achromatic backgrounds. Although our daily visual experience tends to reinforce this perception (e.g., distant objects such as mountains may appear bluish), the chromostereopsis effect is normally small relative to other depth effects (Steenblik, 1987) and the stereotypical association of blue with far objects and red with near objects is not strong. The utility of chromostereopsis as a display depth cue is obviously limited by the magnitude of the effect as well as constraints imposed on the selection of colors in the display.

Binocular Depth Cues

A smaller number of depth cues are recognized as requiring binocular vision. These cues are also distinct in that they either have not or cannot be incorporated into 2-D visual renderings.

Vergence. When the two eyes turn inward toward each other (convergence) or outward away from each other (divergence) to bring a common point of visual attention to bear on each retina, the proprioceptive feedback from the oculomotor system provides a cue to depth for the point of fixation. As with the accommodation cue, it is now believed that the useful depth information is derived from neural signals sent to the oculomotor muscles, rather than from muscular feedback itself (Braunstein, 1976). The vergence cue is normally associated with the accommodation cue and has similar limitations in usefulness. Beyond approximately several meters, the vergence cue is ineffective (Graham, 1965) as the optical axes become closer to parallel and less convergence occurs.

The angle formed by the intersection of the two optical axes is called the angle of convergence. It may be expressed in degrees of visual angle in the following manner:

$$\theta_C = (180 / \pi)\,(T / Dv), \qquad (4)$$

where θ_C is the convergence angle in degrees, Dv is the fixation distance, and T is the interpupillary distance (Gulick and Lawson, 1976). Interpupillary distance for adults varies between 52 and 72 mm, with a mean value of 65 mm (Valius, 1966). It is important to note that when naturally viewing the world, the optical axes never diverge beyond parallel (i.e., the minimum angle of convergence is zero).

A classic problem for stereoscopic display use is the so-called accommodation-convergence mismatch. In the case of the stereoscopic CRT, objects displayed on the phosphor plane will be viewed with normal levels of accommodation and convergence. However, when stereoscopic virtual images appear displaced in depth relative to the phosphor plane, convergence also changes, while accommodation remains at the level of the phosphor plane. This conflict can be minimized by either placing the primary objects of interest at the phosphor plane (i.e., using zero disparity) or by using viewing distances greater than 2 m, where accommodation cues are inconsequential (Hodges and McAllister, 1988; Tolin, 1987).

An early description of the accommodation-convergence relationship was published by Swenson (1932). Using a customized stereoscope which allowed orthogonal variation of accommodative distance and convergence angle, Swenson determined that both accommodation and convergence were effective in estimating the distance of a white light at the distances tested (25, 30, and 40 cm). Convergence angle was approximately three times as effective as accommodation as a cue for distance, especially when these cues were dissociated. Highly similar results were reported more recently by Ritter (1977).

Horizontal disparity. Except for a small and variable region in space where the two retinal images exactly correspond, the *horopter*, each retina normally receives an image of the world from a slightly different angle. This angle results from the horizontal separation of the eyes in the head. The degree of noncorrespondence between the two retinal images is referred to as disparity and is represented by the difference between the two angles

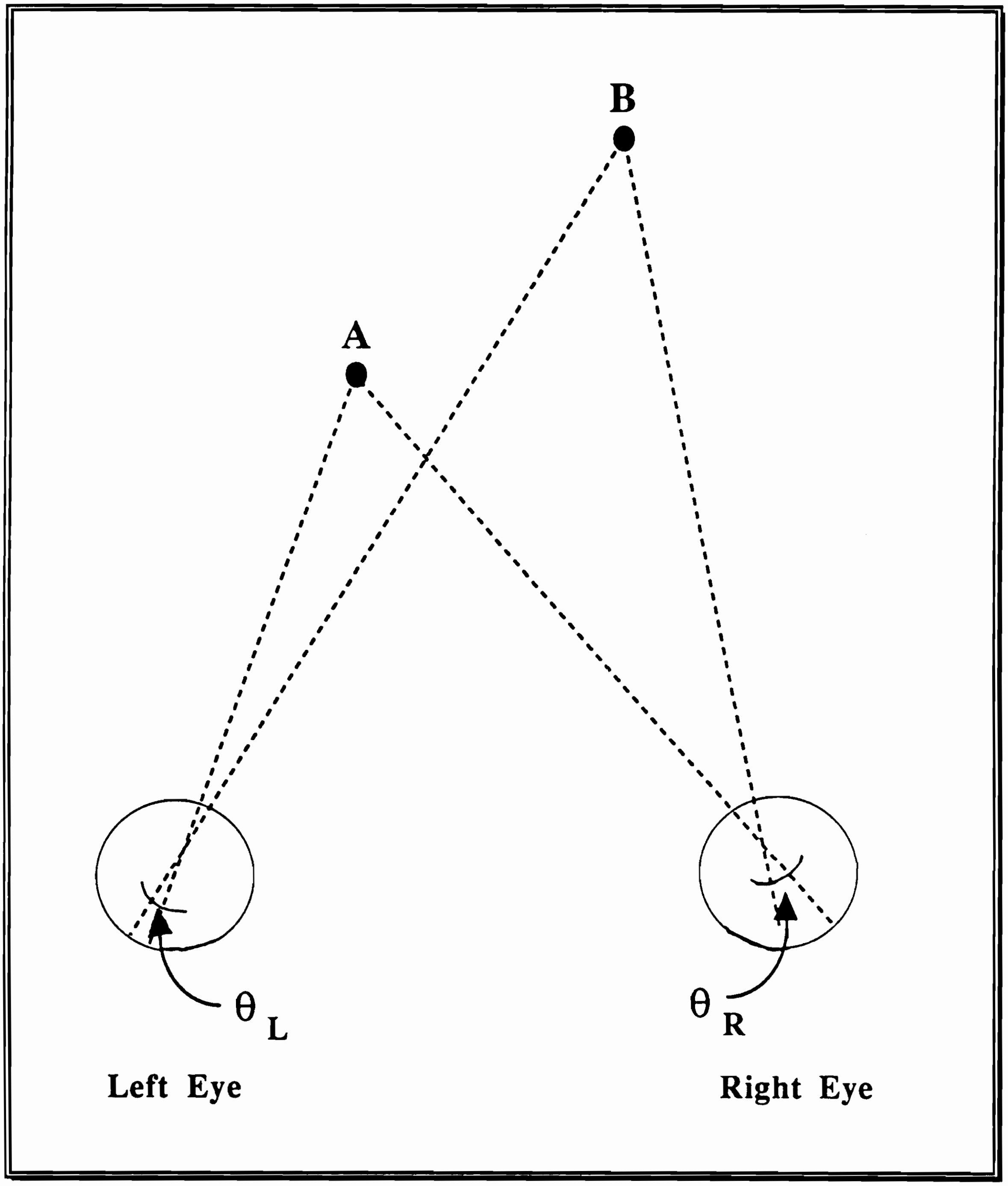


Figure 9. The viewing geometry of retinal disparity. It is the difference between angles θ_L and θ_R which gives rise to stereopsis.

formed by the lines of sight for each eye. In Figure 9, this is represented as:

$$\text{Disparity (deg)} = \theta_L - \theta_R. \qquad (5)$$

Normally, the fusion of the two images with horizontal disparity gives rise to the depth sensation of stereopsis. In order to describe when fusion and stereopsis will and will not occur, it is necessary to understand the concept of the visual horopter. The horopter describes a locus of points in the visual field which, for any given fixation of the eyes, includes all the points in the visual field which will fall on corresponding points on each retina. All points on the horopter will be perceived as single points. Using this locus of points as a reference, it is then possible to describe the locus of points which gives rise to stereopsis and diplopia (double vision). Any points falling immediately outside or inside the horopter will not fall on corresponding retinal locations. The disparity between the resulting retinal points gives rise to stereopsis. If the points fall far enough from the horopter, single vision will give way to diplopia, although double images may still be perceived in depth. Single vision will normally occur for foveal vision if the disparity is less than approximately 10 min of visual arc. This limit is referred to as Panum's fusional area and it increases rapidly with retinal eccentricity (Braddick, 1982; Poggio and Poggio, 1984).

The viewing geometry of stereo pairs is illustrated in Figure 10. In this figure, T is the interpupillary distance and S is the plane at which the stereo pairs rest. When both left-eye and right-eye views are identical, the eyes are converged on point S(0) and no stereoscopic depth is perceived. This is designated as zero parallax.

Perception of the stereoscopic image behind plane S (e.g., point S(+)) occurs when the left-eye and right-eye views are horizontally separated between the two points

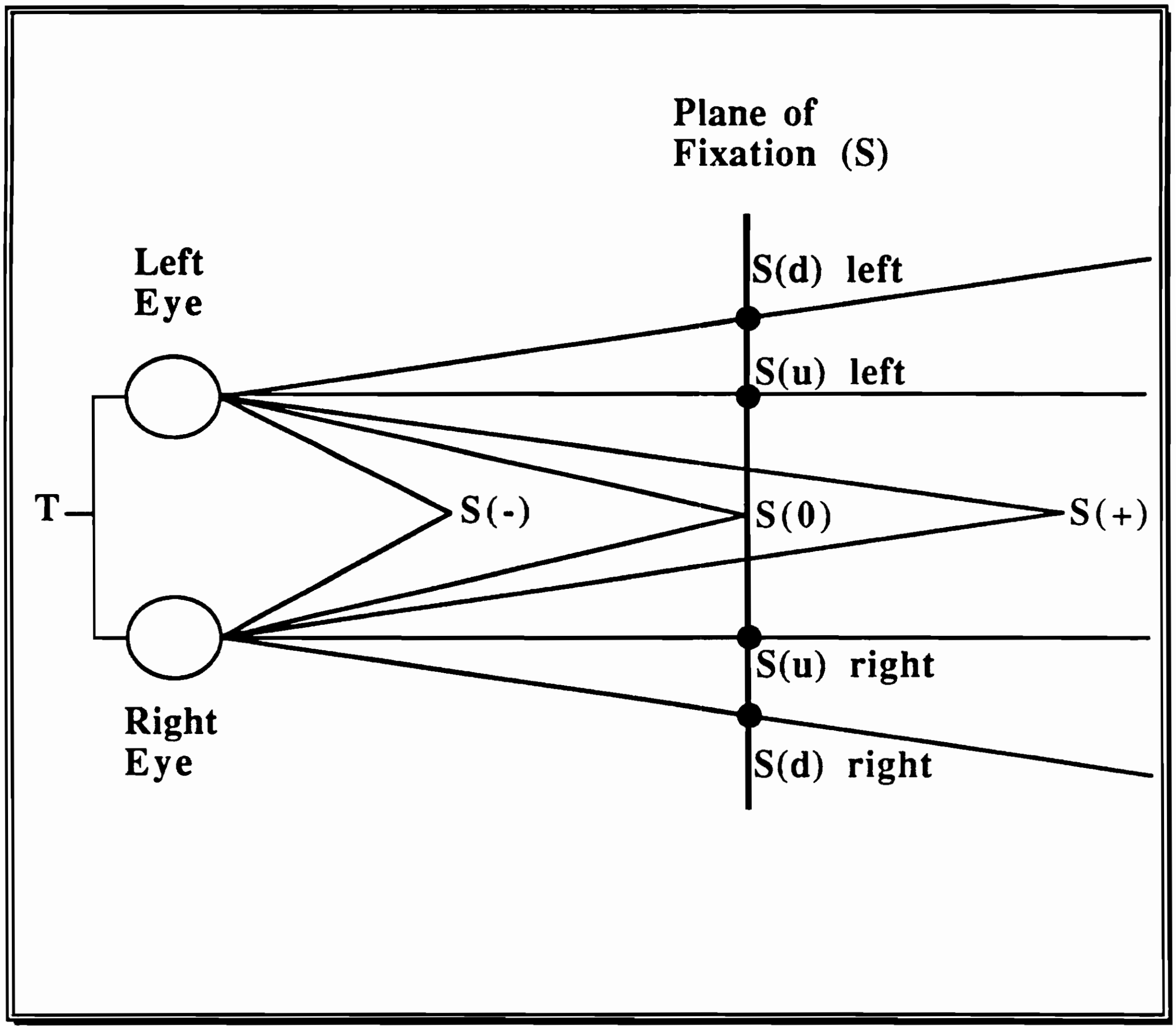


Figure 10. Crossed and uncrossed disparity. See the text for a complete explanation of this figure.

designated as S(u) left and S(u) right, respectively. When the lines of sight for the two eyes do not cross then the parallax is said to be *uncrossed* or *positive* . Uncrossed parallax in stereo pairs stimulates the perception of depth behind plane S up to that seen at great distances where the focal length of the eye is at optical infinity. If disparity values are used which are greater than the interpupillary distance, T, viewing discomfort may occur. Normal binocular viewing does not produce such divergent parallax, since at optical infinity the optical axes are approximately parallel.

The final type of stereoscopic parallax is crossed, or negative parallax, which results in perception of stereoscopic images between plane S and the observer (e.g., point S(-)). For crossed parallax to exist, the two optical axes must cross. In other words, the right stereo figure must exist between points S(0) and S(u) left while the left stereo figure must exist between points S(0) and S(u) right.

Expressed as a function of horizontal separation, disparity may be calculated in the following way:

$$\text{Disparity (deg)} = (180/\pi)\,(Sd/Dv), \qquad (6)$$

where Sd is the horizontal disparity in distance units, and Dv is the distance from object fixation point to the line passing through the optical centers of both eyes. It is important to note that this simplified equation is based on the assumption that points are located close to the line of sight for fixation (within one or two degrees). Violation of this assumption may lead to considerable computational error (Cormack and Fox, 1985).

Horizontal disparity in distance units may also be approximated as a function of the apparent distance of the virtual stereoscopic image, viewing distance, and interpupillary separation in the following way:

$$Sd = TDa / (Da + Dv), \tag{7}$$

where Sd is the horizontal disparity in distance units, T is the interpupillary distance, Da is the apparent distance, and Dv is the viewing distance (Schmandt, 1984).

Alternatively, the distance of the virtual stereoscopic image from the plane of fixation may be approximated to be a function of the viewing geometry as:

$$Da = DvSd / (T - Sd), \tag{8}$$

where Da is the apparent depth of the stereoscopic image from the fixation plane (negative for crossed disparity), Sd is the horizontal disparity in distance units (negative for crossed disparity), Dv is the distance from object fixation point to the line passing through the optical centers of both eyes, and T is the interpupillary distance (Cormack and Fox, 1985). From equation (8) it can be shown that apparent stereoscopic depth can be made to increase by either increasing Dv relative to Sd and T or by increasing Sd relative to Dv and T. It is interesting to note that increases in viewing distance will result in greater apparent depth, despite the consequent reduction in horizontal disparity. Frisby (1980) suggested that this increase in apparent depth with increased viewing distance is the result of a link between vergence angle and the perceptual interpretation of disparity.

Disparity may also be approximated as a function of apparent virtual distance in the following expression:

$$\text{Disparity (deg)} = (180/\pi)\ (TDa/Dv^2), \tag{9}$$

where T is the interpupillary distance, Da is the apparent distance, and Dv is the viewing distance (Graham, 1965; Ritter, 1977). While it has been suggested that the above relationships involving apparent depth (that is, stereoscopic depth constancy) break down as the value of Dv increases beyond 2 m, Cormack (1984) has shown that stereoscopic depth constancy is more likely valid until viewing distances of at least 30 m.

Braddick (1983) suggested that for foveal disparities above 1 deg of visual arc, perceived stereoscopic depth ceases to increase in an incremental fashion. Rather, only the qualitative sense of being closer or farther away is heightened. From formula (8) it can be seen that increases of uncrossed disparity produce increases in stereoscopic depth until positional disparity reaches the value of interpupillary separation, where stereoscopic depth approaches infinity. However, when positional disparity reaches the value of interpupillary separation using crossed disparity, the stereoscopic depth is only one-half that of the fixation depth. Furthermore, the stereoscopic depth produced by crossed disparity can obviously never exceed the fixation distance (Cormack and Fox, 1985) since the virtual image would then be located behind the observer.

The predicted apparent stereoscopic depth differs between crossed and uncrossed disparity. Given two equivalent disparity values, but of different sign, the difference in predicted apparent stereoscopic depth will be approximated by the following:

$$\mathrm{Dau} = \mathrm{Dac}\,(\mathrm{T} + |\mathrm{Sd}|) / (\mathrm{T} - |\mathrm{Sd}|), \qquad (10)$$

where Dau is the apparent uncrossed distance, Dac is the apparent crossed distance, Sd is the horizontal disparity in distance units (negative for crossed disparity), and T is the interpupillary distance (Cormack and Fox, 1985). The difference between crossed and uncrossed disparity is minimized by small ratios of positional disparity to interpupillary distance and maximized when this ratio reaches unity. It follows from the same logic that individual variations in interpupillary distance have a significant impact on this ratio and thus on the apparent stereoscopic depth.

The ability to fuse stereo images is close to full adult capability by approximately five months of age, and there is some evidence to suggest that crossed stereoacuity develops earlier than uncrossed stereoacuity. In contrast, Snellen acuity continues to improve during the first few years of life (Poggio and Poggio, 1984). As with many depth cues, stereopsis in the viewing of natural scenes is most pronounced at closer distances because at greater distances the ratio of the horizontal disparity to the viewing distance becomes smaller. Graham (1965) estimated the ultimate limiting range of normal stereoscopic vision to be approximately 495 yd (453 m).

As previously indicated, the apparent relief seen in distant stereoscopic images may be enhanced by effectively enlarging the interpupillary distance. This is termed *hyperstereoscopy* and is easily accomplished with simple mirror devices such as the telestereoscope (Valius, 1966). It is accomplished photographically by simply increasing the horizontal separation between the two effective optical apertures. Where very large stereoscopic bases are required, as in aerial photography, a single camera may be used to take successive photographs from different aerial positions.

Some of the most significant research describing the underlying processes involved in stereopsis have used Julesz's random dot stereogram (RDS) stimuli. A typical RDS (Figure 11) is composed of two rectangular areas, one left-eye view and one right-eye view, filled with matched patterns of random black and white picture elements (pixels). The left-image pixels are perfectly correlated with the right-image pixels, except for some

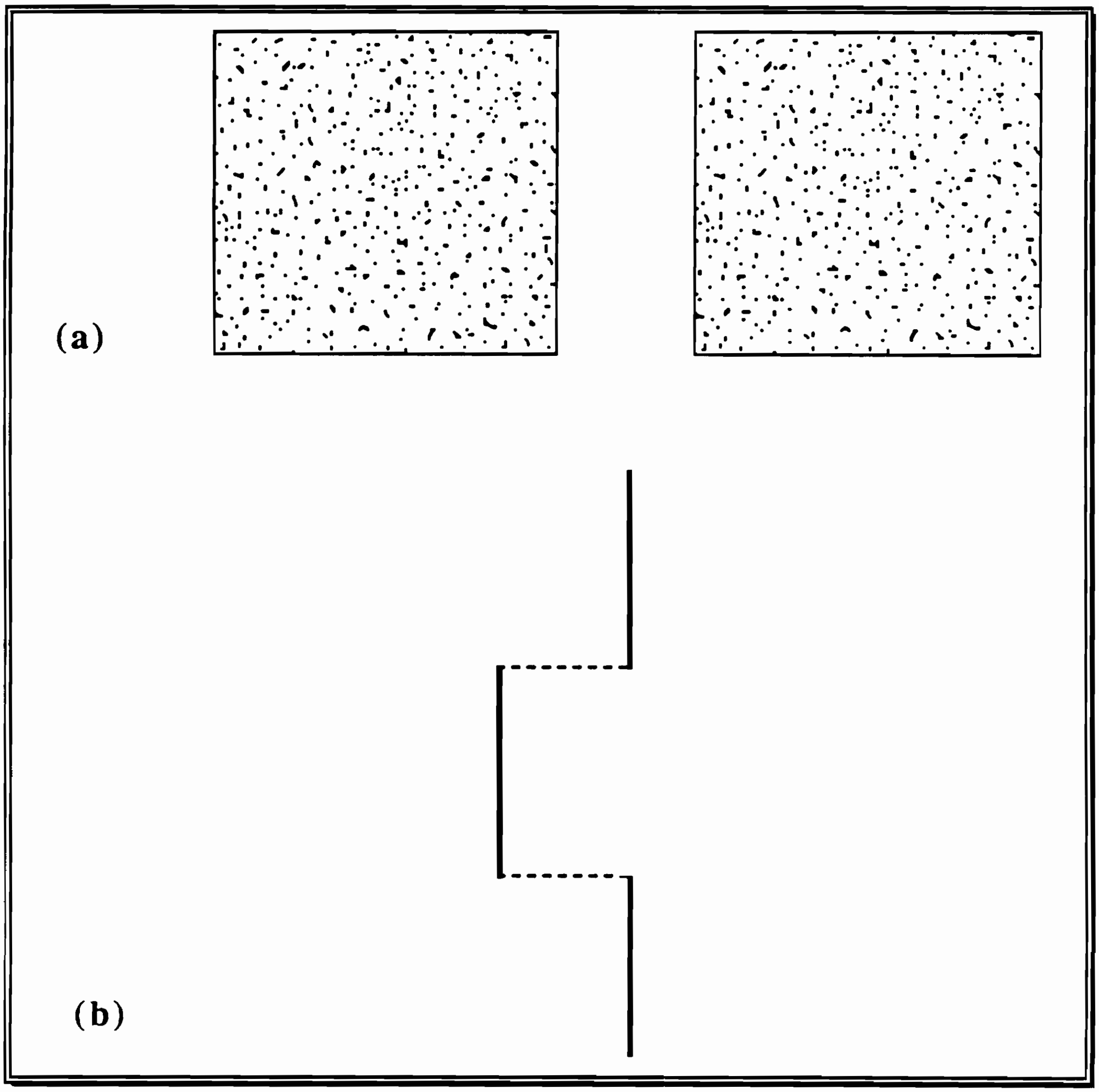


Figure 11. (a) An illustration of the random dot stereogram. The pixels in both frames are perfectly correlated, with the exception of a small square area in the center of each frame which is horizontally shifted relative to the other frame. The stereoscopic perception (b) is that of a small square area of dots floating above the background.

pairs of pixels which possess horizontal disparity relative to one another. When looking at the two images without a stereo selection device, no pattern is apparent in the random dots. However, when viewed stereoscopically, an image forms in apparent depth relative to the pixel plane wherever corresponding dot pairs possess relative disparity. In the RDS shown in Figure 11a, a small square group of pixels in the center of each frame is shifted two pixels horizontally toward the opposite frame. The stereoscopic perception of this RDS (Figure 11b) is that of a square area of pixels floating above the larger framed area of pixels. While some observers are able to fuse such stereograms without optical aids (*free viewing*), the reader will most easily fuse the RDS in Figure 11 with the use of a simple lenticular stereo viewer.

The ability of observers to experience stereopsis in the RDS demonstrates that the human visual system does not require object recognition prior to achieving stereopsis. Prior to the introduction of the RDS in the 1960s, most classical theories of stereopsis assumed that contour matching was necessary to fuse stereoscopic stimuli (Gulick and Lawson, 1976). Rather, it would appear that the relationship may operate in the other direction; that is, the perception of depth may lead to the perception of contour. No sharp luminance gradients are present in RDS images, yet sharp depth gradients are present. The addition of obvious contours to RDS stimuli may speed up stereoscopic fusion times, especially for stereograms with large disparity values (Saye and Frisby, 1975). Speed and disparity threshold for RDS fusion may also depend to a certain extent on the size of the stereogram; large disparity RDSs are more readily fused when the size of the RDS is also large (Julesz, 1971).

RDS fusion also illustrates the correspondence problem, which refers to the difficult problem of successfully matching corresponding image points, or *homologous points* (Baker, 1987), to form the fused stereoscopic image. The correspondence process is "the matching of elements in the two images that correspond to the same location in space" (Poggio, 1984, p. 110). The correspondence problem is alternatively referred to as the problem of global stereopsis (Frisby, 1980). In the case of the RDS, the correspondence process is made especially difficult, since there are no object contours to use in the matching process.

Although many competing computational models exist for describing the process of stereopsis, there is general agreement as to some of the underlying physiological processes involved. Poggio and Poggio (1984) summarized the physiological evidence for the existence of stereopsis-specific neurons. It appears that at least 70% of the cells located in the human striate and prestriate cortices show sensitivity to binocular disparity. Poggio and Poggio classified these cells as either *tuned* neurons or *reciprocal* neurons. Tuned neurons (either excitatory or inhibitory) respond to a narrow range of disparity stimuli, with the peak sensitivity of most cells serving foveal vision falling within the range of +/- 6 arcmin of disparity. Reciprocal neurons are sensitive to the direction of disparity and respond both in excitatory and inhibitory fashions. For example, *far* (uncrossed) neurons show an excitatory response to stimuli located farther than the point of fixation and an inhibitory response to stimuli located closer than the point of fixation. While the exact role that these cells play in the information processing aspects of stereopsis is not yet clear, the association of their location in the brain with the early stages of binocular interaction agrees with the apparently low-level, automatic nature of stereopsis.

Although it has been estimated that 10% of the adult population is incapable of normal stereoscopic fusion (Hodges and McAllister, 1987a; Vlahos, 1965), the empirical source of this figure remains obscured. Presumably these figures have been derived from the practical field experience of the investigators involved. It has also been noted that stereo deficiency may in some cases be specific to either crossed or uncrossed disparity channels. While the exact cause of stereo deficiency is not always known, visual disorders such as amblyopia ("lazy eye") and strabismus (improper alignment of the visual axes) are thought to contribute to many such cases (Braddick, 1982). Weinman and Cooke (1982a) have demonstrated that strong ocular dominance is associated with increased fusion times for simple stereograms and Julesz (1977) attributed stereo deficiency to an inability to properly coordinate vergence eye movements. MacAdam (1954) suggested that stereo deficient individuals may place more dependence on motion parallax than stereo normal individuals, although it would be difficult to determine which condition was the precursor of the other.

Julesz (1977) noted that only about 2% of the general population are actually stereo blind to *small*-disparity RDSs. When participants are asked to fuse *large*-disparity RDSs (1 deg of horizontal disparity), over 15% are typically unable to do so. Thus, a distinction might best be made between those who are stereo blind (approximately 2%) and those who suffer some amount of stereo deficiency. An interesting parallel between color deficiency and stereoscopic deficiency was made by Julesz (1977). The import of color deficiency began to take on new significance for the approximately 10% so afflicted in the early 20th century as color coding became more prevalent in industrial, military, and transportation applications. For those who are stereo deficient, the end of the 20th century may take on similar significance. The use of stereopsis is increasing in importance for industrial, military, and transportation applications, among others. For example, the stereomicroscope has become an invaluable tool for inspection of microelectronics (Julesz, 1977).

Blake, Sloane, and Fox (1981) addressed the matter of stereo deficiency in their review paper on binocular summation. Binocular summation refers to the lowering of visual thresholds when binocular rather than monocular viewing is measured. Although binocular summation is commonly exhibited in a wide variety of visual tasks, stereo deficient individuals generally do not exhibit binocular summation. This result has been consistently reported (e.g., Lema and Blake, 1977; Westendorf, Langston, Chambers, and Allegretti, 1978).

It has been suggested that stereo deficient individuals may suffer a deficit of binocularly innervated neurons (Hohmann and Creutzfeldt, 1975), but other considerations such as research methodology may also play a significant role in influencing stereoscopic threshold values. For example, Patterson and Fox (1984) warned that the stereoscopic testing method used may have a large effect on the determination of stereo deficiency. The authors revealed that participants who were classified as stereoanomolous to tachistoscopic presentations of RDS pairs exhibited normal thresholds when continuous viewing of the stimuli was allowed.

There is some evidence that stereoacuity may be improved through training. At least as early as 1856, Brewster noted that "There are many persons...whose eyes are equal and perfect, but who are not able to unite the pictures in the stereoscope" (Brewster, 1856, p. 231). Brewster noted that this problem may be especially prevalent among men, but acknowledged that for some individuals, the inability to fuse stereo pairs could be overcome by training. More recently, Williams (1966) demonstrated that the accuracy of stereoscopic photointerpretation could be improved through training by as much as 40%. Gould (1964) found that while performance did not improve as a function of daily intra-session practice on a remote, stereoscopic tracking task, performance did improve among daily sessions.

Most of the investigative work which has specifically addressed learning effects in stereopsis has incorporated RDS stimuli. In addition, most of this work has involved the measurement of accuracy and speed of stereoscopic fusion. These fusion times may typically vary from under one sec to over one min for more complex stereograms with multiple depth planes and large disparities (Frisby and Clatworthy, 1975; Ramachandran, 1976).

Long (1982) has presented evidence that RDS training transfer is specific to spatial frequency characteristics of the stimuli. Long's data are consistent with the results of Julesz and Miller (1975), who found that RDS masking effects were specific to spatial frequencies. Similarly, Ramachandran and Braddick (1973) reported that transfer of stereoscopic training was specific to the orientation of short lines used in the RDS stimuli. Conversely, it is apparent that general, nonspecific experience with stereoscopic stimuli may be of special benefit to slow stereoscopic perceivers, while specific experience with the stereograms to be used in testing has been shown to be of benefit to naive observers as a whole (Weinman and Cooke, 1982b). The benefits of such training may be reasonably persistent; Frisby and Clatworthy (1975) found that improved speed of stereogram fusion persisted for at least three weeks.

Aside from the effects of individual differences and practice (Tolin, 1987), it has long been known that stereoscopic thresholds may be influenced by a large variety of display variables. For example, stereoacuity declines at luminance values below 3 cd/m^2 (Tolin, 1987). Stereoacuity is the reciprocal of stereoscopic threshold (Hermans, 1983), although the terms are often used interchangeably in the literature to refer to disparity threshold. Stereoscopic threshold is usually defined as the minimum amount of horizontal disparity required to evoke a sensation of depth.

An early example of such research was reported by Graham, Riggs, Mueller, and Solomon (1949). Stereoscopic threshold values using a lenticular stereoscope were found to range from 15 to 60 arcsec solely as a function of the style of reticle used. A more modern description of stereoacuity was provided by Halpern and Blake (1988), who plotted stereoscopic threshold as a function of luminance contrast and spatial frequency. A mirror stereoscope was used to present vertical lines on two matched CRTs. Stereoscopic thresholds ranged from 5 to approximately 50 sec of visual arc, with stereoscopic thresholds improving as a power function of increasing contrast. The power function with the largest slope (the most rapid improvement of threshold with increasing contrast) was that for the lowest spatial frequency tested (1.2 c/deg). These results are in general agreement with those of Schor and Howarth (1986) who reported that stereoscopic thresholds increase with spatial frequencies below 2.5 c/deg. However, Schor and Howarth (1986) emphasized that suprathreshold stereoscopic depth perception does not depend on spatial frequency if high luminance contrasts and spatial frequencies above 0.5 c/deg are viewed.

Stereoacuity may also be described in terms of discriminable depth, or the number of distinguishable apparent depth planes in space. Simplified, this may be expressed as:

$$Sp = T / RDv^2, \qquad (11)$$

where Sp is the number of distinguishable planes per meter of depth, or stereodiopters, T is the stereoscopic base or interpupillary distance, R is the stereoscopic resolving power of the eye, and Dv is the viewing distance (Valius, 1966). For example, assuming a stereoscopic base of 65 mm, a resolving threshold of 30 arcsec (0.000145 rad), and a viewing distance of 10 m, 4.5 apparent depth planes may be resolved (4.5 planes per meter or a depth threshold of 22 cm).

While very fine stereoacuity is certainly possible, the conditions under which the lowest thresholds are obtained are not robust. McKee (1983) outlined a number of stimulus properties which are necessary to obtain the lowest stereo thresholds (i.e., below

5 sec of arc). Generally, isolated vertical lines ranging in length from 10 to 15 arcsec are presented foveally to achieve these threshold values. Very small displacements of the stimuli into the visual periphery may drastically degrade stereoacuity. In addition, connecting the disparate vertical lines with horizontal lines will also result in a decline of stereoacuity (Mitchison and Westheimer, 1984). More generally, stereoscopic thresholds have been shown to be elevated when other objects share the visual field with the two comparison objects, especially when irrelevant objects intervene between the comparison objects (Mitchison and Westheimer, 1984).

Elevation of stereoscopic threshold has also been demonstrated for slanted surfaces and slanted lines (Gulick and Lawson, 1976; Stevens and Brookes, 1988; Youngs, 1976). Youngs found that horizontal disparity was surprisingly ineffective in evoking a perception of slant for both rectangles and pairs of vertical lines. When stereoscopic presentation was factorially combined with the use of perspective views, the magnitude of perceived slant was determined solely as a function of the perspective cues. Stevens and Brookes found a striking impotency of stereopsis in altering perceived relative depth positions of points on planar surfaces when contradictory monocular cues were present. The authors concluded that, "while depth can be encoded 'directly' from disparity for isolated disparity points, when those points are perceived as lying on a surface, their depth depends on the perceived depth of a surface" (p. 382).

While many of the research reports addressing stereoscopic thresholds concern simple laboratory stimuli, McCann (1979) determined thresholds for stereoscopically presented text for use in cartographic applications. In two pilot experiments, McCann determined several stereoscopic thresholds as a function of horizontal disparity as well as separation between adjacent characters. Most participants could simultaneously fuse all characters presented within 14 to 43 arcsec of each other, provided that the disparities of the stereo pairs were below 1200 arcsec. More time to achieve fusion was required and fewer participants were able to able to attain simultaneous fusion of all characters when larger disparities were used. This result suggests a practical limit for the placement of stereoscopic symbols on a map display.

A second result was that most participants could accurately discriminate between stereoscopic depth planes separated by 200 arcsec of disparity, although with some degree of uncertainty. A separation of 300 arcsec allowed more confidence in depth judgements, but was associated with only a small gain in accuracy. This result suggests that CRT-based stereoscopic displays, which from a typical viewing distance are capable of presenting disparity increments on the order of 120 arcsec, may have sufficient resolution and addressability for some cartographic applications.

The ability of the human visual system to detect very small amounts of disparity means that two principle limitations that designers of electronic stereoscopic displays face are the resolution and addressability of their display media. For example, a 1-pixel change in disparity on a typical Enhanced Graphics Adapter (EGA) monitor from a viewing distance of 1 m should in most circumstances be well above stereoscopic threshold. Although stereoscopic thresholds have been estimated to be as low as 2 arcsec (Clapp, 1986; 1987), if one assumes conservatively that the stereoscopic threshold is 10 arcsec (Tyler, 1977), or 0.05 mm disparity at a viewing distance of 1 m, then a 1-pixel disparity would still be detectable if 6800 x 5120 pixels were available on a 340 mm x 250 mm screen (Butts and McAllister, 1988). This is an order of magnitude beyond the 640 x 512 pixels typically available on a standard EGA monitor.

Finally, while stereopsis is usually described in spatial terms, temporal intervals have been described over which stereopsis may occur. Intervals of up to 300 ms between presentation of left and right stereo pair images will still allow stereopsis (Dodwell, 1970).

This value falls somewhat below the accepted limit of 0.5 s for iconic memory (Wickens, 1984). It has also been shown that stereopsis does not depend on eye movements to calculate retinal correspondence, since tachistiscopically presented stereo pairs may still be fused (Braddick, 1982).

Luminance disparity. In addition to the simple spatial disparity discussed above, it is possible to create a luminance disparity between the two eyes. By placing a neutral density filter before one eye, a phenomenon known as the Pulfrich effect may be shown. The Pulfrich effect occurs when an object which is moving laterally appears to move not only laterally, but elliptically in depth as well. Apparent depth from luminance disparity has also been demonstrated in stereo pairs lacking figural contours (Kaufman, cited by Gulick and Lawson, 1976) and in CRT displays of luminance noise (Almagor, Farley, and Snyder, 1979). These stereo pairs resembled Julesz's RDSs, with the exception that luminance disparity rather than spatial disparity was used.

Luminance disparity has been used to facilitate visual signal separation from noise (Robinson, 1964), suggesting the possibility that spatial disparity might be used toward the same end. Shmakov (cited by Valius, 1966) has observed that CRT image noise appears to be less noticeable in stereoscopic presentations, perhaps because it is distributed through a continuum of apparent depth planes rather than being contained on a single viewing plane. While stereoscopic signal enhancement in the presence of visual noise appears to be a viable application, this hypothesis remains to be tested in a rigorous fashion.

The Use of Multiple Depth Cues

At a recent Human Factors Society meeting, Zenyuh, Reising, Walchli, and Biers (1988) called for "more comprehensive research in the area of depth cue analysis" (p. 56) in the area of stereoscopic cockpit display. In this conference paper, Zenyuh et al. compared visual search performance using a 2-D and a stereoscopic (PLZT goggles) situation awareness display. Both displays were presented with three display densities, with or without the monocular cue of size. While response times were not significantly different in the analysis, there were significant two-way accuracy interactions between display type and display density and between display type and size cuing. In general, an accuracy advantage for the stereoscopic display was significant only at the medium and high display densities. Accuracy was the lowest in the absence of any depth cueing (2-D with no size cueing), the greatest when both stereo and size cueing were used, and intermediate when either stereo or depth cueing was used, thereby suggesting a cue additivity effect.

Mixed evidence exists in the literature pertaining to the interaction or additivity of monocular and binocular depth cues. The most contemporary review of this subject was conducted by Wickens, Todd, and Seidler (cited in Wickens, in press). This survey work was conducted to assess the degree to which depth perception can be described by a weighted additive model. Wickens (in press) concluded that such models generally apply, although the relative weights of depth cues are task dependent and the presence of motion in a display is associated with pronounced deviations from additive models.

Vlahos (1965) also believed that 3-D cues should be generally additive, with necessary attention given to other display factors such as viewing distance, resolution, luminance, contrast, etc. In addition, Vlahos warned that the absence of monocular depth information in stereoscopic images could seriously impair the resulting sensation of depth. This problem is inimical to the modern computer graphics display, since most twentieth century stereoscopic images were real-world images which already contained the needed monocular information.

MacAdam (1954) stated that "Monocular clues to distance do not lose their effectiveness when binocular clues are added. When monocular clues are consistent with the binocular disparities, they greatly reinforce the stereoscopic sense of depth" (p. 278). He then went on to state, "Perceived space is dependent primarily on monocular clues.... Stereoscopic perception then spaces all other objects relative to that distance. This is the only, and quite subsidiary, role of stereopsis in the perception of distance" (p. 285). Vlahos (1965) took a different stand by writing, "The stereopsis cue is the primary source of depth information at distances up to about 30 ft. Within this range the monocular cues play a lesser role in depth perception" (p. 13). However, Merritt (1983) and Graham (1965) noted that stereopsis is a viable source of depth information well beyond 9 m.

Way (1988) investigated the effect of adding color coding and the stereopsis cue to cockpit sensor status displays. One status display incorporated the monocular depth cue of hidden lines (interposition) in a pictorial wire-frame globe which encompassed a model of an aircraft. The other display was an entirely schematic display, incorporating no monocular depth information. While the addition of disparity to the color cue provided a small but significant decrease in response time while using the pictorial display, no such advantage was evident while using the schematic display. Response times in the presence of color and the combination of color and disparity were significantly smaller than when only disparity was used in the schematic display. This is an important finding, since one may infer from it that for some display formats and tasks, the addition of stereopsis may either be not cost-effective or even deleterious.

Other researchers have drawn similar conclusions regarding the combination of stereopsis with monocular depth information. Pepper and Hightower (1984) found that when texture gradients and interposition were present in a depth estimation task, no stereo advantage was evident. They summarized the import of such results well when they wrote, "These results serve to underscore the importance of rich monocular cues in making depth judgements and the fact that providing an operator with a stereo viewing system is not always advantageous" (p. 806). Vlahos (1965) took a similar stand, suggesting that the use of stereoscopic images devoid of monocular depth information would be grossly inadequate.

Spatial Ability and the Perception of Depth

It is tempting to conceive of visual perception as a linear process of encoding environmental stimuli directly into mental analogs. However, as a result of organismic variables such as experience and expectation, mental spatial representations are likely to be substantially different from their physical counterparts (Clapp, 1987). Toward this end, it is reasonable to suggest that individual differences in spatial ability contribute to differences in the nature of mental representations formed from 3-D information displays. Some tools which have been used to operationally define the construct of spatial ability will be briefly discussed here, as well as evidence for gender differences in spatial ability.

Spatial ability may be considered an amalgam of a variety of more specific traits, aptitudes, or skills. For example, Burstein, Bank, and Jarvik (1980, cited by Denno, 1982) discussed spatial aptitude as being composed of "spatial orientation (perception of the position and configuration of objects in space with the observer as a reference point) and spatial visualization (manipulation of parts of a stimulus while maintaining a mental image of the relationships among the parts)" (p. 780). While considerable differences exist in the manner in which this construct is operationally defined among experiments, a male advantage in spatial ability is often reported (e.g., Sanders, Soares, and D'Aquila, 1982; Tapley and Bryden, 1977). Interpretation of such results should be mediated by a careful consideration of methodological factors, as well as the fact that the magnitudes of such differences are often quite small (Caplan, MacPherson, and Tobin, 1985; Denno, 1982).

One test of spatial ability which yields consistently higher scores for males is the Mental Rotations Test (MRT) (Ozer, 1987). This paper-and-pencil test was developed by Vandenberg and Kuse (1978), based on prior work by Shepard and Metzler (1971). In the MRT, participants are asked to identify which two of four 2-D perspective block figures are correct 3-D rotations of a target figure. Sanders et al. (1982) found that gender accounted for 16% of the variance in MRT scores, with males scoring higher than females. Similarly, Tapley and Bryden (1977) reported a significant response time advantage for males in completing such mental rotations. While such gender effects are statistically significant, other factors such as training have been found to account for as much as 35% of the variance in MRT scores (Stericker and LeVesconte, 1982). In the same study, females who received training scored no differently on the MRT than males in the control group, suggesting that MRT gender differences can be mediated by practice. It should be noted that in this study, as well as in at least one other experiment (McGee, 1978), males who received training showed training effects equal to those for females.

Another representative test of spatial ability is the Differential Aptitude Spatial Relations sub-test (DAT). This test requires participants to choose which of four shapes accurately represents a folded version of the target shape. McGuinness and Brabyn (1984) found that DAT scores and RDS fusion times were superior for males. In addition, DAT scores were negatively correlated with the time required for participants to fuse RDSs; higher DAT scores were associated with faster stereo fusion times. This correlation was statistically significant, but not strong ($r = -.33, p < .05$). These results suggest that spatial ability and stereoscopic ability may share common resources. They are also consistent with the possibility of a male advantage for both abilities.

The Display of Depth

Many display technologies have been developed for the presentation of 3-D images. Okoshi (1976) categorized true 3-D displays as either stereoscopic (stereo pair) or autostereoscopic. Autostereoscopic displays differ from stereoscopic displays in that they require no special viewing or image selection mechanisms such as polarized glasses. The two classes of 3-D display may also be distinguished by the amount of information required to construct images. While stereoscopic displays require presentation of exactly two times the amount of information of a comparable monocular display, autostereoscopic displays such as holograms require the encoding of much greater amounts of information, since bandwidth will increase roughly as a function of the number of pixels in depth (Vlahos, 1965). This bandwidth constraint will force tradeoffs among display size, resolution, addressability, and image luminance. Such a tradeoff is evident in the SpaceGraph vari-focal mirror display, where images of meaningful size and depth are limited to wire-frame constructions.

In this section, a variety of autostereoscopic and stereoscopic display technologies will be reviewed. First, a sampling of monocular, or pictorial, display techniques is considered.

Pictorial displays. Perhaps the most widely used pictorial depth cue in modern visual display is that of linear perspective. A common example of a static perspective display is the response surface graph (e.g., Jensen and Anderson, 1987), which is in essence a 3-D bar graph viewed from a perspective transformation. Perspective depth coding in real-time display has in the past been constrained by factors such as limited speed of computation and development of sophisticated graphics algorithms. The accelerated development of computer processor technology has greatly alleviated this problem.

Ellis and McGreevy (1983) reported evidence that the use of perspective displays may improve the quality of air traffic control. In this study, the traditional plan view ("bird's eye") cockpit display of traffic information (CDTI) was compared with a novel perspective view display. Pilots flew simulated encounters with other aircraft and were required to determine appropriate avoidance maneuvers. The plan view display was composed of aircraft symbols, digital data tags, and two parallel lines for horizontal separation reference. In the perspective display, aircraft symbols were displayed above a perspective grid which served as the ground reference. A 30-deg elevation angle was used, viewed 8 deg off center to the right. The sizes of intruding aircraft were scaled according to the perspective used. No texturing or aerial perspective was used.

Pilots made avoidance decisions approximately 10% faster when viewing the perspective display. However, this was not the case when air traffic approached from head-on along the viewing axis. This was most likely due to the fact that from this perspective there was a problem of symbol superimposition. The plan view display had no similar occurrences, since it incorporated an automatic algorithm to avoid the superimposition of data tags. In addition to the speed-of-response advantage, it is interesting to note that a previously observed bias toward making horizontal avoidance maneuvers was substantially reduced through the use of the perspective display. This suggests that the plan view display placed unnecessary constraints on the pilot's use of available airspace for avoidance maneuvering.

A similar display comparison was conducted by Bemis, Leeds, and Winer (1988). The perspective display tested assumed a 41-deg elevation with no horizontal offset. Although relative size coding was not used in the perspective display, participants were able to use it more accurately and generally more rapidly than the conventional plan view display.

In the perspective displays used by Ellis and McGreevy (1983) and Bemis et al. (1988), the perspective transformations were accompanied by the inclusion of a reference grid and vertical lines connecting the targets to the grid. While the presence of the grid itself is visually appealing, Kim, Ellis, Tyler, Hannaford, and Stark (1987) reported that performance on a three-axis manual tracking task was not improved by including such a grid in their perspective display. However, the inclusion of vertical reference lines did improve tracking performance.

Autostereoscopic displays. In contrast to most stereoscopic displays, large groups of observers may view autostereoscopic displays at one time. Another advantage for some autostereoscopic displays is that observers may view the display from a large variety of viewing angles. One such display is the volumetric display, which presents real images in three spatial dimensions. A major obstacle in the development of large, dynamic volumetric displays is the very high bandwidth which is required, especially if the display of complex, real-world imagery is to be achieved (Hesselink, 1985). Several autostereoscopic displays are described in the following paragraphs.

(1) Integral photography. The integral photography technique produces a form of 3-D hard copy called *integrams* (Budinger, 1984). Integrams are produced by covering a photograph with a large number of small convex lenses (i.e., a *fly's eye* lens). The result is a 3-D photograph which can be viewed without the benefit of any special viewing apparatus. This general approach is the same used to create the familiar 3-D postcards and was invented by Lippman in 1908 (Okoshi, 1980).

(2) Lenticular sheets. The integram technique was simplified and extended to the use of half-cylinder lenses (lenticular sheets) and has been applied to hard copy as well as

stereoscopic CRT design (e.g., Borner, 1987; Schwartz, 1986). For example, Schwartz combined the images from two CRTs through a Fresnel lens behind a lenticular array. This array consisted of a large number of half-cylinder lenses placed vertically on the screen next to each other. This technique is a simplification of integral photography since only horizontal parallax is used in the images, whereas the fly's eye views in integral photography provide vertical parallax as well (Okoshi, 1977). These displays are autostereoscopic, but apparent image depth is usually limited to about 10 cm and imperfections in the plastic lens limit the image quality (Hodges, Love, and McAllister, 1987a).

(3) Holography. Although a large variety of holographic techniques exist, the fundamental principle behind the construction of most holograms is the recording on a sheet of film the interference patterns of coherent light. In one simple form of holography (Leith-Upatnieks holography), the production requires one source of coherent light (e.g., a laser) which is split into two beams: the object beam and the reference beam. The object beam is passed over or through the object to be recorded and then strikes the surface of the recording medium. The reference wave strikes the recording medium directly (Okoshi, 1976). Since the two beams of light originated from the same source in phase, the interference pattern between the two waves on the film contains information about the object interposed between the object beam and the film plane. The holographic negative also contains amplitude information in the resulting interference fringes (Hodges, Love, and McAllister, 1987b).

Holograms may usually be viewed simply by passing coherent light (or sometimes white light) through the hologram. The resulting image is a striking virtual image of the recorded scene in depth. While multiple perspective holograms in part solve the problem of false motion parallax by allowing the observer to see around objects, it is not yet technically feasible to produce real-time, dynamic holograms with large numbers of perspective views (Hodges and McAllister, 1987b). In addition, the simultaneous production of good contrast, size, color, and apparent depth in the same hologram is difficult without driving the cost prohibitively high (Benton, 1985).

Hesselink, Johnson, and Perlmutter (1983) described a recent application of incoherent superposition holography (ISH). Using a multiple film exposure technique, tomographic cross-sections of human organs can be superimposed to create a single hologram. The result is a serial reconstruction of the organ in three spatial dimensions. This application of holography could prove invaluable for improving the diagnostic accuracy of medical imagery.

(4) Vari-focal mirror. Several researchers have developed autostereoscopic displays based on the construction of a virtual image volume with a vibrating mirror (Baxter, 1981; Harris, 1988; Harris and Camp, 1984; Mark and Hull, 1977; Sher, 1988; Stover and Fletcher, 1983). This usually involves the linking of a lightweight, deformable mirror to a modulator such as a loudspeaker woofer. The system is called *vari-focal* because the focal length of the mirror surface changes as a function of the amplitude and frequency of the driving modulator. By reflecting the image of a CRT off the mirror and driving the loudspeaker in synchrony with the CRT display rate, a display volume may be created as a collection of depth planes in time. The vari-focal mirror concept is seriously limited by bandwidth and phosphor decay constraints, such that only monochrome, wireframe images can realistically be displayed (Hodges and McAllister, 1987b).

A similar display concept was proposed by Buzak (1985a). Rather than vibrating a single mirror surface, this display makes use of a stack of fixed, electrically switchable liquid crystal mirrors. A CRT image is projected onto the front of the mirror stack, the image of which is viewed through a dielectric mirror. The depth of the image at any given moment in time is determined by which of the mirrors are in a transmissive state and which are in a reflective state. For example, in a five-mirror display, an object would be projected to the middle depth by placing the first two mirrors in a transmissive state and the third mirror in a reflective state.

(5) Gas volumes. Lewis, Verber, and McGhee (1971) and Verber (1977) discussed a volumetric display concept based on laser excitation of a volume of transparent gas. Display elements are addressed by creating fluorescent spots at the intersection of two laser beams. This display concept is desirable for many reasons. A true volumetric display could be easily viewable by multiple display operators from multiple perspectives. Another advantage is that the computational difficulties in producing accurate depth cues which have plagued other 3-D display technologies are eliminated in this concept, because the display truly exists in three spatial dimensions. However, the concept is not without problems, such as laser speckle, which are inherent in the light source and display media.

(6) Rotating solids. A recent example of this class of volumetric display was discussed by Williams and Garcia (1988). Their display concept is based on addressing the surface of a translucent, rotating disk (400 to 600 rpm) with one or more laser sources. Scanners are used to create X and Y laser display planes. Multiple planes on the Z axis are presented by synchronization of the beam with the position of the disk surface in depth. While this display is still in development, it overcomes the problems of limited viewing angles and the requirement of special viewing glasses.

A very similar display concept was proposed by Yamada, Masuda, Kubo, Ohira, and Miyaji (1986) who described a spiral display surface mounted on a rotating disc, also addressed by a laser. A rotating display medium which does not incorporate laser light was discussed by Budinger (1984). This conceptual display medium consists of a two-dimensional array of light emitting diodes (LED) which rotates about a central axis. The display concept described by Simon (1969) and Simon and Walters (1977) resembles a hybrid of Budinger's (1984) display and the vari-focal mirror technology: a rotating, inflexible mirror displays a moving image from a stationary CRT. An earlier incarnation of this type of volumetric display was proposed by Ketchpel in 1964 (cited by Lipton, 1982) and used a rotating phosphor-covered disk located inside a CRT.

(7) VISIDEP. The Visual Image Depth Enhancement by Parallax Induction (VISIDEP) technique produces apparent depth though dynamic vertical disparity (Jones, McLaurin, and Cathey, 1984; McLaurin, Jones, Cathey, 1984; 1986). Two images are separated by a rotation on the horizontal axis by 1 or 2 deg and are alternated at approximately 10 Hz (Hodges and McAllister, 1987a; 1987b). The VISIDEP display is an autostereoscopic display since no attempt is made to present the disparate images separately to each eye.

The VISIDEP technique provides a sense of real-time color depth while requiring no special glasses or shutters. Subjective responses as to visual or physical distress experienced during VISIDEP use have revealed no unusual problems or differences compared to normal CRT viewing (McLaurin and Jones, 1988). The image is not entirely satisfactory, however, since a slight vertical rocking motion is induced by the low frequency alternation of views. Attempts to increase the frequency of alternation result in the loss of the depth sensation (McLaurin et al., 1986).

McLaurin and Jones (1988) reported that color imbalances used in the VISIDEP stereo cameras may lead to color fluctuations in the perceived image. In the same study, subjective ratings of depth magnitude did not reliably differ between groups viewing real-world imagery on the VISIDEP system and those using a standard CRT. This result suggests that any monocular cues present in the video image itself may provide depth sensations of much greater magnitude than is provided by the VISIDEP system.

Merritt (1984) also questioned the value of the VISIDEP display technique. While alternating frame motion parallax did evoke a sensation of depth, Merritt's participants were not able to successfully use this information to guide a teleoperated robot arm. Participants using a standard stereoscopic display accomplished this task with no great difficulty.

Chromostereoscopic displays. While the process of chromostereopsis is autostereoscopic, strictly speaking, chromostereoscopic displays are usually not. Nor are such displays categorized as stereoscopic. Therefore, chromostereoscopes are discussed separately here. Steenblik (1987) invented a process whereby the limited chromostereopsis effect may be made more pronounced. Steenblik's process involves viewing colored images through a double set of low and high dispersion prisms placed before each eye. The prism arrangement may be used to augment the otherwise weak chromatic dispersion effect of the human crystalline lens. Alternatively, by reversing the prisms the relative depth ordering of the chromatic spectrum can be reversed (i.e., blues closer and reds farther away). The amount of chromatic dispersion is controllable by changing the relative orientation of the two prisms in relation to one another.

The chromostereoscopic display medium remains limited in the use of image color coding. The relative depth seen in the display will follow the relative spectral ordering of the colors used in the display. As Steenblik (1987) noted, this may be a problem, since "Green people and blue sunsets are not commonly encountered" (p. 33). Furthermore, colors with high spectral purity are necessary to yield the sharpest chromostereoscopic images.

Hodges and McAllister (1988) reviewed the effectiveness of Steenblik's superchromatic prisms for use in a CRT-based chromostereoscopic display. They observed that readily discernable depth differences could only be obtained among the colors of red, green, blue, and yellow while using a black background. Use of a white background caused inversion of the normal apparent depth effect. Furthermore, the total apparent depth in the display was only 10 cm.

Early stereoscopic displays. The history of stereoscopic display extends over approximately 150 years, with a very large number of stereoscopic display techniques having been proposed during those years. Some critical developments in stereoscopic display technology are reviewed here.

(1) Wheatstone mirror stereoscope. The word *stereoscope* is constructed from the Greek root words of *stereos* (solid) and *skopeo* (see) (Valius, 1966). Although Wheatstone is usually credited with the invention of the first stereoscope between 1833 and 1838, there is a certain amount of ambiguity as to which of several inventors deserves priority of invention. There is evidence to suggest that a simpler device was conceived of by Elliot as early as 1834 (Brewster, 1856; Gulick and Lawson, 1976). Elliot's device was simply a long wooden box with a slot on the far end to insert stereoscopic pairs. No optics were contained in the box, so that fusion of the stereo pairs relied solely on the ability of observers to control their ocular convergence.

Wheatstone's invention of the reflecting stereoscope was a significant improvement over Elliot's design, since mirrors were incorporated to aid binocular fusion (Figure 12). One operates the Wheatstone stereoscope by looking into the two mirrors and adjusting the distances of the two image plates from the mirrors until image fusion occurs.

(2) Brewster lenticular stereoscope. In 1849, Brewster addressed several inherent problems in the Wheatstone reflecting stereoscope by producing the lenticular stereoscope. The lenticular stereoscope replaced the angled mirrors and image plates of the reflecting stereoscope with small viewing lenses. When viewing the two images through the edges

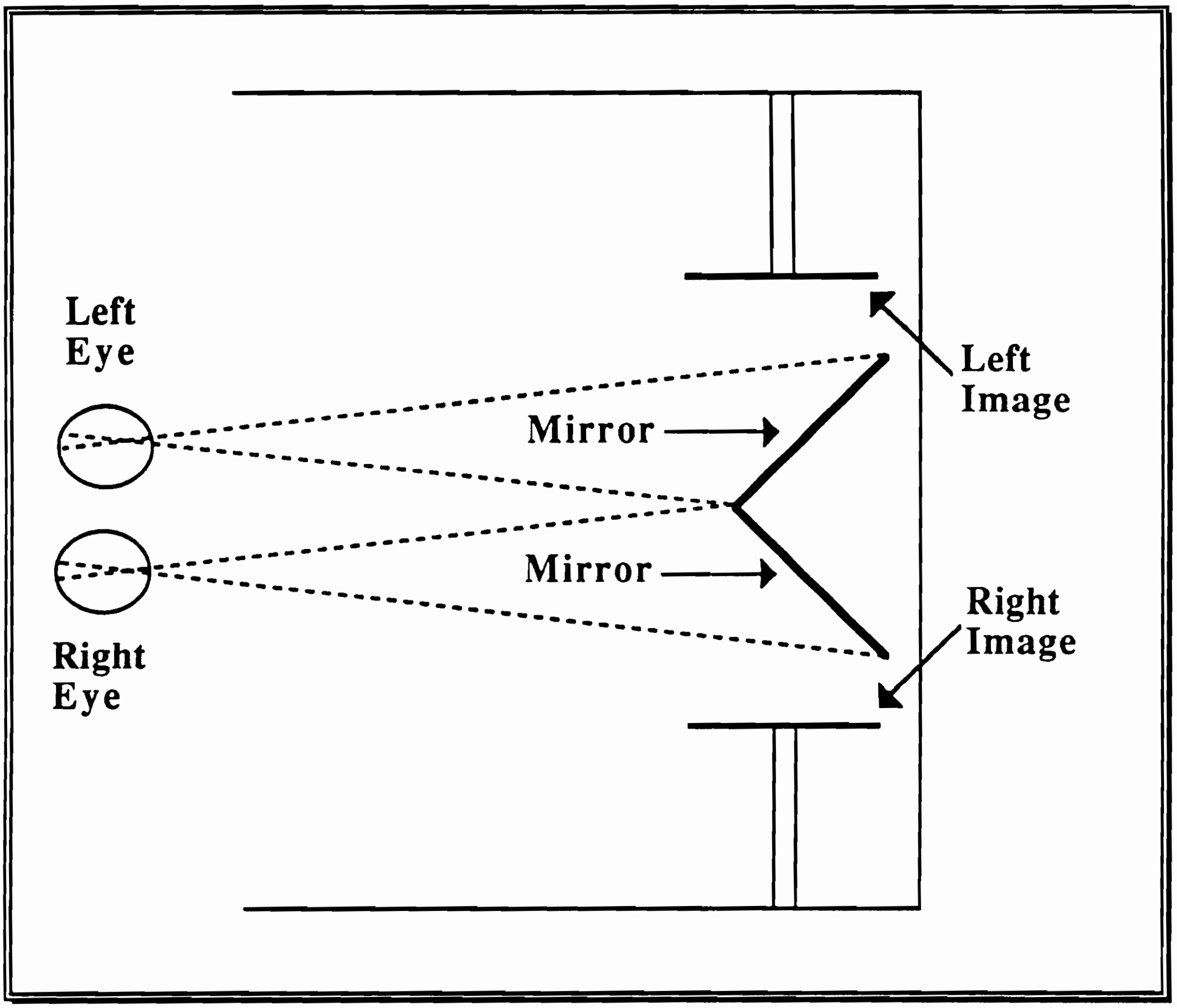


Figure 12. The Wheatstone mirror stereoscope. The positions of the left and right images were adjusted to accommodate a variety of interpupillary distances.

of convex lenses several inches away from the images, optical convergence (and consequently stereoscopic fusion) will occur (Brewster, 1856). This device provided the advantages of smaller size, variable image magnification, and less light loss than the reflecting stereoscope. In addition, the use of convex lenses to project the virtual image at a greater distance permitted the effective removal of the accommodation cue, which would conflict with the disparity and convergence cues (Okoshi, 1976). An alternative version of the Brewster stereoscope used a single prism to aid optical convergence of the two images.

(3) Anaglyph stereograms. The first anaglyph stereograms were produced in 1891 by Louis Ducos du Hauron (Hermans, 1983). This stereo technique separates left- and right-eye images by using colored images (usually red and green) in conjunction with colored filter glasses. Assuming that the left image is portrayed in red and the right image is portrayed in green, filter glasses are worn such that a red lens covers the left eye and a green lens covers the right eye. Initial image separation and eventual fusion occurs because each filter will admit only light of its own color to the eye behind the filter.

While anaglyph stereograms are inexpensive to produce and relatively simple to use, they have a number of severe limitations compared to other stereo technologies. First, since colored filters are used, it is not possible to present original images in their full and true colors (Harris, Geddes, and North, 1986). Additionally, some blurring of the image may occur (Buzak, 1985b) and observers may experience visual discomfort.

(4) Projection stereoscopy. Many of the stereoscopic technologies reviewed here have substantial limitations as to the maximum number of viewers. This problem has been solved for stereoscopic cinematography by projecting the disparate images onto a large screen and providing viewers with the appropriate viewing lenses to separate the right and left images (e.g., Hines, 1984). This technique has been applied to both anaglyph and the polarized light technology. If polarized light is used, it is necessary to use a metallic screen

which will preserve the polarization of the projected light (Hodges, Love, and McAllister, 1987a).

Selection devices for CRT-based stereoscopes. Perhaps the most critical aspect of the development of CRT-based stereoscopes is the design of the stereoscopic selection mechanism. The stereoscopic selection device is responsible for delivering the left image to the left eye and the right image to the right eye, with perfect image separation being the ideal. While stereoscopic selection devices have continued to improve, high development and manufacturing costs have made the best selection devices expensive.

(1) Anaglyph stereo CRTs. The anaglyph technique has been applied to a limited extent to CRT displays. Perhaps the first such application was by Baird, as early as 1936 in England (Balasubramanian and Rajappan, 1983). More recently, Crooks et al. (1975) demonstrated that participants were better able to manipulate a robot arm when using an anaglyph stereo display as compared to a nonstereoscopic display. This system produced anaglyph stereoscopic images by routing the video signals from left and right cameras to the red and blue monitor inputs.

Anaglyph CRT displays have also been used to display atmospheric contour maps (DesJardins and Hasler, 1980). However, the color distortions in this display were bothersome and the anaglyph technique was abandoned in favor of a space-multiplexing technique. In general, the anaglyph technique is seen as an inexpensive way to achieve stereo presentation, but one which suffers serious image quality limitations.

(2) Mechanical shutters. Mechanical shutters have been used to alternate left and right image channels, but they are difficult to sequence reliably with the video signal at high refresh rates. An example of a simple mechanical shuttering device is a rotating drum with alternating holes through which the display is viewed (Herman, 1986). A similar shutter was used by Waldern, Humrich, and Cochrane (1986), but their system used two

synchronized rotating units. Valius (1966) described an early shutter system composed of springs, blades, and motors synchronized with film projector motors and built directly into the viewing spectacles. This may well have been the first production of active stereoscopic viewing glasses.

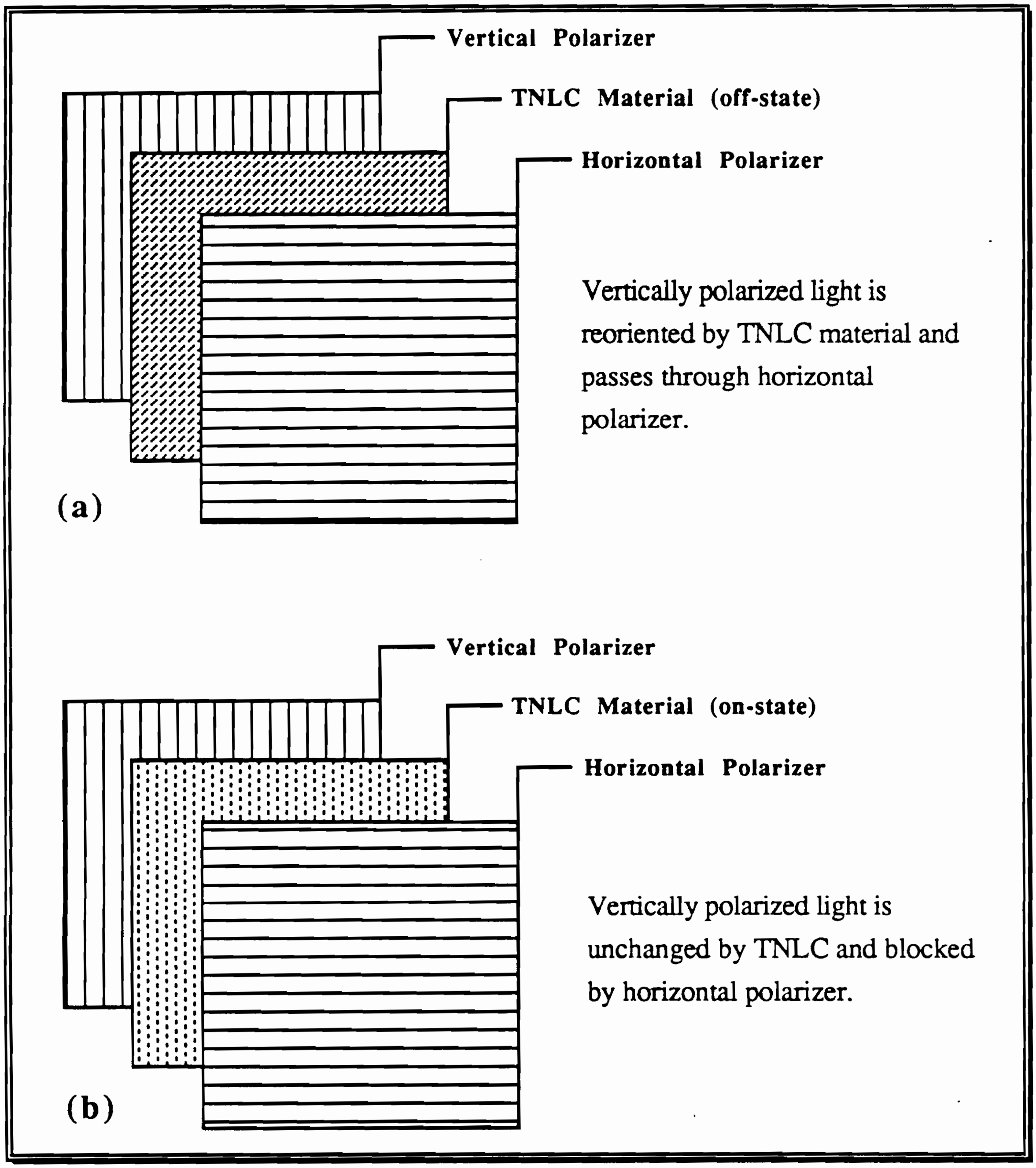
(3) Polarization. The unsatisfactory performance of the anaglyph technique and mechanical shutters gave rise to the use of linear polarization to control presentation of horizontally disparate images to the left and right eyes. The primary difficulty with the use of linear polarization to view stereograms is the sensitivity to head position. For example, if the left and right images were polarized vertically and horizontally, respectively, with a corresponding polarization of a viewer's glasses, then a tilt of the head in the transverse plane relative to the direction of propagation would alter the acceptance and rejection of the filters and the eyes would not see the proper image channels. The failure of the stereoscopic selection device to adequately separate the left and right eye views will prevent the proper perception of stereoscopic images.

The problem of head position sensitivity associated with linear polarization has been overcome by using circular polarization. Circular polarization is achieved by first passing light through a linear polarizer and then a quarter-wave linear retarder. The net effect is the passage of light which is propagated not in a single plane, but rather in a clockwise or counter-clockwise helix (Walworth, Bennett, and Trapani, 1984). The chief advantage is that the absorption of a circular polarizer is largely insensitive to rotations in the transverse plane of the direction of light propagation. Consequently, changes of head position will not jeopardize the quality of stereoscopic images when circular polarizers are used.

One common technology for producing polarized light is the twisted nematic liquid crystal (TNLC). TNLC shutters rely on unique properties of the liquid crystal (LC) to control the polarization direction of light. LC is a class of material which has both fluid properties of liquids as well as structural properties of crystals. The TNLC shutter generally illustrates how many of the electrooptic shutters operate (Figure 13). Typically, a TNLC cell is sandwiched between a vertical and a horizontal polarizer. As light first passes through the vertical polarizer and enters the TNLC, the LCs may rotate the direction of polarization by 90 deg, depending on the state of the electrical signal applied across the TNLC. If the polarization direction is rotated, the light will pass through the horizontal polarizer and the image will be transmitted to the viewer (Figure 13a). However, if the polarization direction is not rotated (Figure 13b), the light will be absorbed by the horizontal polarizer and the eye will not receive the image (Harris et al., 1986). The use of polarizers in this fashion causes a serious disadvantage for these electrooptic shutters: light transmissivities are very low (Milgram and Van der Horst, 1986).

Early TNLC shutters were limited by the relatively slow (> 20 ms) relaxation time necessary for the LCs to switch from their active to passive states. More recently, the use of active switching with low and high driving voltages has improved switching times to more acceptable levels (< 10 ms) (Milgram and Van Der Horst, 1986). These cells are most typically used in an active glasses arrangement, since the production of full screen sized LC shutters is expensive and difficult.

An alternate polarization technique uses lead lanthanum zirconate titanate (PLZT) ceramics. PLZT shutters were used in early active glasses systems (e.g., Roese and McCleary, 1979) and represented a large improvement over mechanical and early TNLC shutter systems. However, they were expensive and had low (approximately 17%) transmissivities (Harris et al., 1986). Additionally, they required high operating voltages which generated damaging levels of heat (Hartmann and Hikspoors, 1987). More recent PLZT developments (Roese, 1984) are improved, but still are generally inferior to modern LC devices.



Vertically polarized light is reoriented by TNLC material and passes through horizontal polarizer.

Vertically polarized light is unchanged by TNLC and blocked by horizontal polarizer.

Figure 13. TNLC technology. LC material is used to reorient the polarization sense of light (a). When an electric current is applied to the LC material (b), the LCs change their orientation.

Another alternate material to the TNLC is ferroelectric liquid crystal (FLC). FLC shutters are generally capable of faster switching times (approximately 400 μs) and lower operating voltages than many TNLC shutters (Hartmann and Hikspoors, 1987). However, the most recent improvement on stereoscopic LC shutter technology is the LC π-cell shutter. Early π-cell shutters were demonstrated with switching times between 170 μs (Bos, Johnson, and Koehler/Beran, 1983) and 100 μs (Haven, 1987). These shutters are typically mounted directly over the CRT faceplate and used in conjunction with passive glasses. More recently, these shutters have been used in active glasses systems. These new systems have substantially lower levels of optical crosstalk than earlier π–cell implementations.

Space-multiplexing stereoscopic CRTs. Early attempts to use CRTs for stereoscopic display accomplished the stereo presentation through the use of two separate camera-display channels. For example, Gould (1964) used prisms to combine images from two separate CRTs, producing stereoscopic images in much the same way as Brewster's early lenticular stereoscope. Each CRT received a signal from one of two video cameras which converged on the target of interest. These systems may provide good stereoscopic imagery, but they require two CRTs, which is costly not only in dollars but also in workspace and weight. Additionally, any mismatched performance characteristics between the two CRTs may detract from stereopsis.

An alternate form of the space-multiplexing stereoscopic CRT divides a single screen into left and right views which are displayed simultaneously (e.g., DesJardins and Hasler, 1980). This display strategy overcomes the requirement for two CRTs, but it suffers from the loss of available display area since the screen must be divided in half.

Time-multiplexing stereoscopic CRTs. Limitations of space-multiplexing stereo displays may be overcome by using time-multiplexing displays, which sequentially present horizontally offset images to the right and left eyes. Time-multiplexing systems produce satisfactory stereoscopic images provided that sufficient display refresh and selection device switching rates are used such that the eye integrates the images over time and flicker is not perceived. In recent years, several successful implementations of ceramic and liquid crystal shutters have proved to offer significant gains in shutter performance so as to make time-multiplexing stereoscopic CRTs technically viable.

These shutters (discussed above) are either built into viewing glasses which are then plugged into the host computer for sequencing with the video signal (active glasses) or, more recently, are mounted directly over the CRT faceplate and used in conjunction with polarized (passive) glasses. Modern time-multiplexing systems use circular polarization to defeat the head-position problems associated with linear polarization. Passive glasses have the advantage of not requiring a physical connection between the glasses and computer which might otherwise interfere with movement in the operator's work space. Furthermore, multiple display viewers are more easily accommodated with the passive glasses. Although recent advances in cordless, infrared active glasses have improved their usability (e.g., Hartmann and Hikspoors, 1987), passive glasses remain lighter and more comfortable to wear.

Problems inherent in CRT-based stereoscopic displays. Several technical and perceptual aspects of CRT-based stereoscopic displays are important in the understanding of the capabilities and limitations of this display medium. CRT-based stereoscopic displays are commercially available which, when used properly, may present excellent stereoscopic images. However, most stereoscopic presentations have room for improvement in one of more of the following areas.

(1) Flicker. Display flicker has been a topic of concern among CRT designers for some time, although the presence of flicker in a display has been mostly associated with

subjective complaints rather than performance decrements. While CRT flicker thresholds depend on a large variety of display parameters, one critical parameter is the vertical retrace frequency of the electron beam. The field-sequential stereoscopic CRT has special requirements for vertical retrace frequency.

Beaton, DeHoff, and Knox (1986) compared flicker frequency thresholds between a field-sequential stereoscopic CRT and a noninterlaced CRT. Flicker thresholds were approximately 4% lower in the stereoscopic display condition. The authors attributed this small but significant threshold difference to the *Sherington effect.* The Sherington effect refers to the elevation of flicker thresholds for in-phase binocular summation relative to out-of-phase binocular summation. It is important to note that the flicker thresholds obtained with this stereoscopic display condition actually represented a vertical retrace time of approximately twice that used in the noninterlaced display, since in order to achieve a comparable frame rate in the stereoscopic display condition, a field rate of two times the frame rate (left and right) was necessary.

(2) Binocular Asymmetry. Lipton (1984) used the term *binocular symmetries* to refer to a host of stereoscopic design flaws which could reduce the effectiveness of stereoscopic presentations and generate unpleasant visual side-effects. In general, this term refers to any difference between left and right stereo fields other than the intended horizontal disparity. Common binocular asymmetries in stereoscopic displays include luminous, chromatic, and geometric asymmetries. From the principle of binocular asymmetry, it should come as no surprise that extended viewing of anaglyph stereo displays leads to visual discomfort, since chromatic asymmetry is used as the selection device for separating left and right stereo images. Electrooptic stereo displays suffer predominantly from optical crosstalk, a special class of geometric asymmetry.

(3) Ghosting. Ghosting is a perceptual phenomenon produced by optical crosstalk. Optical crosstalk in the stereoscopic CRT may be the result of two principal display factors: slow phosphor decay times and filter leakage. Phosphors which decay too slowly will still be partially excited during the presentation of the alternate display field. Filter leakage is the inverse of the dynamic range. The dynamic range is the ratio of transmissivity in the open state to that in the closed state.

Lipton (1987) has used the term *phosphor point* to describe the interaction of these two display variables in the elimination of stereoscopic crosstalk. The phosphor point is that point at which improvements in shutter dynamic range no longer lead to a reduction in crosstalk, with phosphor decay time becoming the limiting factor. The phosphor point may typically occur at dynamic ranges between 35:1 and 40:1 (Lipton, 1987). Bos, Haven, and Virgin (1988) effectively raised the phosphor point of their display by dividing their LC π-cell shutter into two separate cells, divided horizontally. By addressing the two cells independently, more time is made available for the phosphor to decay in the lower one-half of the display, while the CRT beam is addressing the top one-half of the display.

Crosstalk may also be caused by screen depolarization in stereo projection systems (Vlahos, 1965). It is also known to be more apparent with the use of larger parallax values (Tolin, 1987), greater luminance contrast, and figures with high spatial frequencies (Lipton, 1987). In addition, the effective shutter dynamic range may vary as a function of phosphor chrominance (Beaton, 1989). Despite the distraction and possible discomfort, there does not seem to be any appreciable degradation of stereopsis in the presence of ghosting (Lipton, 1984), except in extreme cases (Lipton, 1987).

(4) Vertical disparity. Another form of geometric asymetry which may lead to visual discomfort is vertical disparity (Vlahos, 1965). Vertical misregistration is a potential problem for systems using two cameras for generation of the stereoscopic pairs. Graphic

image generation on a field-sequential stereoscopic CRT should be relatively free of this problem, although use of rotational stereo pair generation algorithms will produce vertical misalignment (Baker, 1987; Hodges, 1988; Lipton, 1988). Tolin (1987) estimated that vertical misregistration as small as 5 min of visual arc may produce double vision, viewing discomfort, and degraded stereopsis. Poggio and Poggio (1984) estimated this value to be in the range of 4 to 7 min of visual arc.

(5) Divergence. Stereo pair geometry should not require divergence of the eyes. Since the eyes normally assume a convergence angle of zero when focused at infinity, stereo pairs which require divergence of greater than 2 deg will produce visual discomfort (Vlahos, 1965).

User Interaction with 3-D Displays

The effective visual display of information in 3-D brings with it unique questions regarding user input and 3-D image manipulation (e.g., 3-D cursor control). A very limited number of performance studies have been conducted to evaluate the use of traditional 2-D and novel 3-D cursor control devices in the 3-D realm. Traditional pointing devices that might be used for 3-D manipulations include direct manipulation devices such as light pens and touch screens, and indirect pointing devices such as the mouse, trackball, joystick, and graphics tablet (Shneiderman, 1987).

Beaton, DeHoff, Weiman, and Hildebrandt (1987) and Beaton and Weiman (1988) evaluated several indirect 3-D pointing devices as either *vector-oriented*, *plane-oriented*, or *free-space* pointing devices. Speed of cursor positioning and positioning errors were recorded in a 3-D cursor positioning task. Participants moved a cursor (crosshair) to a single pixel target within a virtual stereoscopic cube. Required movements were either single vectors (X, Y, or Z) , plane movements (XY, XZ, or YZ), or free-space movements (XYZ). Similarly, participants used three different pointing devices, each device being used to accomplish all three types of cursor positioning (vector, plane, and free-space movements).

Vector-oriented devices were those which controlled 3-D cursor movement via the manipulation of three individual controls, one control for each axis. Plane oriented devices were used in any two spatial dimensions at one time, while a trackball was used as an example of a free-space cursor positioning device. Forward/backward and side-to-side movement of the trackball produced corresponding cursor movement in the XY plane. Movement in the apparent depth (Z) plane was accomplished by rotating the trackball on its vertical axis. Beaton et al. (1987; 1988) found that the vector devices supported superior performance (matched only by the mouse in XY motions) and motion in the Z axis was accompanied by both longer positioning times and a greater number of positioning errors.

A set of three rotating position dials was described by the Evans & Sutherland Corporation (1988) and is clearly vector-oriented. Some state-of-the-art 3-D pointing devices are free-space pointers. For example, Schmandt (1984) and Herman (1986) both discussed the use of a magnetic digitizer wand in virtual stereoscopic volumes. This direct pointing device is similar in use to that used by Wixson and Sloanne (1988) which uses infrared video sensors. The binocular infrared eyetracker has been proposed for 3-D cursor control (i.e., Wixson, Garrett, and Sinak, 1987) but remains problematic with currently available technology.

Perhaps the most novel interaction device for 3-D manipulations is the DataGlove (Ward, 1989). This device fits over the user's hand and translates movements of the hand's joints into digital control signals.

The Efficacy of Stereoscopic CRTs

The use of the stereoscopic CRT in commercial and military workstations is very new. To illustrate this novelty, a description of advanced flight stations of the 1990s by Bridges at the Lockheed-Georgia Company (Bridges, 1984) included plans for the use of virtual CRT heads-up displays (HUDs), but made no mention of stereoscopic CRT technology. Similar reports released only two years ago (Bridges and Reising, 1987a; 1987b) contain detailed discussion of the great potential benefit of stereoscopic display in the cockpit environment, but no formal testing had yet been accomplished. One of the earliest military applications of electronic stereoscopic displays is described by Lippert and Benser (1987). Trained photointerpreters were asked to estimate the position of a moving tank while viewing a video tape of forward looking infrared (FLIR) sensor imagery. This tape was displayed either monoscopically or stereoscopically (field-sequential). Participants were able to estimate when the fender of the tank was level with range markers with more accuracy in the stereoscopic presentation.

Performance comparisons using both standard 2-D CRTs and stereoscopic displays have been mixed. Smith and Gould (1964) reported that real-time stereoscopic CRT display was of no advantage beyond monocular CRT viewing for completion of a remote assembly task. On the other hand, Pepper, Cole, and Smith (1977) found that participants could manipulate a robot arm both faster and with fewer errors when using a stereo display.

Woodruff, Hubbard, and Shaw (1986) compared pilot simulator performance using two HMDs, a wide-field-of-view (FOV) CRT, and a stereoscopic CRT using PLZT goggles. The HMDS presented either the same image to each eye or incorporated horizontal disparity as a depth cue. Unlike the PLZT goggle arrangement which limited the maximum display luminance to approximately 14 cd/m^2, the stereoscopic HMD was capable of luminous output up to 68 cd/m^2. Participants flew a simulated aerial refuelling task. In addition to making depth estimations, pilots also completed the refuelling task while horizontal and vertical flight control deviations were measured. There were no significant differences between display groups in the ability to estimate when the participant's plane was at 25 or 50 m from the refuelling plane. However, significant differences between display groups were found in flight control deviations. Refuelling performance in terms of fore and aft control was superior for both stereoscopic display conditions. A slight advantage was found for the HMD over the PLZT goggle arrangement, which the authors attributed to the poor available contrast and the presence of flicker in the PLZT display. In summary, stereoscopic display provided a specific performance advantage, more so for the HMD display than the PLZT goggle display.

A similar display comparison between a stereoscopic HMD and a PLZT goggle display was carried out by Mountford and Somberg (1981). Pilots flew a brief simulated combat mission in a wire-frame visual environment and their speed of completion was recorded. The only performance difference between the display groups occurred when a difficult maneuver (barrel roll) was required. In this case, the task was accomplished faster by the PLZT display users. Pilot opinion favored the PLZT system, although pilots felt that if the HMD could be improved, it could be superior to the PLZT display.

Upon review of such comparison studies, a number of factors become evident which may contribute to the ambiguity of these comparisons. These factors may be categorized as display characteristics, task nature, methodology, stimuli, cues to flatness, and training factors.

Display characteristics. Contrast and resolution may be strong mediating factors in the effectiveness of depth information presented via electrooptical display systems (Buffett, 1980). Clearly, effective use of depth cues such as texture gradients and aerial perspective necessitates the use of a display capable of faithfully rendering large ranges of color, luminance, and spatial frequencies. In addition, if the stereoacuity of the average observer is to be fully exploited in the stereoscopic CRT, dramatic improvements in resolution and addressability will be required. Such improvements may be especially important in avoiding stereoscopic "jaggies" where stereoscopic gradients are displayed.

Although the discussion of electrooptic stereoscopic displays in this paper is limited to CRT applications, a variety of stereoscopic flat panel displays have been proposed (e.g., Balasubramanian, 1987; Miyashita, Uchida, and Nagata, 1987). Furthermore, many of the CRT-based stereoscopic displays discussed could easily be adapted to flat panel use. While flat panel displays typically fall short of CRT luminance, resolution, and off-axis viewability, the ability to manufacture miniaturized flat panel displays could have important application to direct-view stereo systems such as might be found in HMDs.

Task nature. Ambiguity is often found in the literature regarding the efficacy of stereoscopic displays because of the task dependent nature of this comparison. For example, Merritt (1984) used the example of an underwater remote salvage operation to illustrate a task which may be virtually impossible without binocular information. In the undersea environment, poor imaging conditions (e.g., very little natural light, murky water) often make familiar monocular cues unavailable. It is not difficult to imagine other situations, such as high altitude flight, where available cues to distance from another aircraft might be scarce (Morrison and Whiteside, 1984).

In the Smith and Gould (1964) study, participants completed their assembly task by monitoring their own arm over the closed-circuit video system, their arm being hidden by a curtain. The task involved little more than grasping pins out of a bin and plugging them into a pegboard. Not only were there significant proprioceptive and tactile cues involved in the completion of the task, but the task was so simple that it most likely could have been accomplished blindfolded with a minimal amount of practice.

The use of relatively sterile laboratory tasks for 2-D and stereoscopic display comparisons has been criticized (e.g., Merritt, 1983). In particular, measures such as speed of response are seen as not always fully reflective of the true stereoscopic advantages. Speed of response, however, is by no means an illegitimate performance measure for this type of display, especially for cockpit display applications in high speed vehicular control. As Mountford and Somberg (1981) pointed out, "Performing skilled airborne maneuver in a high speed dynamic combat environment largely depends upon an ability to identify a problem or solution quickly and to initiate appropriate responses quickly" (p. 235). This may be especially so in nap-of-the-earth (NOE) helicopter flight, where pilots rely primarily on out-the-canopy visual monitoring for low altitude terrain avoidance (Erwin, 1978).

Finally, it has been observed that performance measures in 3-D display comparisons may dissociate from subjective reports of depth sensation. For example, Lippert, Post, and Beaton (1982) found no overall difference in accuracy of depth judgements between 2-D and stereoscopic images, although a small increase in confidence of depth ratings was associated with use of the stereoscopic images.

Methodology. Another strong factor affecting the data base in this area of research has been the quality of the research design and the adequacy of research conclusions. For example, Erwin's (1978) suggestion that "the perception and reaction to three-dimensionality takes 600-800 ms" (p. 84) is a rather bold statement, especially in light of the enormous constraints of his design. This particular conclusion was based on 24 trials for each of two participants in a choice reaction time task.

One methodological factor which should be obvious but which may be overlooked is relative image quality between the 2-D and 3-D presentations. Merritt (1988) noted that, whenever possible, the same display device should be used to present both the 2-D and 3-D images. Similarly, since many field-sequential stereoscopic CRTs provided greater vertical addressability when operating in the monoscopic display mode, 2-D comparison images should be presented in stereoscopic mode.

Stimuli. Merritt (1984; 1988) made an excellent point when he called attention to the fact that stereopsis may not only help an observer to determine *where* an object is in depth, but may also aid in determining *what* an object is. Stereopsis may be of special benefit for object recognition in a display containing visual noise, where separation of figure from background is difficult. Laboratory studies using simple, familiar objects may not capitalize on the advantage of figure-ground separation that stereoscopic images may provide (Merritt, 1983).

The number of stereoscopic stimuli presented at one time may also have an influence on performance. Nakayama and Silverman (1986) extended Treisman's work on simple and conjunctive visual search to include the coding dimension of binocular disparity. According to Treisman, visual search for targets which are identified on single stimulus dimensions may occur in a rapid, parallel search while targets identified by the conjunction of two or more dimensions must be searched for in a more time consuming serial fashion (Treisman and Gelade, 1980; Treisman, Sykes, and Gelade, 1977). Evidence for these different search strategies is usually taken from the slope of the function of reaction time and set size (the number of possible targets). Simple or parallel searches usually yield very low slopes while conjunctive or serial searches yield higher slopes.

Nakayama and Silverman (1986) presented participants with a visual search task using target sets identified by either color, motion, color and motion, stereo and color, or stereo and motion. The number of possible targets ranged from 25 to 35. The simple search functions for motion and color both yielded slopes approximating zero, as hypothesized. Similarly, the conjunctive search for the combination of motion and color yielded a characteristically high slope for conjunctive search, as well as an elevated y-intercept. Surprisingly, the search functions for both conjunctive searches which incorporated a stereo coding dimension closely resembled those of the simple searches, suggesting that these searches were conducted in parallel. However, these results may not apply to search tasks where small target set sizes are used. For example, Staller, Lappin, and Fox (1980) noted that response times for identification of random dot stereogram targets increased as a function of target set sizes, where set sizes of 1, 2, 3, and 4 items were used.

Cues to flatness. The use of viewing hoods or testing in darkened rooms may also affect the relative efficacy of 3-D cues, since the presence of a frame around a scene may alter its perceived three-dimensionality. For example, the presence of a luminous frame at the phosphor plane appears to enhance the apparent depth in a scene, unless objects presented in crossed disparity intersect this frame. When this occurs, the frame appears to pull the object from viewer space into CRT space. Similarly, close viewing distances may be problematic since any visible texturing of the CRT screen will be in disagreement with the displayed depth in the scene and convergence and accommodation will be in conflict. Braunstein (1976) called these factors *cues to flatness* and suggested the use of viewing distances greater than 6 ft (1.8 m).

Training. The adequacy of participant training may have a strong bearing on the presence or absence of a stereo advantage. Pepper et al. (1983) reported that a stereo advantage for telemanipulator positioning found with highly practiced participants was significantly diminished when the experiment was replicated with naive participants.

Earlier, Williams (1966) demonstrated that the accuracy of stereoscopic photointerpretation could be improved through training by as much as 40% and Gould (1964) found that while performance did not improve as a function of daily intra-session practice on a remote, stereoscopic tracking task, performance did improve across daily sessions.

Summary

Known depth cues were classified as monocular (or pictorial) cues or binocular cues. The relative strengths and weaknesses of these cues were discussed, with special attention given to horizontal disparity. While all of the depth cues can provide at least modest amounts of depth information in a display, it was shown that a considerable number of questions remain regarding display effects associated with the use of multiple depth cues. In particular, possible interactions in the use of multiple depth cues remain to be empirically described.

Next, it was suggested that individual differences in spatial ability could be related to the perception of 3-D displays. The MRT was described as one tool by which spatial ability can be operationally defined. While MRT scores appear to be related to fusion times for RDS stimuli, the degree to which spatial ability influences performance in more sophisticated stereoscopic task environments is unclear. Similarly, it is unclear if previously found gender differences in spatial ability will be present in these new task environments.

Finally, a large number of approaches to the display of 3-D were described, and details concerning electronic stereoscopic CRTs were discussed. While the development of these technologies has proceeded at a very rapid pace, important questions regarding user interaction and the relative efficacy of such displays remain unanswered. Of particular importance is the identification of stimulus and task properties which are likely to be associated with the most effective use of electronic stereoscopic displays.

RESEARCH OBJECTIVES

The broadest goal of this research program was the establishment of empirically based guidelines to direct engineering implementations of modern stereoscopic display systems. These guidelines were established by assessing the need, appropriateness, and expected outcomes of using the field-sequential stereoscopic CRT in a variety of representative contexts. In the summary of the literature, three research areas related to the use of stereoscopic displays were identified as meriting further investigation.

The first topic of importance concerned the use of singular and multiple depth cues. One of the goals of this research program was to illustrate any possible interactions among multiple depth cues, as well as to describe the relative efficacy of these cues when implemented singularly. In order to effect such a comparison, it was necessary to identify those depth cues which could be meaningfully manipulated in an orthogonal fashion. In addition, it was desirable to choose depth cues which were likely to have a potent and reliable effect on the perception of apparent depth. Based on these criteria and the literature review, the monocular depth cues of luminance contrast, relative size, and interposition were chosen. The binocular depth cue of horizontal disparity was also selected, since disparity is a critical parameter in the use of field-sequential stereoscopic displays.

Next, it was decided that the generality of the primary results should be tested. That is, the nature of the relationships among these depth cues should be examined for change among a variety of stimulus and task parameters. A consideration of prior research indicated that performance advantages for stereoscopic displays were especially sensitive to such changes. Therefore, a variety of tasks and stimuli were selected for this research. The tasks are relative depth judgements, image quality judgements, visual search, and cursor positioning. Stimuli included simple geometric figures as well as more geometrically complex symbols.

Finally, the third objective of this research was related to the suggestion that individual differences in spatial ability could be related to the perception of 3-D displays. It was shown in the literature review that MRT scores appear to be related to fusion times for RDS stimuli, and that significant gender differences may exist in spatial ability. The MRT was selected for measurement of spatial ability in this research. The objective was to test the robustness of the relationship between fusion time and spatial ability, as well as to investigate possible gender differences for both spatial ability and performance on stereoscopic tasks.

These three research objectives are restated below:

1. Determine the relative impacts of pictorial depth cues, binocular disparity, and the factorial combinations of these cues on performance and subjective image quality;
2. Establish which task environments and classes of visual stimuli might be most favorably impacted, both in terms of performance and subjective image quality, by stereoscopic display technology; and
3. Assess the degree to which a measure of spatial ability and gender are related to individual differences in stereoscopic task performance.

These objectives were addressed by conducting three experiments. The initial experiment was conducted to measure response time and accuracy advantages for the factorial combinations of stereopsis and three monocular depth cues in a relative depth judgement task. A second experiment was executed to investigate further the subjective value of the various depth cues and the possibility that a task-demand (objective vs.

subjective) discrepancy existed in the utility of stereoscopic depth cues. Experiment 3 extended the results of Experiments 1 and 2 by incorporating visual search and cursor positioning in the context of a horizontal situation display (HSD).

The importance of this research is underscored by the fact that while technological advances have been made in the field of stereoscopic display, very few usability data exist either from laboratory testing or from the implementation of such displays in operational systems. This research provides information to complete cost/performance benefit analyses for 3-D display designs which could in turn significantly impact industry acceptance of the field-sequential stereoscopic CRT.

APPARATUS AND EXPERIMENTAL ENVIRONMENT

The apparatus and general experimental environment remained consistent among all three experiments, with any exceptions noted here. The testing environment is diagrammatically summarized in Figure 14, and is the subject of the following discussion.

Apparatus

Display system. All stimuli were presented via a Tektronix SGS 620 Stereoscopic 3-Dimensional Graphics Display System. The system was composed of a 19-inch (diagonal) Trinitron color CRT, a 19-inch (diagonal) LC modulator (LCM), and passive stereo-viewing glasses (Figure 15). The CRT operated at 62.25-KHz horizontal and 120-Hz vertical scan rates (60-Hz field-refresh rate for monoscopic viewing and 120-Hz field refresh rate for stereoscopic viewing). The monitor displayed a maximum of 1280 pixels horizontally and 1024 horizontal lines using a P22 phosphor. In the stereoscopic mode, only 512 lines were available due to the doubling of the field-refresh rate.

The LCM was bezel-mounted directly over the CRT faceplate and controlled the circular polarization sense of the CRT image. The modulator was composed of two LC π-cells, horizontally joined in the middle of the modulator. While the π-cell activation time was only 0.2 ms, 2 ms were required to return the cells to the nonactive state. The system was field-sequential, such that left and right image fields were alternately presented in time, one every 1/120 s. For example, at any given time, t, the CRT image was polarized in either a clock-wise or counter clock-wise direction by the LC π-cells (Figure 16). The image was then viewed by either the left or right eye, depending on the polarization sense of the image and the polarization sense of the passive viewing glasses. At time t + 1 /120 s

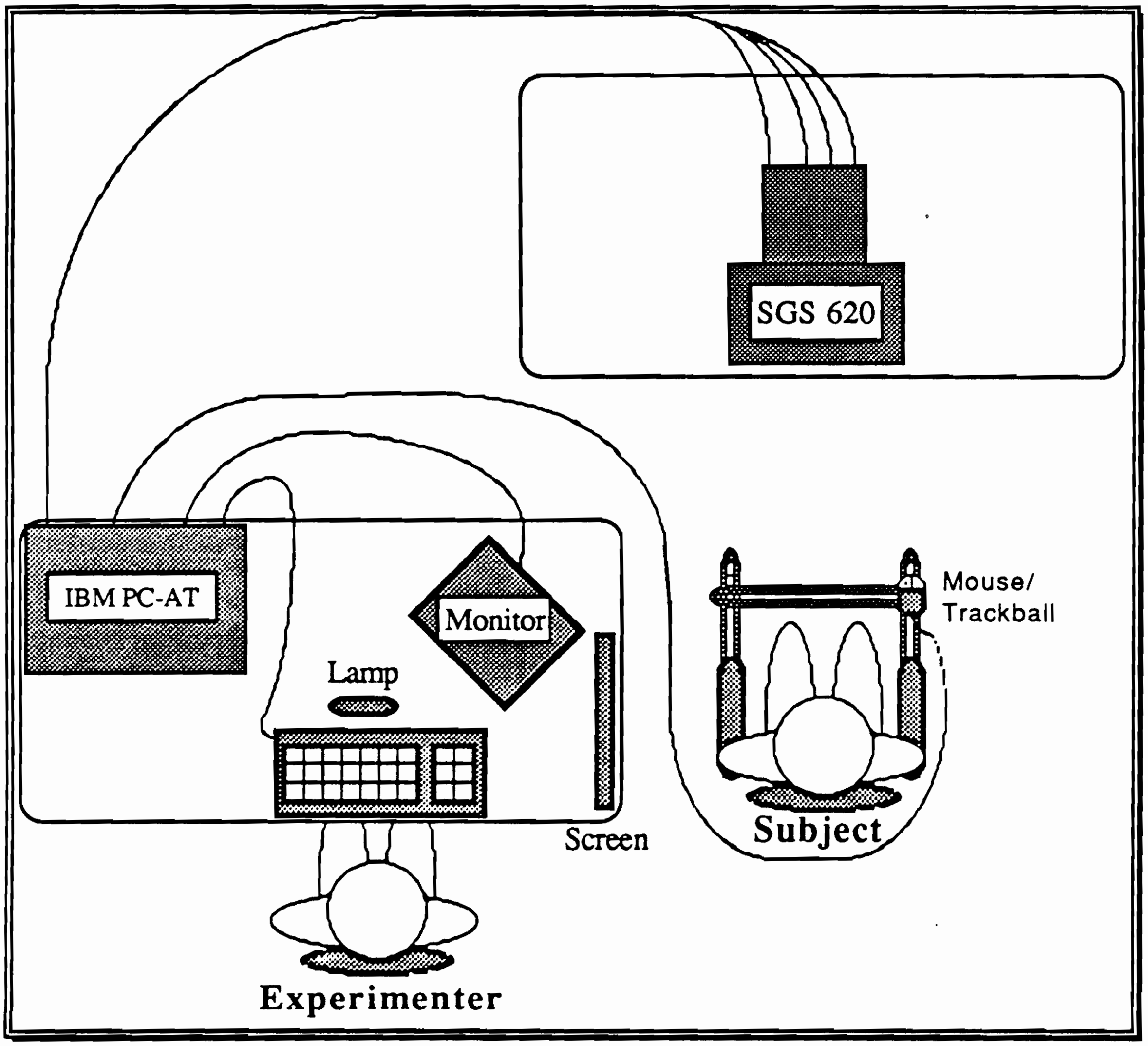


Figure 14. Schematic of the experimental environment. In Experiments 1 and 2, the experimenter recorded the participant's verbal responses, while response times were automatically registered via a mouse switch. In Experiment 3, the mouse was replaced by a trackball pointing device and all data were input via this device.

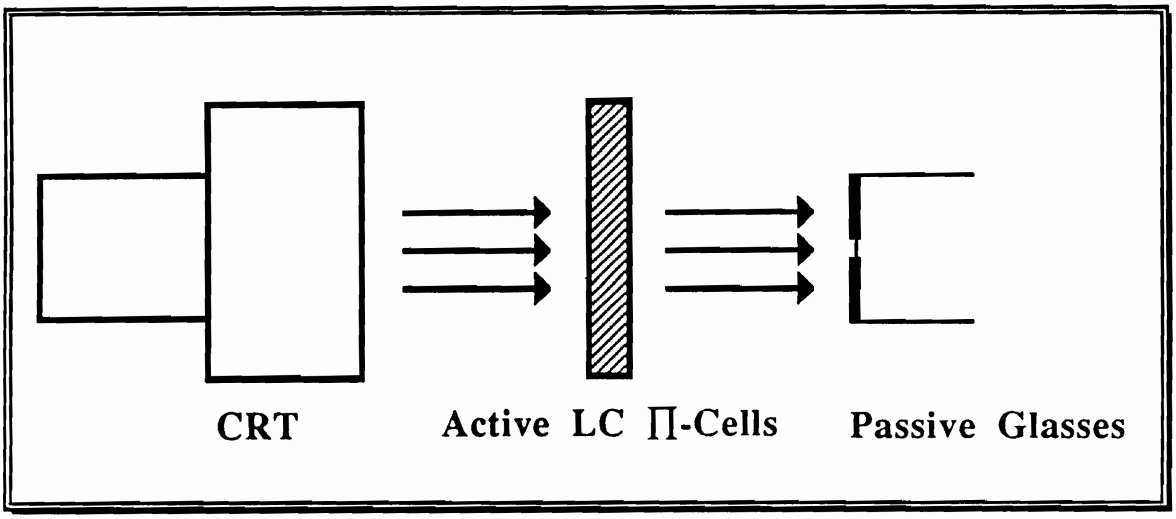


Figure 15. The three principal components of the Tektronix SGS 620 Stereoscopic 3-Dimensional Display System.

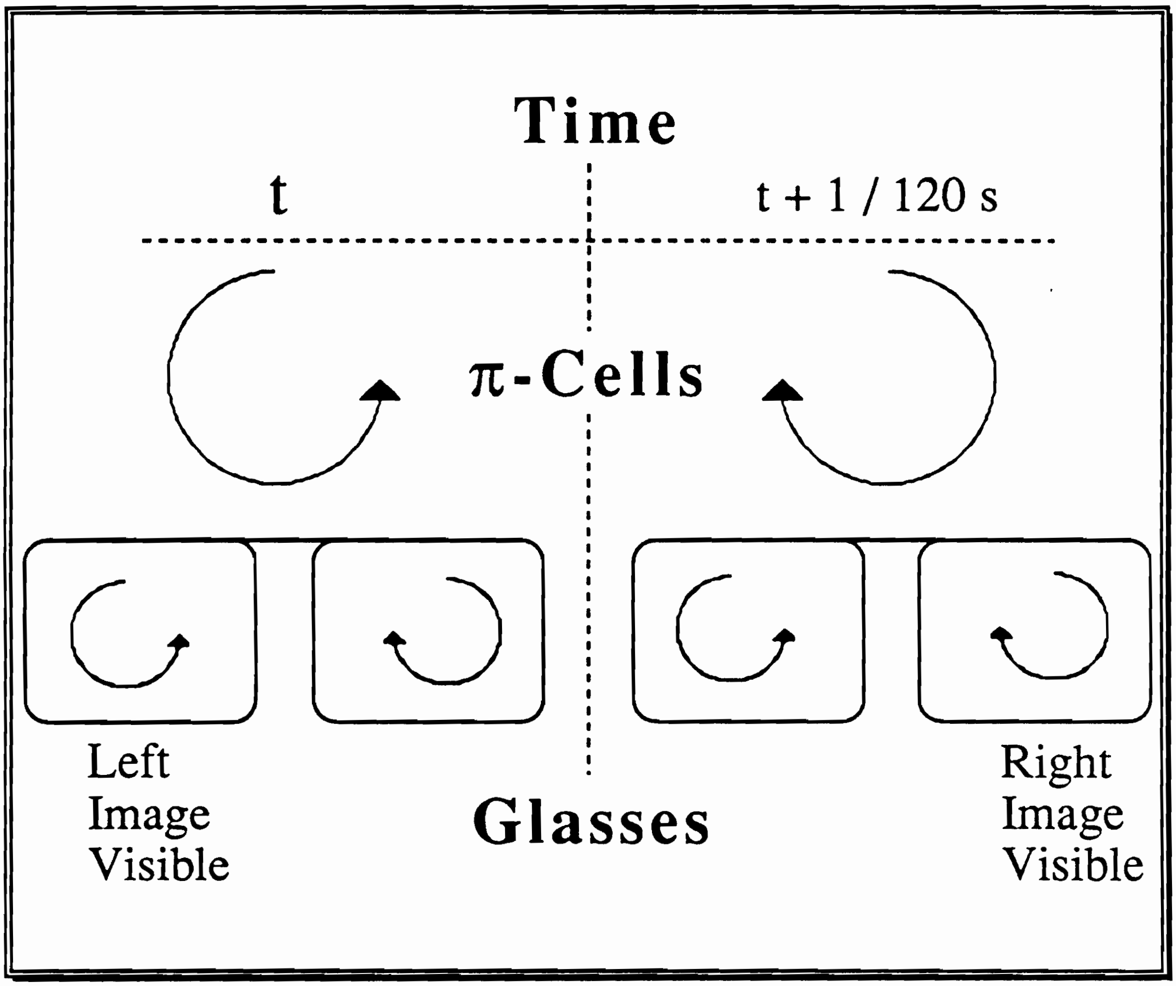


Figure 16. Field-sequential stereoscopic display. Left and right image fields are alternately displayed every 1 / 120 s.

the alternate (left or right) image was displayed, the polarization sense of the LC π-cells changed, and the image was visible to the alternate eye. Because a very high field rate was used with the monitor in the stereo mode (120 Hz), the two π-cells were multiplexed in such a way as to minimize optical crosstalk between the alternating left and right channels (Tektronix, 1988). The stereo-viewing glasses used circularly polarized, plastic lenses. The LCM was driven by an IBM PC-AT fitted with a Tektronix Stereoscopic Graphics Adapter card.

The optical leakage of the stereoscopic system has been previously described as a function of π-cell uniformity (Beaton, 1989). Beaton's leakage measurements were taken at 16 points along the vertical dimension of the LCM, with half of the measurements falling on either side of the split line dividing the two π-cells (Figure 17). The leakage ratio was defined to be the luminance of the *off* field divided by the luminance of the *on* field, with measurements taken through the appropriate viewing lenses and LCM. Leakage ratios were greatest approaching the bottom of each π-cell (Figure 18). In addition, leakage ratios were approximately four times smaller for red light than for blue light. To minimize perceptible ghosting, the red CRT electron gun was used in exclusion of the blue and green guns in Experiments 1, 2, and 3.

Input devices. Participant responses in Experiments 1 and 2 were registered via a Microsoft mouse switch. The mouse was fastened to a flat aluminum bar extending from the arm of the participant's chair. This bar was attached to the chair arm which corresponded to the participant's preferred hand. The position of the mouse on the bar was adjustable to accommodate a variety of forearm lengths. In experiment 3, the mouse was replaced by a Microspeed FastTrap tri-axis pointing device (Figure 19). This pointing device was composed of a trackball (for X-Y cursor positioning), a thumbwheel (for Z (depth) cursor positioning), and three buttons, the middle button being used by participants

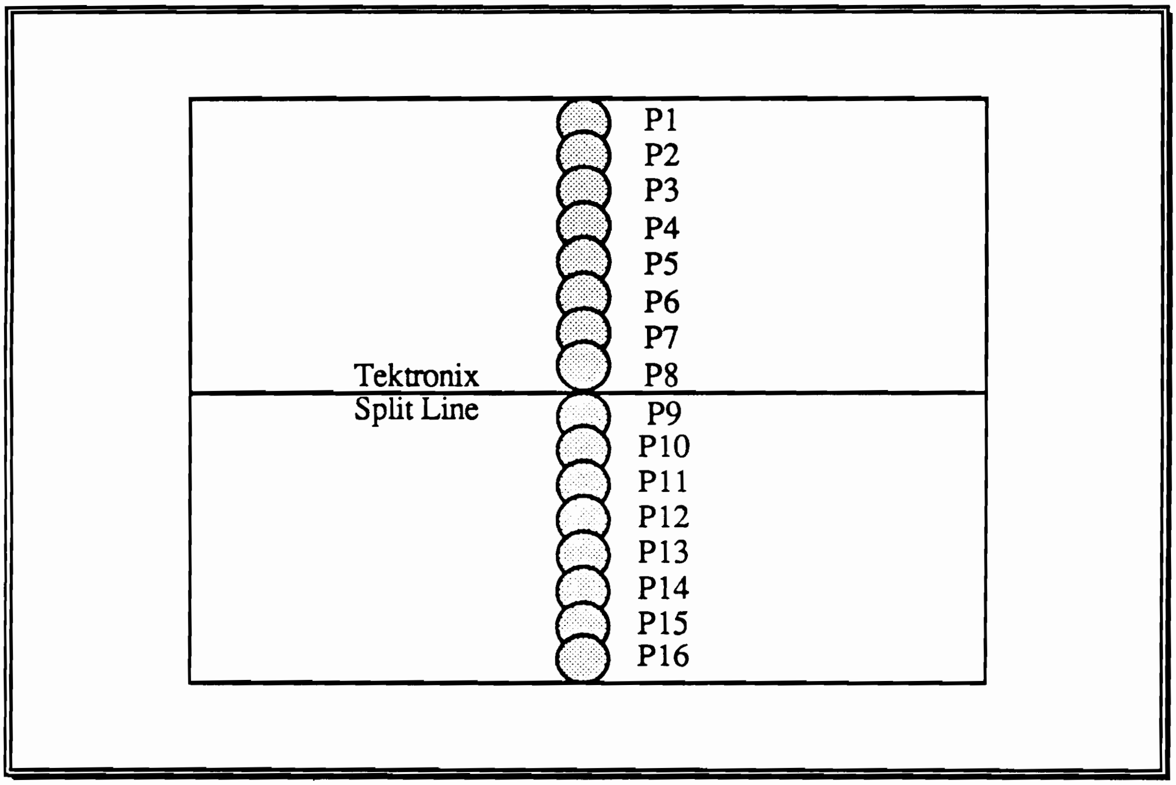


Figure 17. Measurement positions used for leakage uniformity test. The split line refers to the joining of two separate liquid crystal π-cells. From Beaton (1989), reprinted with permission from the author.

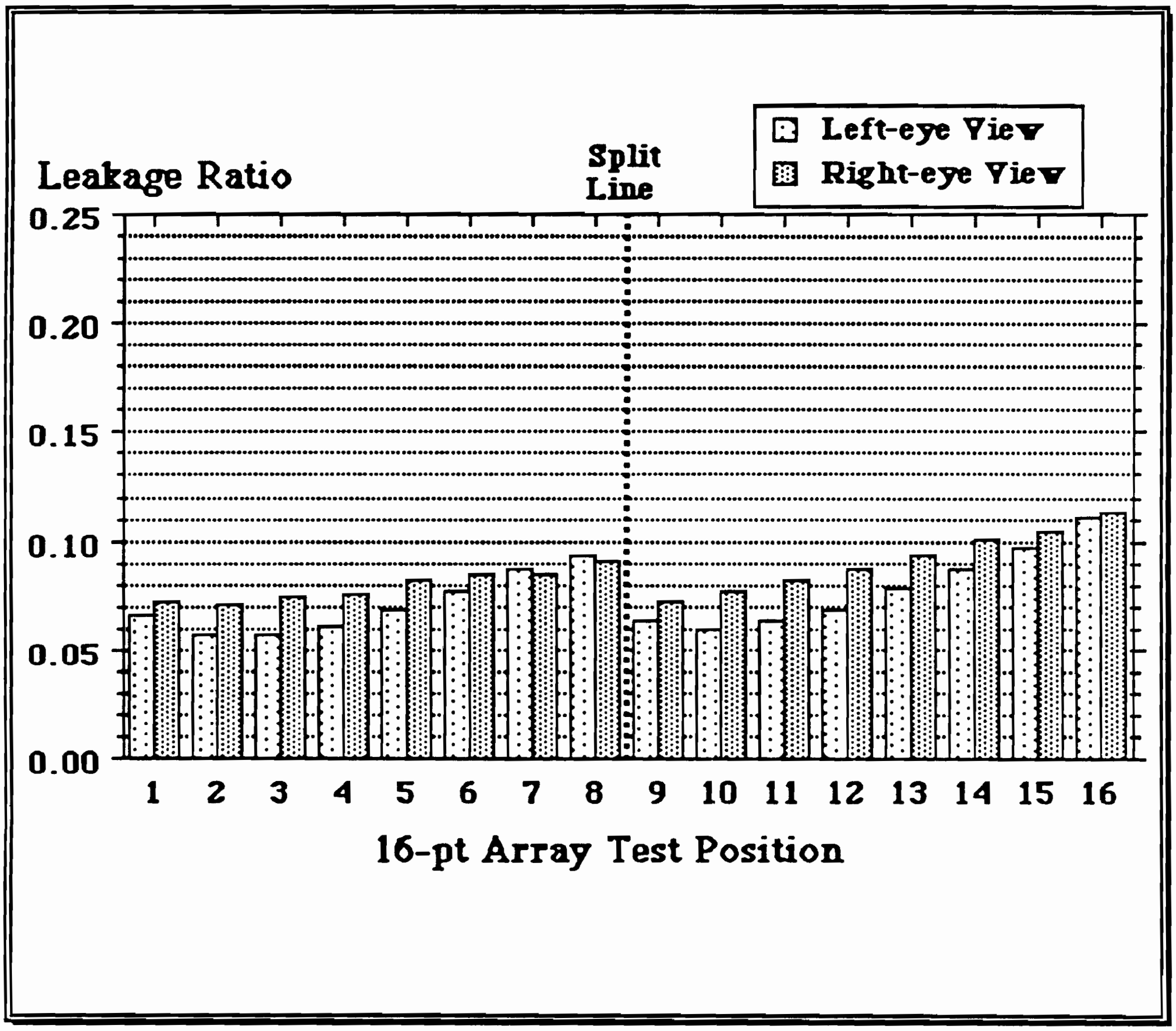


Figure 18. Leakage ratio as a function of test position. From Beaton (1989), reprinted with permission from the author.

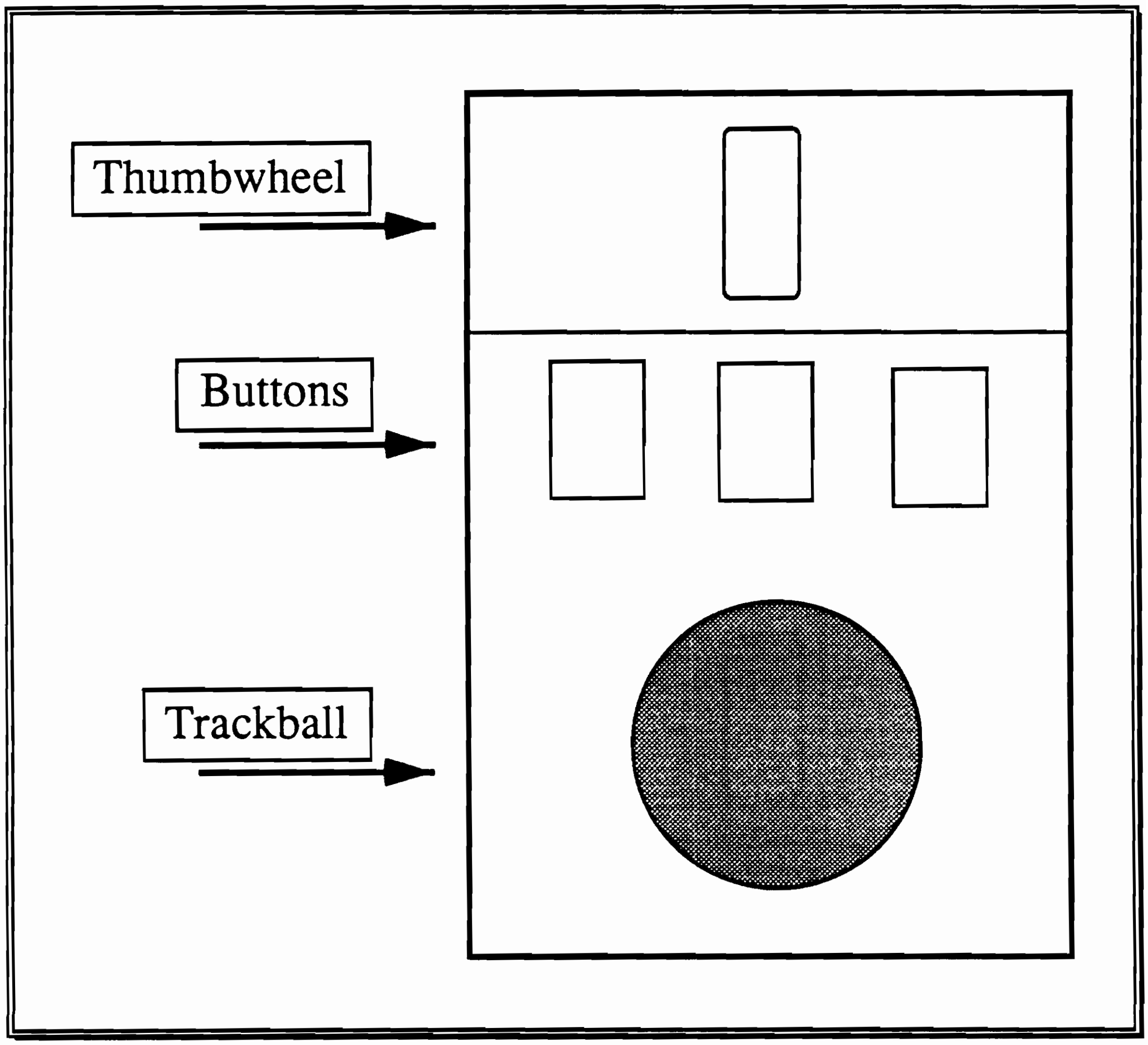


Figure 19. Microspeed FastTrap tri-axis pointing device used in experiment 3. Participants used the trackball for X-Y cursor movements, the thumbwheel for Z (depth) cursor movements, and the middle button for trial advancement.

to advance trials. An additional aluminum crossbar was used (Figure 14) to allow participants two degrees of freedom in their placement of the pointing device. Participants operated the trackball with their preferred hand, and the button and thumbwheel with their nonpreferred hand. In all three experiments, a Data Translation 2806 real-time clock card was used in the IBM PC-AT to capture response times with a 1-ms resolution.

Stimulus Generation

In the monoscopic display mode, the Tektronix system provided double the number of horizontal display lines as compared with the stereoscopic mode. Consequently, all stimuli were presented using the stereoscopic display mode. By using the stereoscopic display mode but incorporating no binocular disparity in the images, monoscopic viewing was accomplished without confounding the treatment effects with differences in the number of horizontal lines. In addition, by requiring participants to wear the passive polarizing glasses for all display conditions, inadvertent changes in the display luminance among display conditions were avoided. Stimulus images were constructed using the Microsoft C Optimizing Compiler (Version 5.10) and Tektronix SGS 620 graphic routines.

Viewing Environment

Participants were seated in a fully darkened room with the monitor positioned slightly below eye level at a distance of approximately 90 cm. The elevation of the participant's chair was adjusted to maintain a constant eye height relative to the center of the CRT. At this eye height, the visual line of sight was declined approximately 30 deg and was perpendicular to the CRT faceplate. The experimenter sat behind and to the left of the participant. A darkened room was used to eliminate first and second surface reflections on the LCM surface and the faceplate of the CRT. Tektronix (1988) recommends operating this display in a darkened room and it was thus assumed that a darkened room was representative of a typical viewing environment. Participants wore either full-frame stereo-viewing glasses or clip-on lenses, as appropriate. During the training trials, a small lamp remained on to allow participants to read the printed instructions.

EXPERIMENT 1

As previously discussed, one of the principal objectives of this research was the comparison of singular and multiple implementations of depth cues. To accomplish this objective, it was necessary to identify those depth cues which could be meaningfully manipulated in an orthogonal fashion. The monocular depth cues of luminance contrast, relative size, and interposition were chosen as cues which were likely to meet this criterion. These cues were also seen as being likely to have a potent and reliable effect on the perception of depth. The binocular depth cue of horizontal disparity was also selected, since it is a critical parameter in the use of field-sequential stereoscopic displays.

It was recognized that the relative effects of these four depth cues would depend on their relative magnitudes. Since one of the objectives of experiment 1 was to validate the use of these depth cues for subsequent research, the decision was made to use suprathreshold values for depth cue manipulations. The use of suprathreshold cue manipulations was expected to yield two significant advantages. First, it should have allowed the assumption of saliency for all stimulus changes. Second, assuming the magnitudes of stimulus change were far enough above threshold, ceiling effects should have been found in the resulting data. This second point is of particular importance, since it was critical to learn whether each of the four depth cues could be fruitfully applied in subsequent research. If no significant effects were apparent at suprathreshold cue levels, it should then be a generally fair assumption that threshold manipulations would be of no effect as well. Note, however, that upper bounds to this assumption do exist. For example, if a sufficiently large amount of stereo disparity were introduced between image fields, it would become impossible to fuse them and impossible to properly perceive the resulting stereoscopic image. Noting that such upper bounds existed, cue magnitudes were selected which produced a high degree of saliency without perturbing normal visual appreciation of the stimuli.

Once again, a principal objective of Experiment 1 was the clear demonstration of cue effects. For this reason, a simple task and relatively simple stimuli were chosen. If the depth cues could be validated, they could be tested in more complex environments in subsequent experiments. The experimental task was designed to represent the most simple form of relative depth judgement which might be made with a stereoscopic display; participants simply identified the relative ordering of three stimuli which occupied three separate apparent depth planes. Similarly, planar geometric stimuli were selected which were easily identified and possessed a small number of sides. These stimuli had uniform color, a black border, and no texture.

Finally, it was earlier suggested that individual differences in spatial ability could be related to the perception of 3-D displays. McGuinness and Brabyn (1984) have shown that spatial ability may be related to fusion times for RDS stimuli. There is also reason to believe that these differences may be related to gender, with males typically scoring higher on tests of spatial ability. The MRT (i.e., Vandenberg and Kuse, 1978) was selected to test the robustness of the relationship between fusion time and spatial ability, as well as to investigate possible gender differences for both spatial ability and performance on stereoscopic tasks.

The specific hypotheses tested in this experiment were:

1. The individual use of Luminance, Size, Interposition, and Disparity cues should have allowed faster target identification, with fewer errors, relative to display conditions which contained no depth information;

2. The use of multiple depth cues should have produced complementary effects. That is, the fastest response times and the most error-free performance should have occurred in responses to stimuli which incorporated all four depth cues;
3. MRT scores could have been correlated with response times and error rates; and
4. MRT scores and task performance could have been superior for male participants.

Method

Participants. Ten subjects (five males and five females, 18 to 29 years of age) participated in this experiment. Participants were recruited through campus flyers and were paid $15.00 for participation in the experiment. All participants were required to pass a two-part screening procedure. Participants were first screened for near and far visual acuity as well as lateral and vertical phoria with a Bausch and Lomb Master Ortho-Rater. Criteria for this test were a normal or corrected monocular Snellen acuity (near and far) of at least 20/22 in both eyes and phoria scores within approximately the central 70th percentile. Visual phoria is a measure of the tendency of the eyes to turn away from each other in the absence of a stimulus to fusion. Eleven candidate-participants failed to meet one or more of these criteria and 13 were accepted, 3 of whom were subsequently dropped from the experiment for failure to meet training criteria.

Participants were next screened for contrast sensitivity, both near and far, with the Vistech Vision Contrast Test System. Circular patches of sine-wave luminance modulation were presented at five contrast levels and at spatial frequencies of 1.5, 3, 6, 12, and 18 c/deg. The criteria for these tests were based on the upper 90th percentile from a normal population described by the Vistech Consultants, Inc. Contrast sensitivity is normally correlated with visual acuity, and no participants who passed the Ortho-Rater procedure failed to meet the contrast sensitivity criteria.

Experimental task. The dependent variables used were response time (the total elapsed time between stimulus presentation and switch closure) and total errors. Triads of solid planar geometric figures (a circle, square, and triangle) were displayed (Figure 20). The figures were presented at different apparent depths, placed according to the appropriate depth cues being used in each trial. Participants were to determine, as quickly as possible without making an error, which figure was the target. Specification of the target was accomplished by presenting one of the following questions to the participants prior to stimulus presentation:

1. Which figure is the farthest away?;
2. Which figure is the middle figure?; or
3. Which figure is the closest figure?

Design. The experimental design was a 2 x 2 x 2 x 2 full-factorial design and all independent variables with the exception of Gender were within-subjects variables. There were four replications of each of the 16 experimental conditions. In addition, each depth cue combination was presented for each of the three target locations (i.e., closest, middle-most, and farthest figure in apparent depth). Therefore, each participant contributed 192 observations. Trials were presented in a randomized order, nested within replications (48 trials per replication, 16 trials per target position per replication). In addition to Gender, the following independent variables were included in the design.

(1) Size (two levels). The display did or did not incorporate relative size cues for indication of apparent depth (Figure 21). In the Size condition, closer figures were appropriately larger in angular subtense. Stimulus sizes ranged from 46 to 152 min of

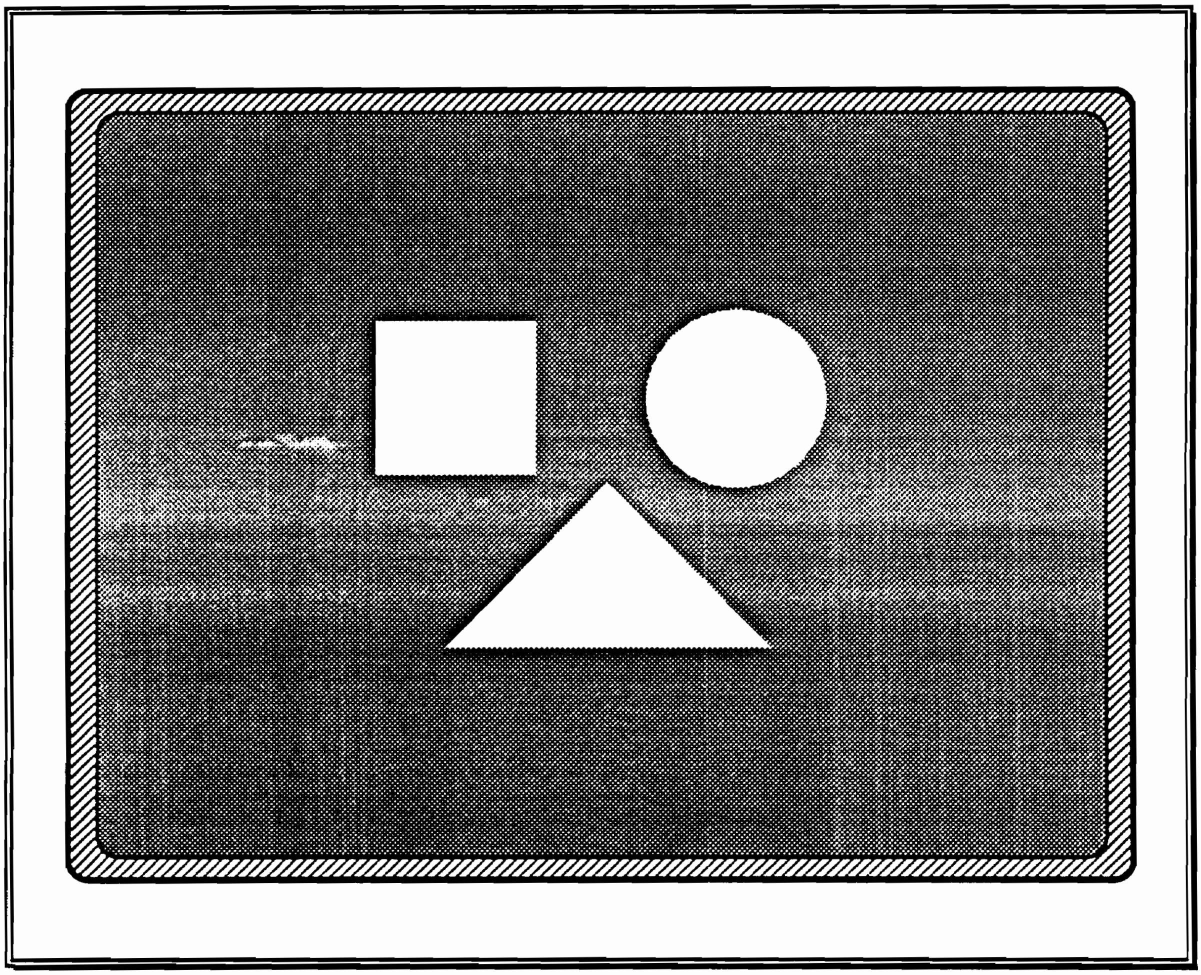


Figure 20. Experimental stimuli with no depth cues applied, Experiments 1 and 2.

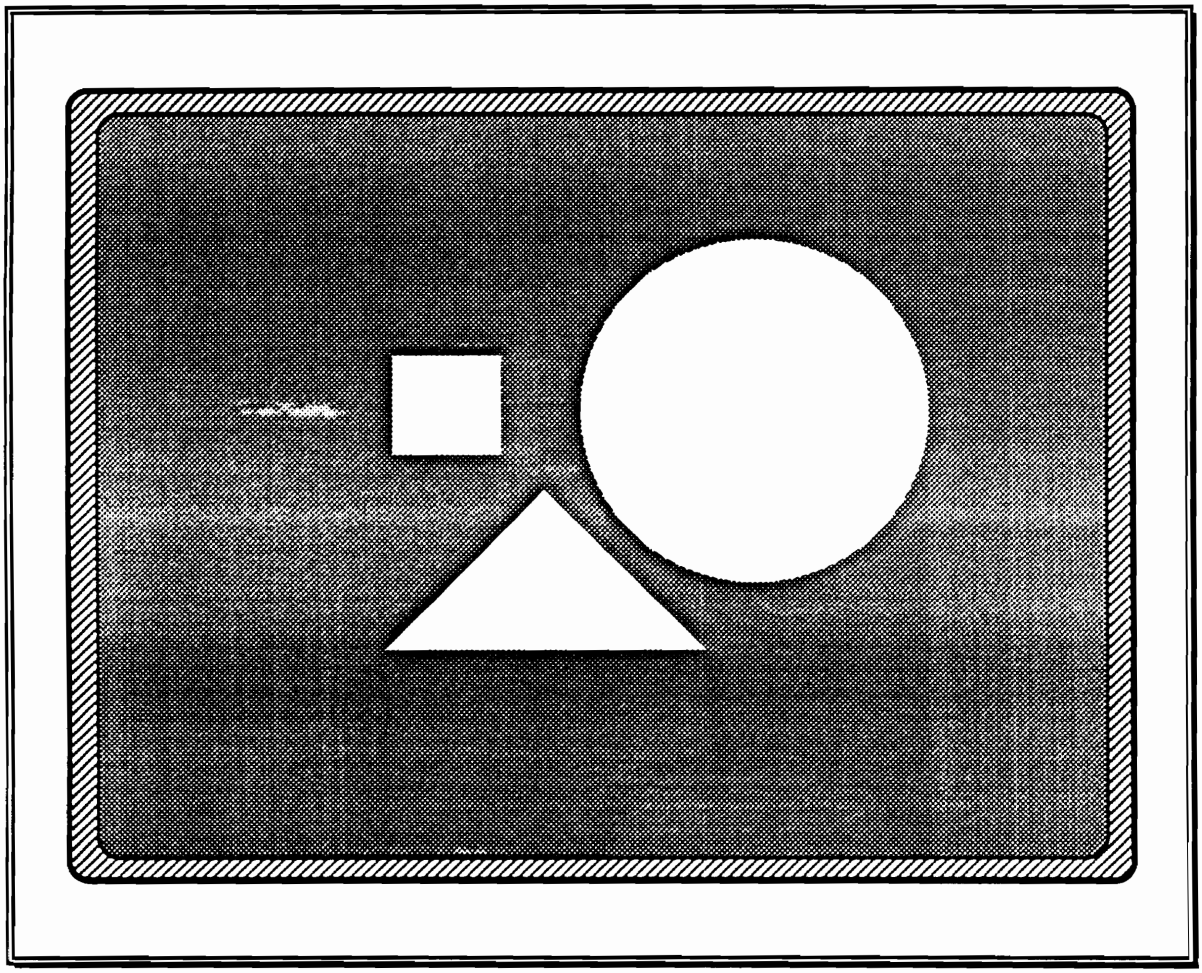


Figure 21. The relative sizes of stimuli, Experiments 1 and 2.

visual arc (Table 2). These stimulus sizes were selected though informal pilot testing to represent subjectively equal depth intervals.

(2) Interposition (two levels). The display did or did not incorporate interposition (overlap) cues for indication of apparent depth (Figure 22). In the Interposition condition, the three figures produced hidden surfaces (overlap), where hidden surfaces were indicative of a position of greater apparent depth. Approximately 30% of occluded figure areas were hidden.

(3) Luminance (two levels). The displayed image did or did not incorporate luminance cues for indication of apparent depth. In the Luminance condition, closer figures had a proportionally greater luminance. The background luminance of the monitor as well as the average luminance and chrominance of the various stimuli were measured with a Minolta CS-100 spot chrominance meter (Table 3). Chrominance is given in CIE (1931) chromaticity coordinates. The color of stimuli was that produced by the CRT with the red CRT electron gun on in exclusion of the blue and green electron guns. These luminance values were selected though informal pilot testing to represent subjectively equal depth intervals. The transmissivity of the LCM and stereo viewing lenses were approximately 35% each, such that approximately 12% of the CRT luminance reached the observer's eyes.

(4) Binocular disparity (two levels). The display did or did not incorporate binocular disparity cues for indication of apparent depth. In the Disparity condition, one figure was positioned at each of crossed, uncrossed, and zero parallax. Horizontal disparity values were approximately 12 min of visual arc (6 pixels, or approximately 2 arcmin per pixel at the viewing distance of 90 cm). These disparity values were selected though informal pilot testing to represent subjectively equal depth intervals.

TABLE 2

Screen Height (mm) and Angular Subtense (Degrees and Minutes of Visual Arc) of Experimental Stimuli

	Circle[1]	*Square*[2]	*Triangle*[3]
Small	13	12	13
	49'	46'	49'
Medium	26	24	27
	1° 38'	1° 31'	1° 43'
Large	39	36	40
	2° 28'	2° 17'	2° 32'

[1] Size of vertically measured diameter.

[2] Length of vertical sides.

[3] Distance from base to apex.

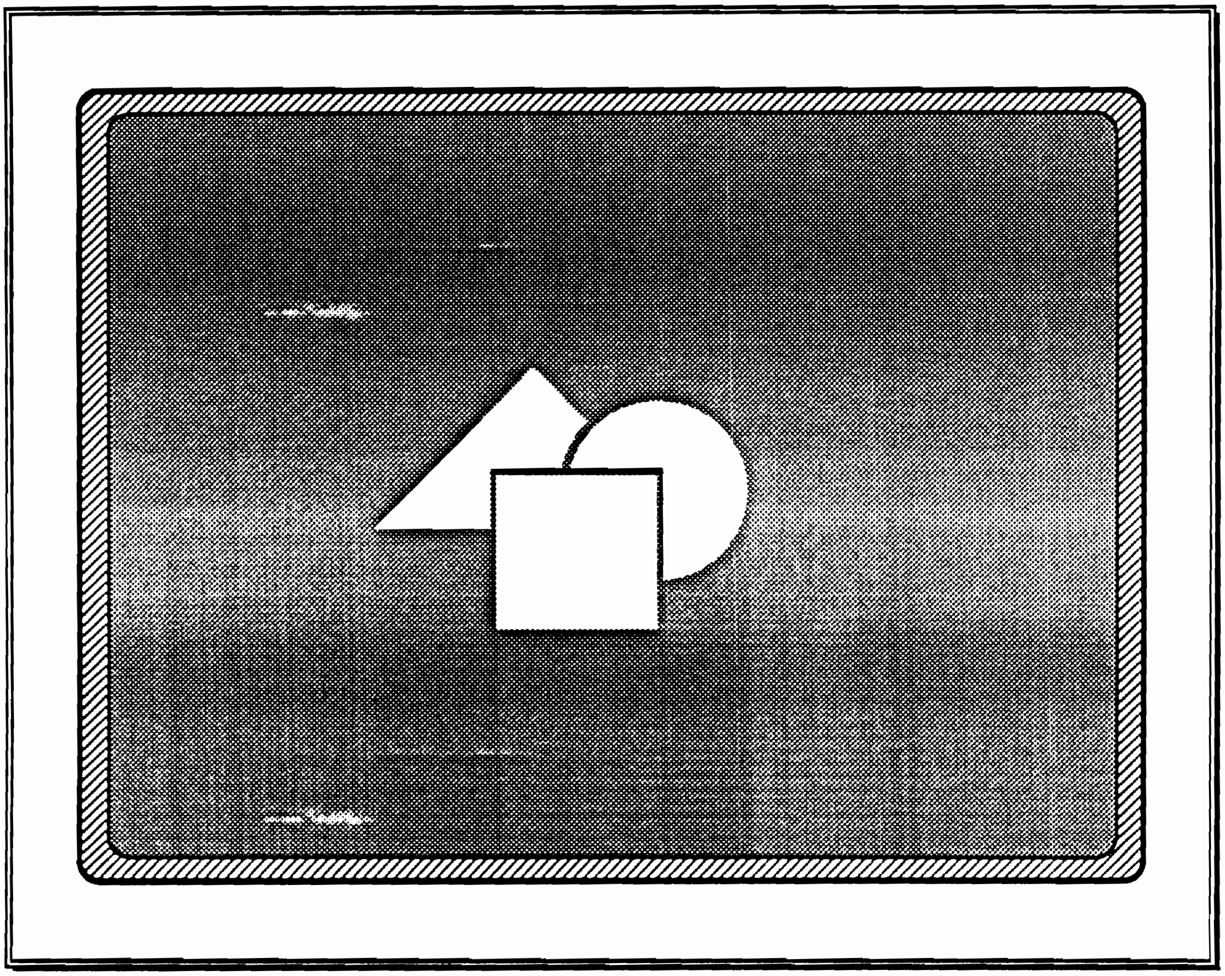


Figure 22. Interposition of stimuli, Experiments 1 and 2.

TABLE 3

Background CRT Luminance (cd/m^2) and Luminance and Chrominance (CIE x , y) of Experimental Stimuli

	CRT [1]	*LCM* [2]	*LCM and Glasses* [3]	
Background	< 0.1	< 0.1	< 0.1	cd/m^2
Far	3.2	1.1	0.4	cd/m^2
	.604	.596	.560	x
	.343	.344	.338	y
Middle	8.7	3.0	1.2	cd/m^2
	.608	.605	.598	x
	.347	.347	.351	y
Near	17.4	6.2	2.3	cd/m^2
	.608	.608	.601	x
	.347	.347	.352	y

[1] Luminance and chrominance values without LCM or polarizing glasses.

[2] Luminance and chrominance values with the LCM.

[3] Luminance and chrominance values with the LCM and polarizing glasses.

Procedure. (1) Informed consent. All participants read and signed informed consent forms which outlined the benefits, risks, and rights associated with participation in the screening procedure and the experiment (Appendix A).

(2) Training. As was previously noted, individual differences may exist in the ability to fuse stereo pairs. Since it was believed that these differences can in part be mitigated through training, all participants received approximately 30 min of practice on representative tasks to established criterion levels for speed and accuracy of performance. Training was conducted on the same day as the experimental trials and commenced no later than two weeks following administration of the visual screening procedure. All instructions (Appendix B) were read aloud by the experimenter as the participant read along. During the initial training, participants simply viewed three representative triads of figures for each experimental depth cue, as well as an example of figures incorporating none of the depth cues. Participants were given detailed explanations of the meaning of each of the four depth cues. This phase of the training was informational only, and no responses were recorded.

The second phase of training involved the presentation of the same geometric triads, grouped according to each of the four depth cues. Participants were required to identify the correct apparent depth order of each set of figures, from closest to farthest from the participant. These trials were conducted to ensure that participants were fully conversant with the use of the depth cues in the experiment. Participants were instructed to respond as accurately as possible, without regard for speed of response, and were provided with detailed feedback following any error. This feedback detailed the nature of their error as well as the correct response. Presentation of trials in each cue group was preceded by five practice trials, after which participants were presented trials until correctly responding to five consecutive trials. Failure to meet this criterion within 30 trials would have resulted in a repetition of the entire training phase. Failure to meet this criterion a second time would have led to participant dismissal. No participants failed to meet this training criterion.

During the final training phase, each trial was preceded by the display of one of three possible questions:

1. Which figure is the farthest away?;
2. Which figure is the middle figure?; or
3. Which figure is the closest figure?

After reading the question, participants controlled trial presentation by pressing and holding down the mouse button with their preferred thumb to view the figures. After releasing the button, the screen was blanked and the participant gave a vocal response to the experimenter. When no depth cues were present, participants responded by saying, "no depth cues." Participants were instructed to respond as quickly as possible without making an erroneous response.

Participants were provided with detailed feedback following any error. Presentation of trials in each cue group was preceded by five practice trials, after which participants were presented trials until correctly responding to five consecutive trials. Failure to meet this criterion within 30 trials resulted in a repetition of the entire training phase. Failure to meet this criterion a second time resulted in participant dismissal. Participants were given a five-min rest break following the completion of these training trials.

Three male participants failed to meet the final training criterion, and an additional male participant required a second exposure to the training phase to meet criterion. These participants experienced difficulty in responding to the stereo images rapidly and accurately. Review of their experiences suggested that a critical difference between participants may include not only stereoacuity per se, but also the time with which binocular fusion may be accomplished. This observation is consistent with those of Patterson and Fox (1984), who found tachistoscopic stereo presentations to present more difficulty for participants than presentations which were relatively unlimited in duration.

Upon termination of the training, these three participants were reexamined with the Ortho-Rater for visual acuity and phoria. Their scores were within the criteria used in this experiment and there did not appear to be any relationship between the inability of the participants to meet the training criteria and their visual screening scores. This observation is also in agreement with those of Patterson and Fox (1984), who found that stereoanomolous participants did not differ from stereo-normal participants on Ortho-Rater scores of vertical phoria, lateral phoria, monocular acuity, and binocular acuity.

(3) Experimental trials. The experimental trials proceeded in the same manner as the final training trials. However, no feedback was given during the experimental trials and no response criteria were administered. The experimental trials were preceded by a five-min visual adaptation phase, during which participants viewed a figure triad with no depth cues, presented at the median experimental luminance value. Participants were given a five-min rest break following completion of one-half of the experimental trials (96 trials) and again after completing the balance of the experimental trials. The entire experimental procedure required approximately 45 min to administer.

(4) Subjective evaluation. Following the completion of experimental trials, participants were administered the 3-D Questionnaire (Appendix C). This instrument was used to assess the participant's experience of a variety of symptoms of discomfort on a 10-point scale, where a rating of 1 indicated no discomfort and a rating of 10 indicated intense discomfort. In addition, the questionnaire included a cue-effectiveness scale. This 10-point scale was used to asses the degree to which participants believed each of the four

depth cues assisted them in completing their experimental task, with a rating of 1 indicating no effectiveness and a rating of 10 indicating great effectiveness.

(5) Mental Rotations Test. The MRT was included as the final assessment instrument in the experiment (Appendix D). As discussed in the background material, this instrument provides a validated measure of spatial ability. The test is made of two sections, each section including 10 problems. Following completion of the instructions and practice figures, participants were allotted three min to complete each of the two sections.

Results

Response time. All data were analyzed using the Statistical Analysis System (SAS) on an IBM 3090-300 computer. Response time data were collapsed across replications and target positions and submitted to a five-factor ANOVA (Luminance x Size x Disparity x Interposition x Gender). Three main effects are statistically significant (Table 4): Luminance (p = .0172), Interposition (p = .0008), and Size (p = .0032). In general, responses were faster in the presence of Luminance (Figure 23), Interposition (Figure 24), and Size cues (Figure 25). It is important to note that there is no statistically significant main effect of Disparity (mean response time without Disparity = 1011 ms, mean response time with Disparity = 1008 ms, p = .97), nor are there any statistically significant interactions with the Disparity factor.

Three two-way interactions are statistically significant: Size x Interposition (p = .0063), Luminance x Interposition (p = .0126), and Luminance x Size (p = .0327). Post-hoc simple-effect F-tests were conducted to determine more precisely where the significance is located in these interactions (Appendix E, Tables E-1 through E-3). Responses were significantly different in the presence of the Size cue, but only in the

TABLE 4

ANOVA Summary Table for Response Time (ms), Experiment 1

Source	*df*	*MS*	*F*	*p*
Gender (G)	1	1685410.39	1.98	.1977
Subjects (Gender) (S(G))	8	854240.13		
Luminance (L)	1	3656520.12	8.97	.0172
L * G	1	25250.63	0.06	.8098
L * S(G)	8	407816.97		
Interposition (I)	1	9311285.03	27.67	.0008
I * G	1	7507.60	0.02	.8850
I * S(G)	8	336497.16		
Size (Sz)	1	5809551.92	17.15	.0032
Sz * G	1	24144.94	0.07	.7962
Sz * S(G)	8	338689.80		
Disparity (D)	1	382.34	0.00	.9731
D * G	1	387860.20	1.23	.3002
D * S(G)	8	316104.61		
L * I	1	3706222.20	10.24	.0126
L * I * G	1	2372.88	0.01	.9374
L * I* S(G)	8	361858.17		
L * Sz	1	2527491.83	6.64	.0327
L * Sz * G	1	14150.14	0.04	.8519
L * Sz * S(G)	8	380448.39		
L * D	1	180286.57	0.70	.4285
L * D * G	1	215001.13	0.83	.3891
L * D * S(G)	8	259267.63		
I * Sz	1	4287303.01	13.47	.0063
I * Sz * G	1	2814.01	0.01	.9274
I * Sz * S(G)	8	318227.47		
I * D	1	20074.13	0.06	.8064
I * D * G	1	337043.70	1.08	.3297
I * D* S(G)	8	312924.00		
Sz * D	1	53753.34	0.22	.6491
Sz * D * G	1	158445.16	0.66	.4405
Sz * D * S(G)	8	240569.62		

TABLE 4 (continued)

ANOVA Summary Table for Response Time (ms), Experiment 1

Source	*df*	*MS*	*F*	*p*
L * I * Sz	1	2216016.40	6.42	.0350
L * I * Sz * G	1	20547.33	0.06	.8133
L * I * Sz * S(G)	8	345006.07		
L * I * D	1	22747.93	0.42	.5343
L * I * D * G	1	401835.43	1.38	.2728
L * I * D * S(G)	8	291042.32		
L * Sz * D	1	196385.19	0.93	.3630
L * Sz * D * G	1	135169.69	0.64	.4466
L * Sz * D * S(G)	8	211025.16		
I * Sz * D	1	58083.45	0.22	.6483
I * Sz * D * G	1	124945.82	0.48	.5068
I * Sz * D * S(G)	8	258763.19		
L * I * Sz * D	1	134946.94	0.65	.4448
L * I * Sz * D * G	1	105781.23	0.51	.4970
L * I * Sz * D * S(G)	8	208936.04		
Total	159			

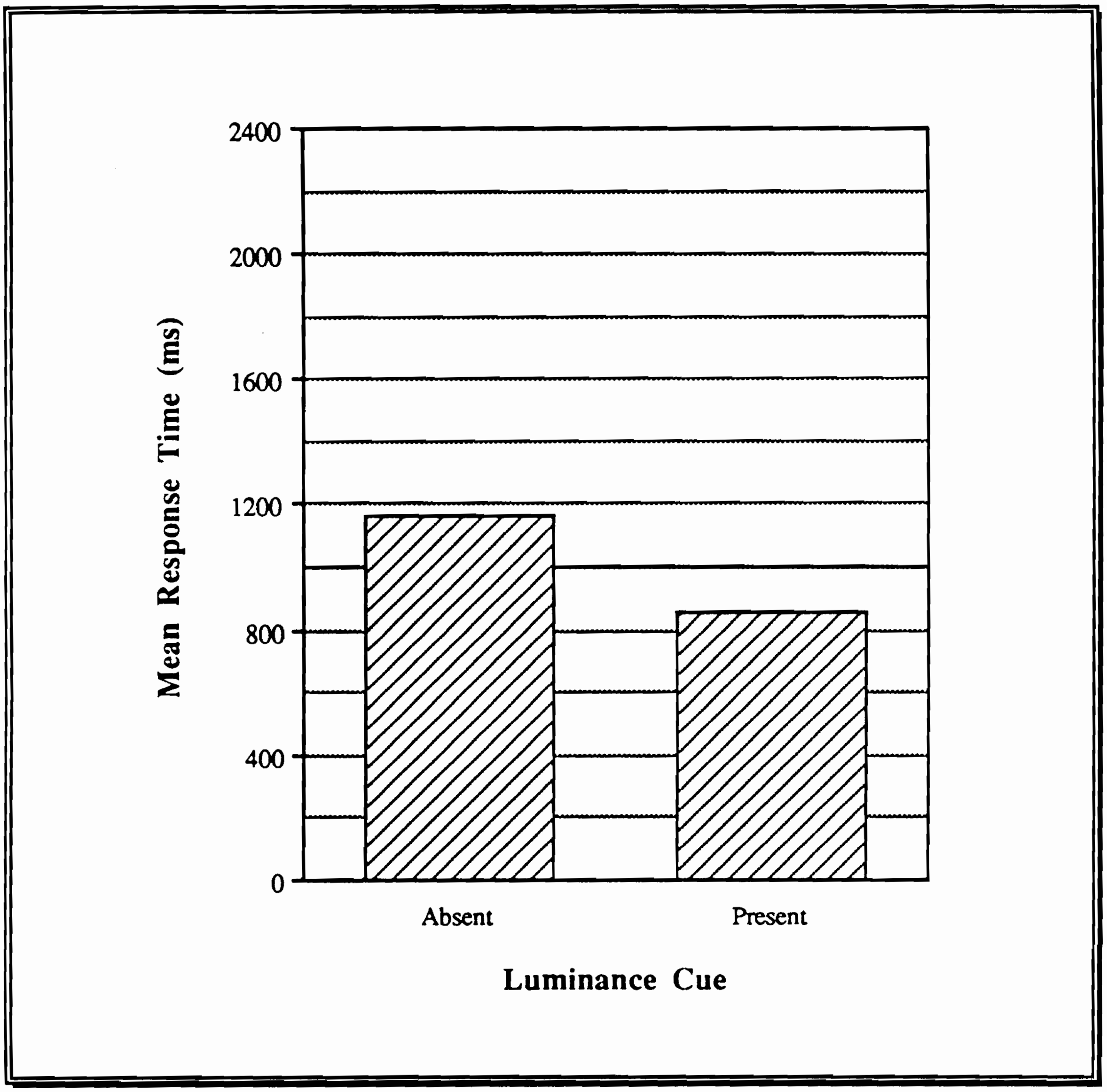


Figure 23. Mean response time as a function of Luminance cue, Experiment 1.

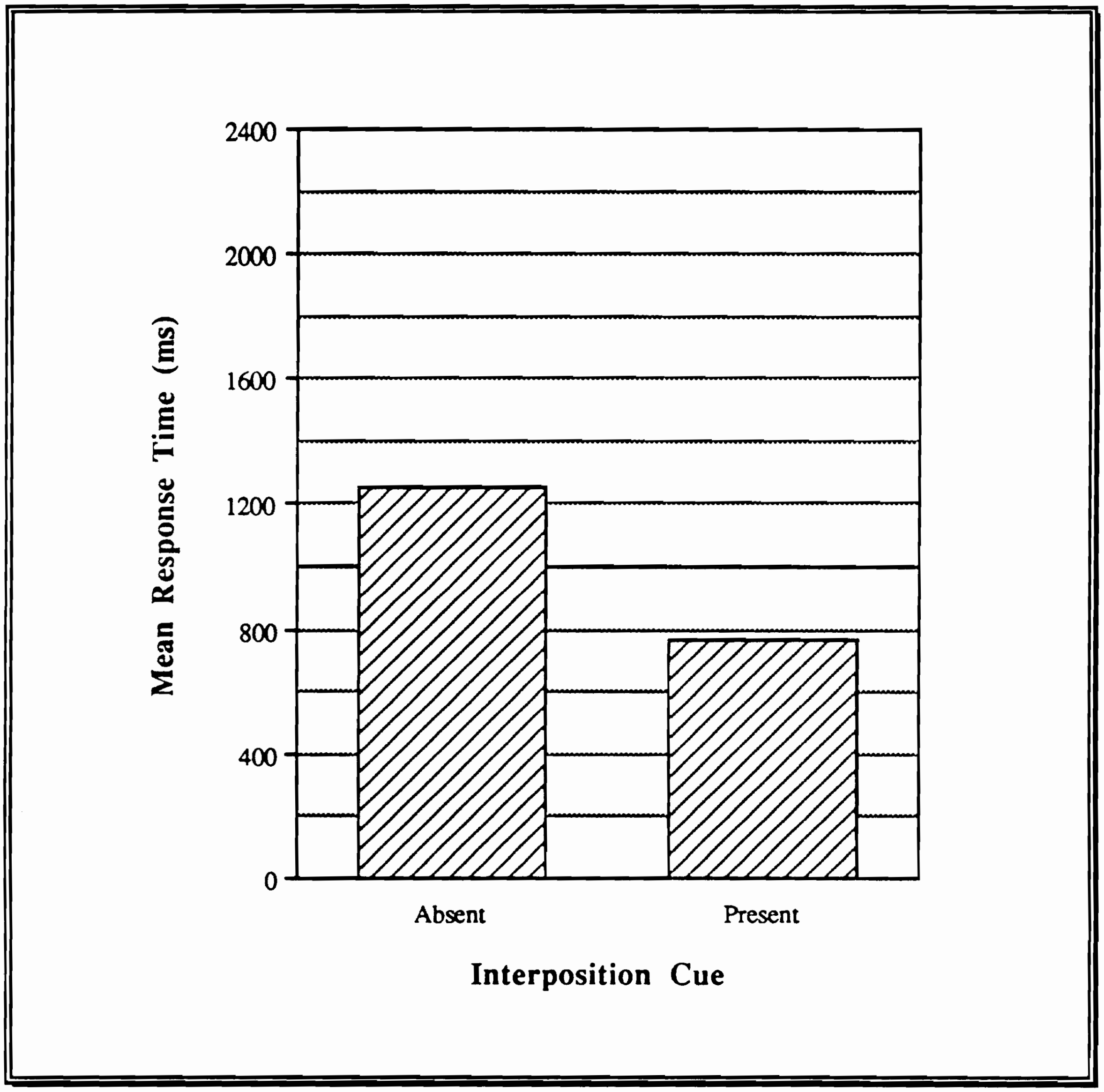


Figure 24. Mean response time as a function of Interposition cue, Experiment 1.

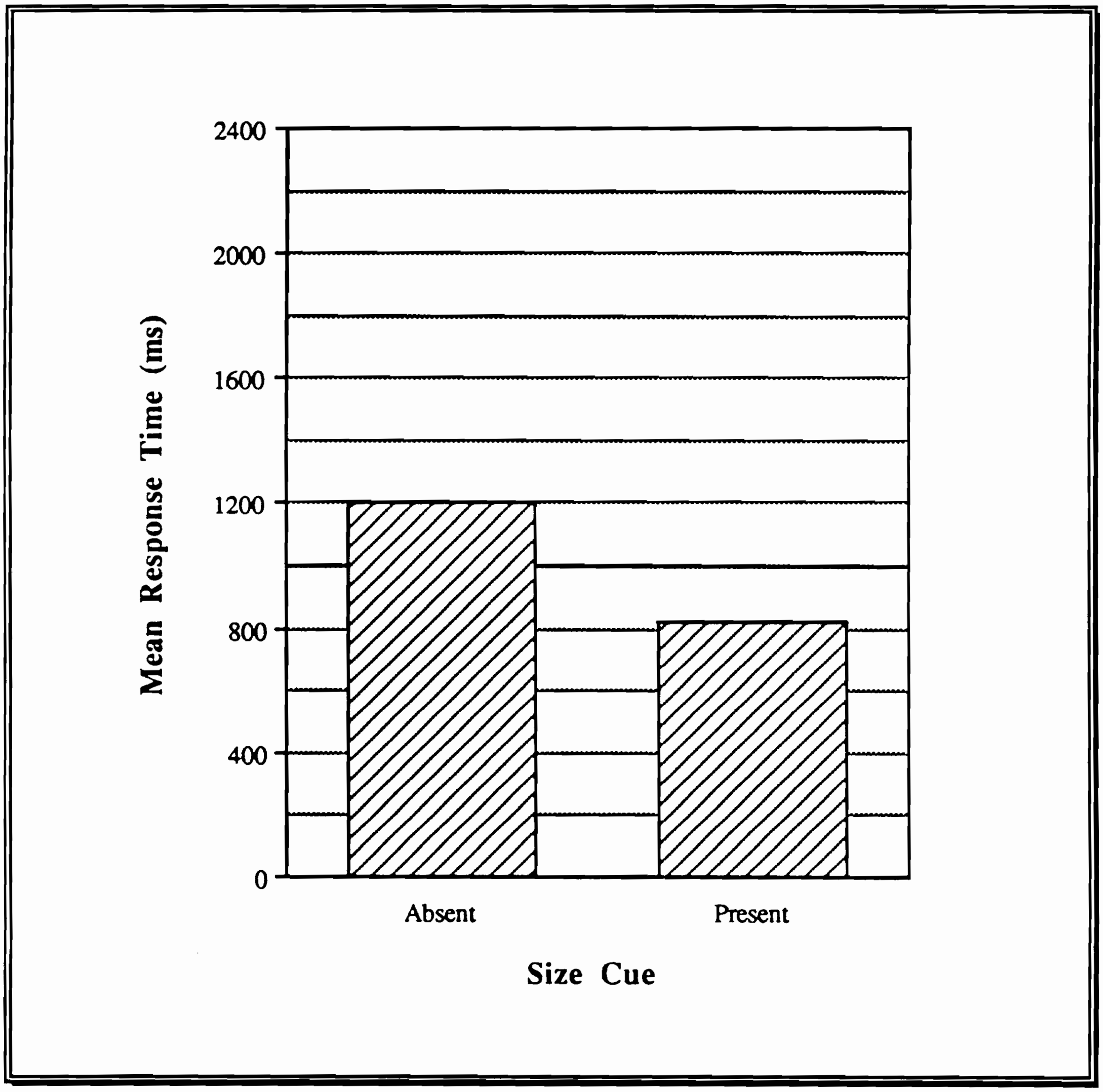


Figure 25. Mean response time as a function of Size cue, Experiment 1.

absence of the Interposition cue (Figure 26). Responses were significantly different in the presence of the Luminance cue, but only in the absence of the Interposition cue (Figure 27) and in the absence of the Size cue (Figure 28).

A more complete description of these interactions may be found by considering the statistically significant three-way interaction (Figure 29) of Luminance x Interposition x Size ($p = .0350$). Post-hoc simple-effect F-tests were conducted to determine more precisely where the significance is located in this interaction (Tables E-4 and E-5). Response times were significantly different as an interaction of Size and Luminance cues, but only in the absence of the Interposition cue. Within this interaction, and in the absence of the Interposition cue, the effect of Luminance is significant.

Errors. Error rates are low, with an overall error percentage of 1.5%. Error data were collapsed across replications and target positions and submitted to a five-factor ANOVA (Luminance x Size x Disparity x Interposition x Gender). Two main effects (Size, $p = .0503$, and Luminance, $p = .0704$), one two-way interaction (Interposition x Luminance, $p = .0402$), and one three-way interaction (Luminance x Interposition x Size, $p = .0685$) are statistically significant or near statistical significance (Table 5). Because these error effects represent such a small proportion of the total experimental trials, they are not discussed in detail here. The interested reader will find illustrations of these effects in Appendix F (Figures F-1 through F-4).

3-D Questionnaire. Mean ratings were computed for questionnaire items 1(a) through 2(d). Although the data are arguably only ordinal in nature, recent statistical simulations have indicated that parametric statistical procedures which make means comparisons of ordinal data are often as reliable as, and sometimes more reliable in terms of Type I and Type II errors than, comparable nonparametric techniques (Gregoire and Driver, 1987; O'Brien, 1979). Examination of mean responses to items 1(a) through 1(f)

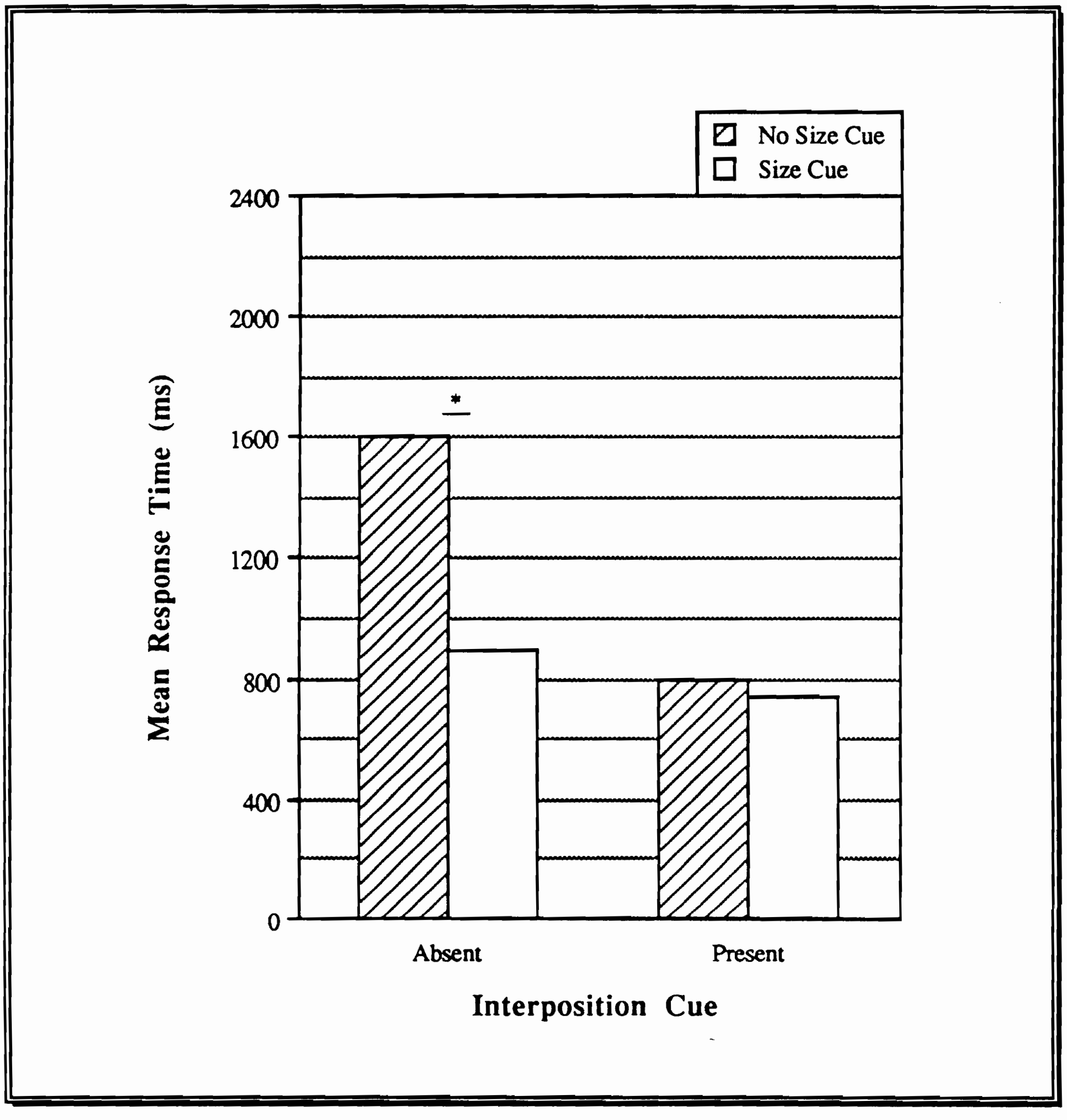


Figure 26. Mean response time as a function of Interposition and Size cues, Experiment 1. Asterisk indicates mean difference at $p \leq .05$.

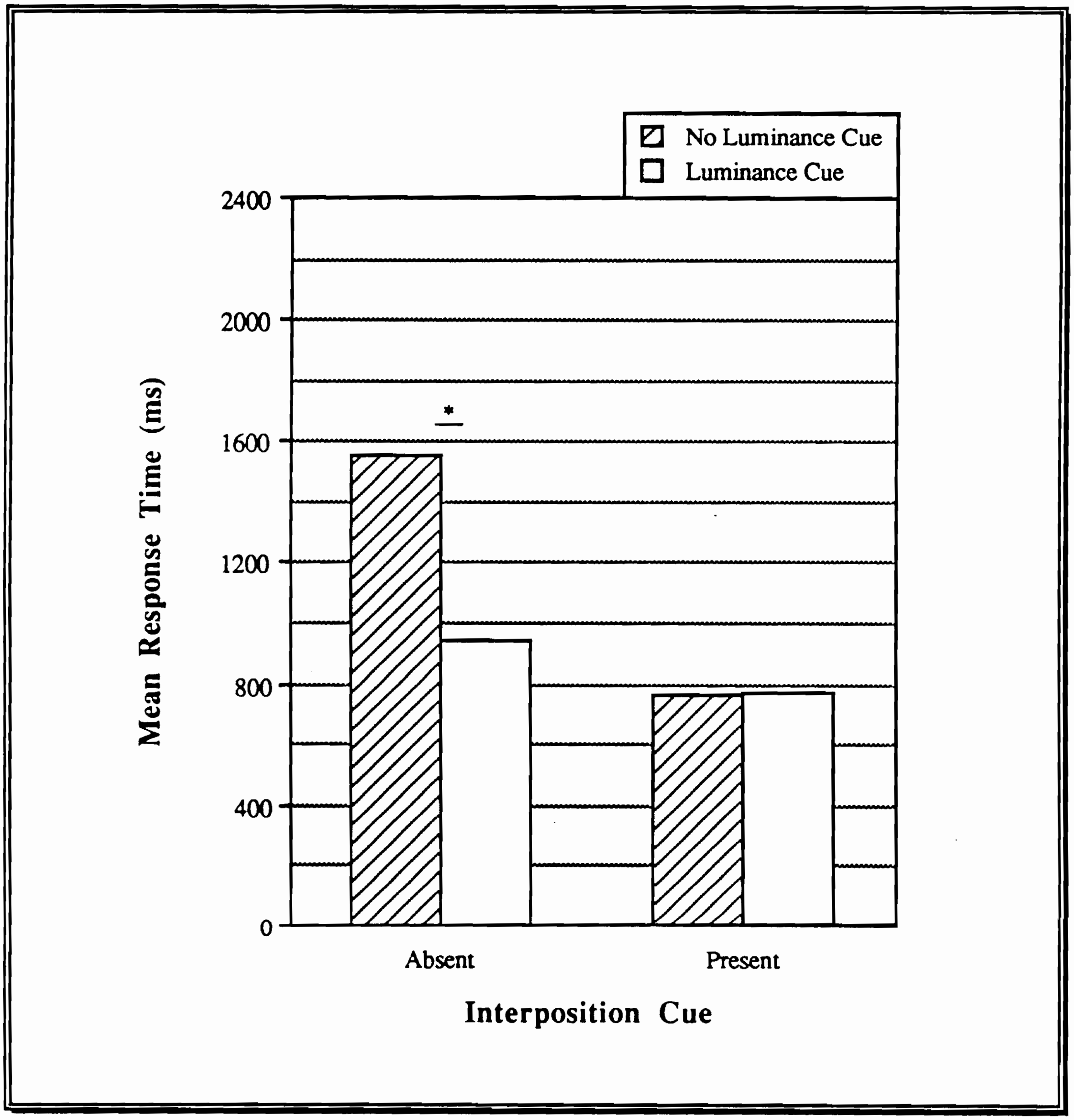


Figure 27. Mean response time as a function of Interposition and Luminance cues, Experiment 1. Asterisk indicates mean difference at $p \leq .05$.

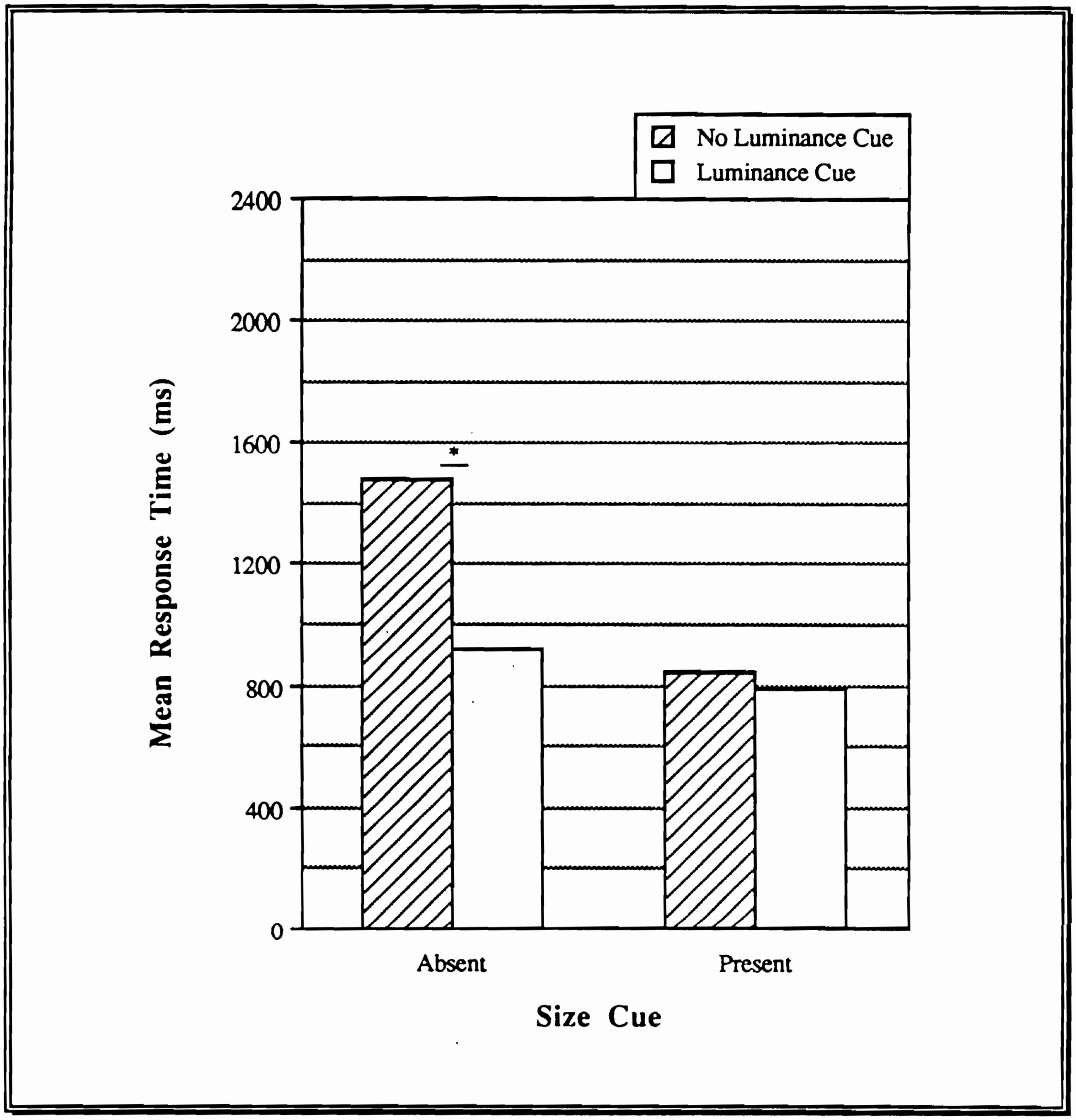


Figure 28. Mean response time as a function of Size and Luminance cues, Experiment 1. Asterisk indicates mean difference at $p \leq .05$.

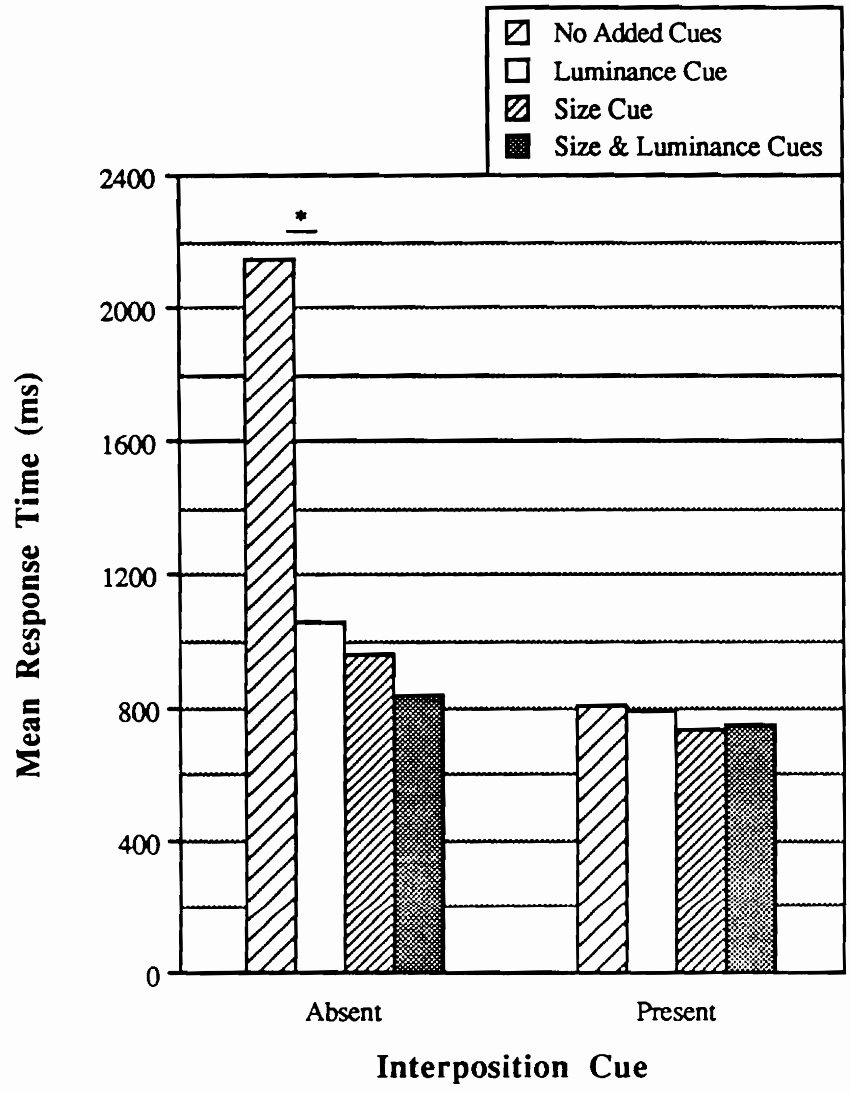


Figure 29. Mean response time as a function of Interposition, Size, and Luminance cues, Experiment 1. Asterisk indicates smallest tested mean difference at $p \leq .05$.

TABLE 5

ANOVA Summary Table for Total Errors, Experiment 1

Source	*df*	*MS*	*F*	*p*
Gender (G)	1	0.0063	0.01	.9319
Subjects (Gender) (S(G))	8	0.8031		
Luminance (L)	1	3.3063	4.35	.0704
L * G	1	0.0563	0.07	.7924
L * S(G)	8	0.7594		
Interposition (I)	1	3.3063	3.28	.1079
I * G	1	0.0563	0.06	.8193
I * S(G)	8	1.0094		
Size (Sz)	1	4.5563	5.30	.0503
Sz * G	1	0.0063	0.01	.9341
Sz * S(G)	8	0.8594		
Disparity (D)	1	0.0063	0.01	.9248
D * G	1	1.4063	2.13	.1823
D * S(G)	8	0.6594		
L * I	1	3.9063	5.98	.0402
L * I * G	1	0.0563	0.09	.7766
L * I* S(G)	8	0.6531		
L * Sz	1	2.7563	3.43	.1011
L * Sz * G	1	0.0063	0.01	.9319
L * Sz * S(G)	8	0.8031		
L * D	1	0.0563	0.12	.7404
L * D * G	1	1.0563	2.21	.1755
L * D * S(G)	8	0.4781		
I * Sz	1	2.7563	2.47	.1546
I * Sz * G	1	0.0063	0.01	.9422
I * Sz * S(G)	8	1.1156		
I * D	1	0.0063	0.01	.9237
I * D * G	1	1.8063	2.82	.1316
I * D* S(G)	8	0.6406		
Sz * D	1	0.0563	0.08	.7881
Sz * D * G	1	1.0563	1.45	.2628
Sz * D * S(G)	8	0.7281		

TABLE 5 (continued)

ANOVA Summary Table for Total Errors, Experiment 1

Source	*df*	*MS*	*F*	*p*
L * I * Sz	1	3.3063	4.43	.0685
L * I * Sz * G	1	0.1563	0.21	.6596
L * I * Sz * S(G)	8	0.7469		
L * I * D	1	0.0063	0.01	.9112
L * I * D * G	1	1.4063	2.98	.1226
L * I * D * S(G)	8	0.4719		
L * Sz * D	1	0.1563	0.29	.6034
L * Sz * D * G	1	0.7563	1.42	.2683
L * Sz * D * S(G)	8	0.8031		
I * Sz * D	1	0.0063	0.01	.9248
I * Sz * D * G	1	1.4063	2.13	.1823
I * Sz * D * S(G)	8	0.6594		
L * I * Sz * D	1	0.0563	0.12	.7404
L * I * Sz * D * G	1	1.0563	2.21	.1755
L * I * Sz * D * S(G)	8	0.4781		
Total	159			

(Table 6) revealed that participants experienced only a small amount of discomfort while viewing the display (Figure 30).

Ratings of cue effectiveness were submitted to a one-way ANOVA. Ratings are significantly different ($F(3,27) = 4.92, p = .0074$). Examination of mean ratings (items 2(a) through 2(d), Table 6) showed Interposition to be the favorite, with ratings for the depth cues of Size, Luminance, and Disparity falling within a narrow range (Figure 31). A Newman-Keuls post-hoc means comparison showed that the rating for Interposition is significantly higher than the rating for the other three cues. The differences among ratings of Disparity, Size, and Luminance are not statistically significant (Table E-6).

Mental Rotations Test. Correct MRT responses were scored as one point per correct response. Incorrect responses were scored as minus one-half point to weight the score for guessing. Pearson product-moment correlation coefficients were calculated for pairs of the following factors: MRT score, mean response time, and total errors (Table 7). A statistically significant negative correlation was found between MRT scores and mean experimental response time ($r = -.67, p = .0336$). There is no statistically significant gender difference between mean MRT scores (Table 8, $t = .68$, $df = 8$, $p = .5155$).

Discussion

Response time. The three monocular cues (Interposition, Size, and Luminance) produced significantly faster depth judgments when implemented singularly relative to the display condition containing no depth cues. This is an important result, since it provides a degree of validation for the use of these depth cues in subsequent research. When used in combination with Interposition, response times were not significantly different. This result is consistent with those of Rhodes (1980) who reported that kinetic interposition dominated

TABLE 6

Means, Standard Deviations, and Ranges for Questionnaire Ratings, Experiment 1

Questionnaire Item	*Mean*	*SD*	*Min*	*Max*
1(a) Headache	1.6	1.08	1	4
1(b) Eyestrain	2.8	1.48	1	6
1(c) Nausea	1.0	0.00	1	1
1(d) Blurred Vision	1.7	1.06	1	4
1(e) General Discomfort	1.7	0.95	1	4
1(f) Other	2.1	1.85	1	6
2(a) Luminance	6.4	2.41	3	9
2(b) Size	7.7	2.31	2	10
2(c) Interposition	9.7	0.68	8	10
2(d) Disparity	6.6	2.46	2	10

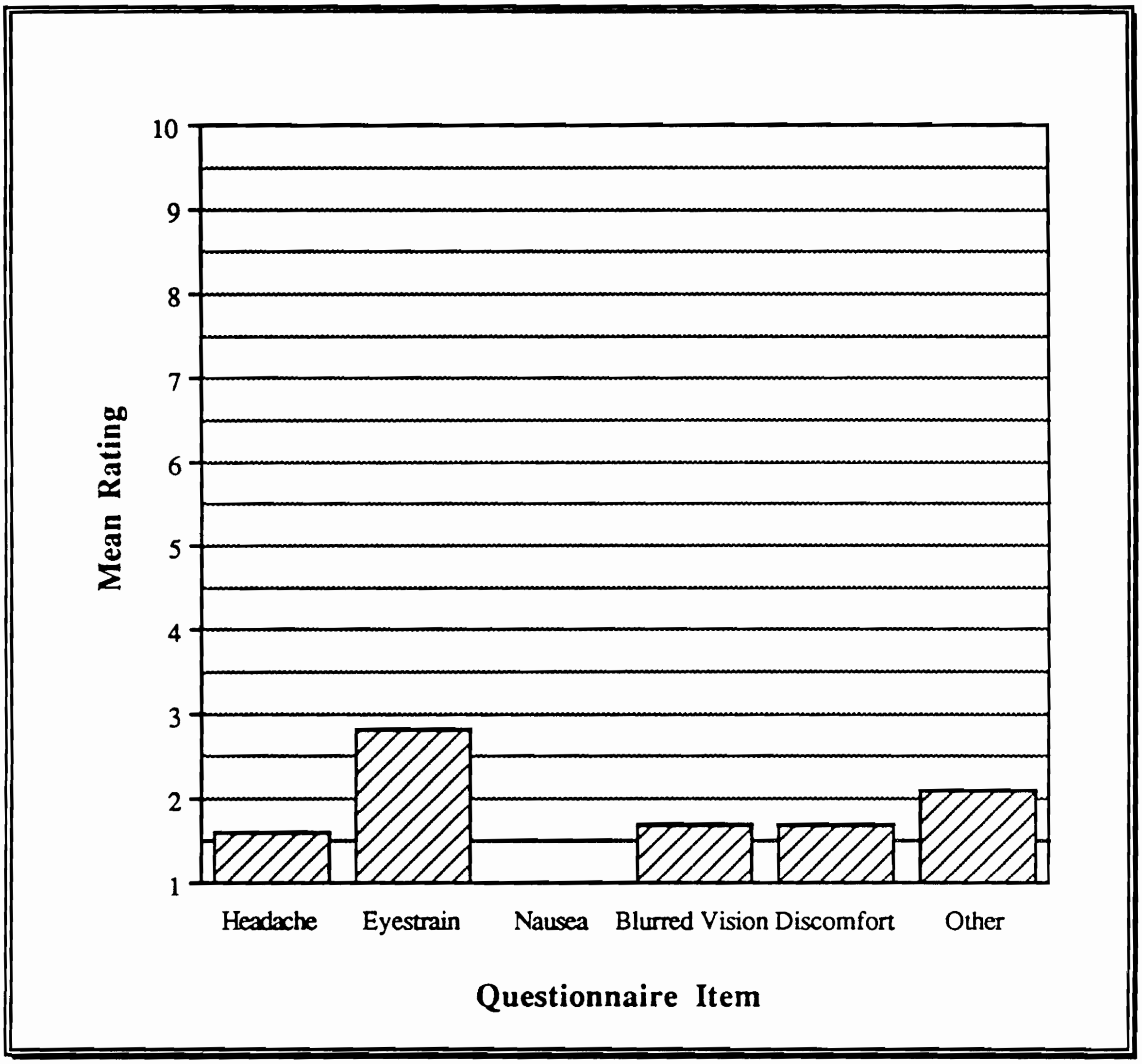


Figure 30. Mean questionnaire ratings of physical discomfort, Experiment 1.

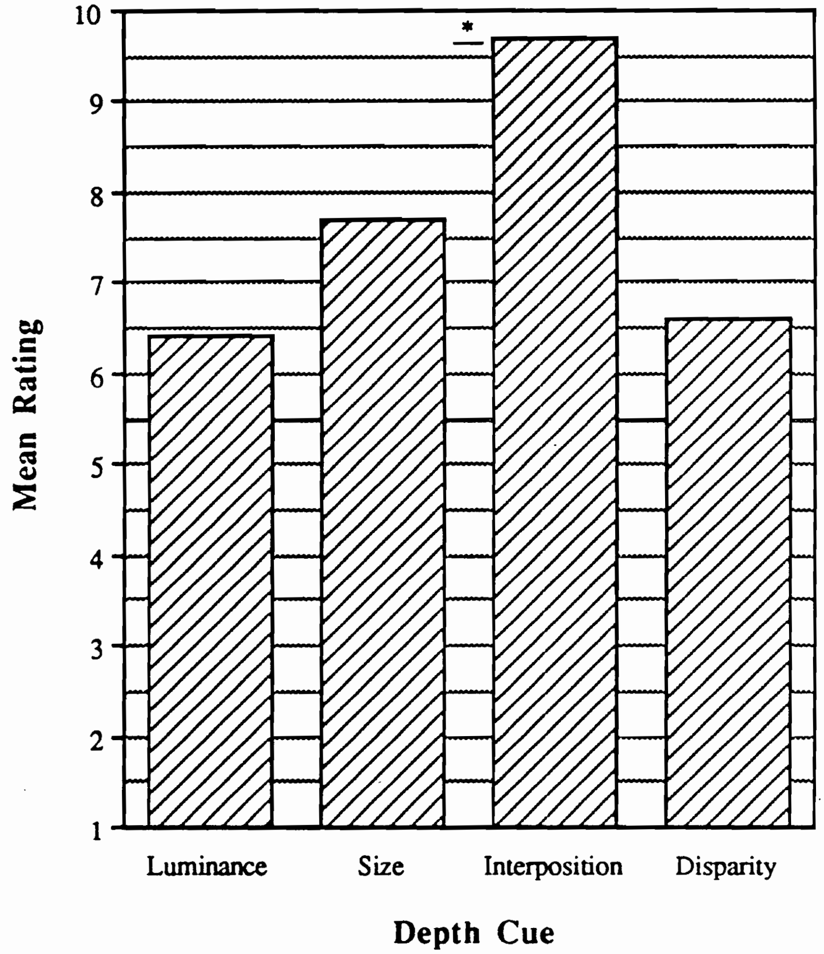


Figure 31. Mean questionnaire ratings of cue effectiveness, Experiment 1. Asterisk indicates smallest mean difference at $p \leq .05$.

TABLE 7

Pearson Product-Moment Correlation Coefficients[1] for MRT Scores[2], Mean Response Times[3], and Total Errors[3] in Experiment 1

Compared Scores	*r*	*p*
MRT x Mean Response Time	-.67	.0336
MRT x Total Errors	.30	.3974
Mean Response Time x Errors	.24	.5113

[1] Calculated with 10 data points.

[2] One observation per subject.

[3] Calculated from 192 observations per subject.

TABLE 8

Means, Standard Deviations, and Ranges for MRT Scores as a Function of Gender, Experiment 1

Gender	*Mean*	*SD*	*Min*	*Max*
Female	18.8	11.37	3.5	30.5
Male	22.8	6.48	16.5	32.5

relative depth perception, where kinetic interposition, texture density, and luminance of planar images were varied to indicate relative depth position. It should be noted that the Interposition cue as implemented in this experiment was necessarily confounded with spatial position and consequently the proximity of the target objects. This may be an important confound, since it has long been suggested by Gestaltists in their *proximity principle* that the spatial relationships among visual objects may influence their perceptual organization (Gulick and Lawson, 1976). In addition, the results of McCann (1979) suggest that spatial proximity may affect the accuracy and speed of relative stereoscopic depth judgements.

It is worth noting that visual inspection of Figure 29 shows an interactive rather than additive performance effect among Interposition, Size, and Luminance depth cues, although post-hoc analyses showed that this three-way interaction is not robust. Cue additivity has been suggested in some of the literature (e.g., Dosher et al., 1986; Vlahos, 1965; Wickens, in press) but it is likely influenced by the nature of the stimuli and task. In particular, the use of suprathreshold cue levels in this experiment may have washed out a cue additivity effect by producing a ceiling on cue effects.

The most surprising result associated with the response time data is the absence of any statistically significant response time effects associated with binocular disparity. It is possible that inadequate training was given to participants on performing field-sequential stereopsis. Gould (1964) found that while performance did not improve as a function of daily intra-session practice on a remote, stereoscopic tracking task, performance did improve among daily sessions. While participants in this study did receive training to speed and error criteria, this training occurred as mass practice within a 30-min period of time.

A second possibility is that the magnitude of the stereo effect was inappropriate. This is highly unlikely, however, for a number of reasons. First, the ability of participants to successfully identify stereoscopic targets is witnessed by the lack of any statistically significant error effects associated with the use of the Disparity cue. If the salience of stereoscopic depth had been inadequate, a larger number of errors should have been associated with the use of the Disparity cue. Similarly, higher errors rates should also have been associated with the Disparity cue if too much horizontal disparity had been used, such that participants were unable to fuse the left and right image fields.

A more likely explanation is that either the nature of the task (relative depth judgements) or stimuli (planar, geometric figures) were such that stereoscopic presentation yielded no appreciable response time benefit. This result is consistent with those of Pepper and Hightower (1984) and Way (1988); for some display formats and tasks, the addition of stereopsis may not be beneficial or cost-effective.

Errors. Overall error rates are so low that very few error data exist to consider. This result is not surprising, since participants were instructed to make a consistent speed-accuracy tradeoff in favor of accuracy. It is important to note that no statistically significant differences in total errors were associated with the Disparity depth cue. Consequently, the high response times associated with the Disparity cue cannot be said to be attributed incorrect responses. While two statistically significant effects were found in this analysis, their importance is greatly diminished by the fact that error trials represent less than 2% of the experimental trials. Error rates might be considerably higher in more complex task environments.

3-D Questionnaire. An examination of ratings of participant discomfort verifies that participants experienced no unusual problems with the field-sequential technology (given the constraints of the testing environment) above and beyond what might be expected in a comparable 2-D visual inspection task. The highest mean rating is for the category of eyestrain, and even this rating is very low.

Examination of ratings of cue "effectiveness" shows that the Interposition cue was judged most effective, followed next by Size, Luminance, and Disparity cues. While the mean rating for Interposition is statistically different from the other mean cue ratings, differences among Size, Luminance, and Disparity are not statistically significant. The most important result here is that although response time data indicate that the Disparity cue played an insignificant role in the relative depth judgment task, the Disparity cue received moderately high effectiveness ratings. The dissociation of objective and subjective measures is frequently encountered in psychophysical research and points to the importance of using multiple measures. This result suggests that stereoscopic presentations can have a large subjective value which is separate from any associated performance effects.

Mental Rotations Test. Faster response times were significantly associated with higher MRT scores; that is, superior task performance in Experiment 3 was associated with superior spatial ability. Participants who completed a higher number of MRT items within a fixed amount of time also responded to experimental stimuli more rapidly. This result is consistent with the statistically significant correlation between DAT scores and RDS fusion times reported by McGuinness and Brabyn (1984). The correlation found in Experiment 1 appears to be much stronger, although it must be noted that the correlation was computed with only 10 MRT scores.

Unlike previous investigations (i.e., Sanders et al., 1982; Tapley and Bryden, 1977), no statistically significant gender difference exists for MRT scores. A visual inspection of the means (Table 8) does indicate the trend was for a male advantage. Given the usually small magnitude of this effect and the relatively small sample size used in Experiment 1, it is not surprising that a statistically significant difference was not demonstrated. For example, in the study by Sanders et al. (1982), over 1000 participants were tested.

EXPERIMENT 2

Although much can be learned from performance measures such as operator response time and error rate, it is also important to assess subjective dimensions. Image quality judgements are of particular importance for the evaluation of 3-D displays. While much research emphasis has been placed on the technological development of emerging 3-D display strategies, the significant problem of defining 3-D image quality for the evaluation of these displays remains. A variety of metrics have been formulated for the prediction of perceived 2-D image quality on the basis of objective display measures, but no such metrics are available with which to judge 3-D displays. As Snyder (1988) commented, "In the case of virtual images, techniques for image quality measurement have not been developed nor even suitably hypothesized" (p. 470).

This experiment was conducted to investigate further the subjective value of the four depth cues used in Experiment 1. In particular, the apparent dissociation between response-time effects and cue-effectiveness ratings for the Disparity cue which was found in Experiment 1 was examined more closely by introducing a different subjective quality metric.

The specific hypotheses tested in this experiment were:

1. The individual use of Luminance, Size, Interposition, and Disparity cues should have elicited higher image quality ratings, relative to display conditions which contained no depth information; and
2. The use of multiple depth cues should have produced complementary effects. That is, the highest image quality ratings should have occurred in response to stimuli which incorporated all four depth cues.

Method

Participants. Ten subjects (five males and five females, 18 to 29 years of age) participated in this experiment. Participants were recruited through campus flyers and were paid $10.00 for participation in the experiment. All participants were required to pass the same two-part screening procedure described in *Experiment 1.* Nine of the 19 candidate-participants who were screened failed to meet one or more of the screening criteria. No participants who passed the Ortho-Rater procedure failed to meet the contrast sensitivity criteria.

Experimental task. The same triads of solid, planar, geometric figures which were used in Experiment 1 were displayed in Experiment 2. Participants were asked to rate the image quality of each triad of figures according to the quality of depth perceived. Subjective image quality ratings (quality-of-depth ratings) were solicited on a trial-by-trial basis. A nine-point adjective scale was used which ranged from "Worst Imaginable" to "Best Imaginable" (Appendix G). This scale has been validated in a variety of 2-D image quality experiments in the Displays and Controls Laboratory (Hunter, Pigeon, Bowers, and Snyder, 1986) and elsewhere (Beaton, Murch, and Knox, 1985).

Design. The experimental design was a 2 x 2 x 2 x 2 full-factorial design and all independent variables with the exception of Gender were within-subjects variables. There were four replications of each of the 16 experimental conditions. In addition, each depth cue combination was presented for each of the three target locations (i.e., closest, middle-most, and farthest figure in apparent depth). Therefore, each participant contributed 192 observations. Trials were presented in a randomized order, nested within replications (48 trials per replication, 16 trials per target position per replication). The same independent variables from Experiment 1 were included in the design of Experiment 2. The stimuli and basic design of the two experiments were identical, with the major exception being the substitution of image quality ratings for the dependent variables of response time and error rate.

Procedure. (1) Informed consent. All participants read and signed informed consent forms which outlined the benefits, risks, and rights associated with participation in the screening procedure and the experiment (Appendix A).

(2) Training. All participants received approximately 30 min of practice on representative tasks. Training was conducted on the same day as the experimental trials and commenced no later than two weeks following administration of the visual screening procedure. All instructions (Appendix H) were read aloud by the experimenter as the participant read along. During the initial training, participants simply viewed three representative triads of figures for each experimental depth cue, as well as an example of figures incorporating none of the depth cues. Participants were given detailed explanations of the meaning of each of the four depth cues. This phase of the training was informational only, and no responses were recorded.

The second phase of training involved the presentation of the same geometric triads, grouped according to each of the four depth cues. Participants were required to identify the correct apparent depth order of each set of figures, from closest to farthest from the participant. These trials were conducted to ensure that participants were fully conversant with the use of the depth cues in the experiment. Participants were instructed to respond as accurately as possible, without regard for speed of response. Participants were provided with detailed feedback following any error. This feedback detailed the nature of their error, as well as the correct response. Presentation of trials in each cue group was preceded by five practice trials, after which participants were presented trials until correctly responding to five consecutive trials. Failure to meet this criterion within 30 trials would have resulted in a repetition of the entire training phase. Failure to meet this criterion a second time would have led to participant dismissal. No participants failed to meet this training criterion.

During the final training session, participants practiced making subjective image quality ratings. Participants controlled trial presentation by pressing and holding down the mouse button with their preferred thumb to view the figures. After releasing the button, the screen was blanked and the participant gave a vocal response to the experimenter. Participants made their ratings with the aid of a printed copy of the rating scale. Participants were instructed to respond without regard to speed, but with special attention to accuracy. Participants made practice ratings to one complete replication of experimental trials (48 trials). No criteria or feedback were used for this phase of the training, since it was meaningless to define "correct" image quality ratings for the trials. Participants were given a five-min rest break following the completion of these training trials.

(3) Experimental trials. The experimental trials proceeded in the same manner as the final training trials. The experimental trials were preceded by a five-min visual adaptation phase, during which participants viewed a figure triad with no depth cues, presented at the median experimental luminance value. Because the reading lamp was turned off during the experimental trials, participants were unable to use the printed rating list. In its place, the rating list was displayed on the CRT screen after each trial presentation. Participants were given a five-min rest break following completion of one-half of the experimental trials (96 trials) and again after completing the balance of the experimental trials. The entire experimental procedure required approximately 45 min to administer.

(4) Subjective evaluation. Following the completion of experimental trials, participants were administered the same 3-D Questionnaire which was used in

Experiment 1 (Appendix C). This instrument was used to assess the participant's experience of a variety of symptoms of discomfort on a 10-point scale, where a rating of 1 indicated no discomfort and a rating of 10 indicated intense discomfort. In addition, the questionnaire included a cue-effectiveness scale. This 10-point scale was used to asses the degree to which participants believed each of the four depth cues assisted them in completing their experimental task, with a rating of 1 indicating no effectiveness and a rating of 10 indicating great effectiveness.

(5) Mental Rotations Test. The MRT was not included in Experiment 2, since there was no a priori reason to believe that spatial ability would be related to image quality ratings.

Results

Subjective image quality ratings. Image quality ratings were collapsed across replications and target positions and submitted to a five-factor ANOVA (Luminance x Size x Disparity x Interposition x Gender). All effects in the model are statistically significant, with the exception of the interaction of Size x Disparity x Interposition ($p = .0786$) and all those effects involving the Gender factor (Table 9). For the interested reader, an illustration of the Size x Interposition interaction is included in Appendix I (Figure I-1). Four main effects are statistically significant: Disparity ($p < .0001$), Interposition ($p < .0001$), Size ($p < .0001$), and Luminance ($p = .0009$). In general, participants made higher image quality ratings in the presence of Disparity (Figure 32), Interposition (Figure 33), Luminance (Figure 34), and Size cues (Figure 35).

Six two-way interactions are also statistically significant: Luminance x Interposition ($p = .0189$), Luminance x Size ($p = .0003$), Luminance x Disparity ($p = .0021$),

TABLE 9

ANOVA Summary Table for Image Quality Ratings, Experiment 2

Source	*df*	*MS*	*F*	*p*
Gender (G)	1	3.1174	0.29	.6079
Subjects (Gender) (S(G))	8	10.9328		
Luminance (L)	1	28.9000	26.56	.0009
L * G	1	1.3141	1.21	.3038
L * S(G)	8	1.0880		
Interposition (I)	1	61.8766	95.76	< .0001
I * G	1	0.3361	0.52	.4913
I * S(G)	8	0.6462		
Size (Sz)	1	50.8127	84.33	< .0001
Sz * G	1	0.0250	0.04	.8437
Sz * S(G)	8	0.6025		
Disparity (D)	1	448.3418	137.29	< .0001
D * G	1	1.8063	0.55	.4783
D * S(G)	8	3.2656		
L * I	1	2.1007	8.61	.0189
L * I * G	1	0.0766	0.31	.5906
L * I * S(G)	8	0.2439		
L * Sz	1	3.4028	35.63	.0003
L * Sz * G	1	0.1266	1.33	.2829
L * Sz * S(G)	8	0.0955		
L * D	1	3.1174	19.77	.0021
L * D * G	1	0.0085	0.05	.8221
L * D * S(G)	8	0.1577		
I * Sz	1	2.8002	6.41	.0351
I * Sz * G	1	0.0444	0.10	.7578
I * Sz * S(G)	8	0.4365		
I * D	1	17.4460	15.24	.0045
I * D * G	1	0.5063	0.44	.5248
I * D * S(G)	8	1.1449		
Sz * D	1	16.5766	57.92	< .0001
Sz * D * G	1	0.8507	2.97	.1230
Sz * D * S(G)	8	0.2862		

TABLE 9 (continued)

ANOVA Summary Table for Image Quality Ratings, Experiment 2

Source	*df*	*MS*	*F*	*p*
L * I * Sz	1	2.0250	9.95	.0135
L * I * Sz * G	1	0.0002	0.00	.9774
L * I * Sz * S(G)	8	0.2035		
L * I * D	1	1.8063	8.33	.0203
L * I * D * G	1	0.2127	0.98	.3510
L * I * D * S(G)	8	0.2168		
L * Sz * D	1	3.4028	33.02	.0004
L * Sz * D * G	1	0.0210	0.20	.6636
L * Sz * D * S(G)	8	0.1031		
I * Sz * D	1	1.3752	4.06	.0786
I * Sz * D * G	1	0.4000	1.18	.3086
I * Sz * D * S(G)	8	0.3384		
L * I * Sz * D	1	0.7563	10.69	.0114
L * I * Sz * D * G	1	0.0043	0.06	.8106
L * I * Sz * D * S(G)	8	0.0707		
Total	159			

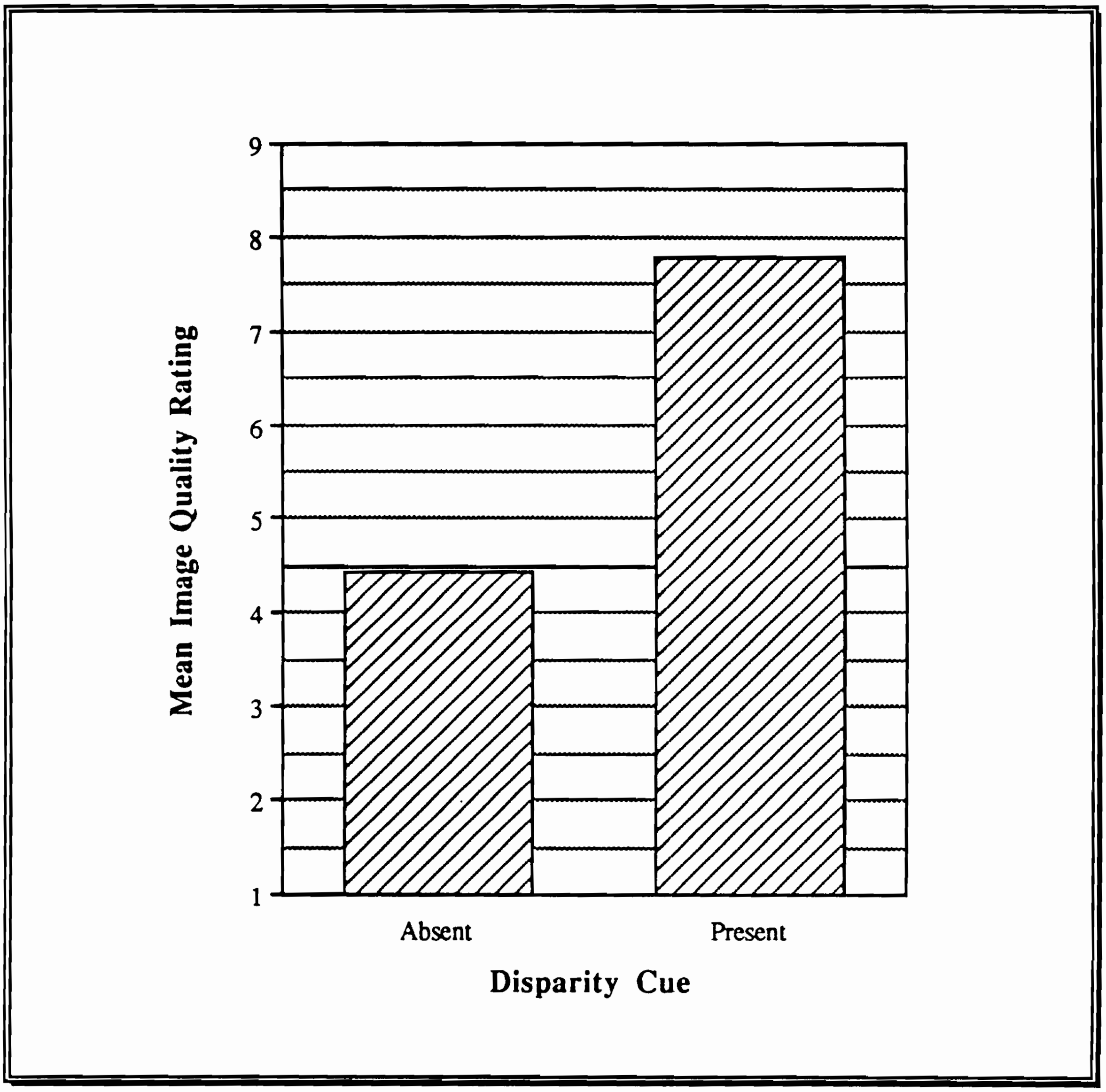


Figure 32. Mean image quality rating as a function of Disparity cue, Experiment 2.

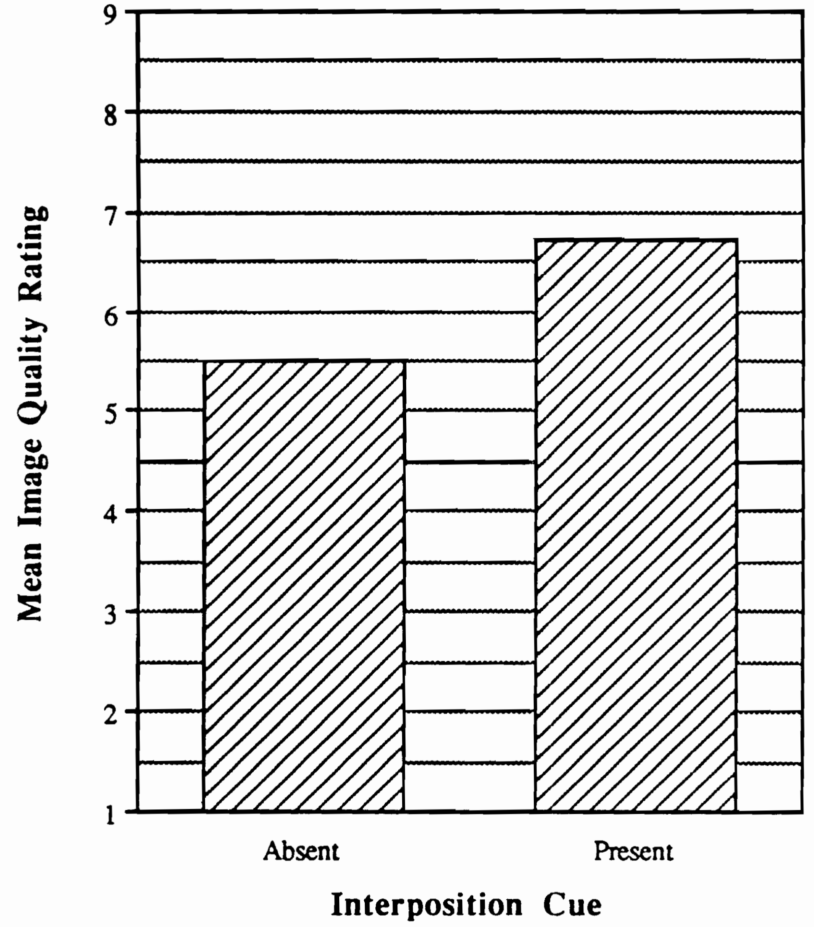


Figure 33. Mean image quality rating as a function of Interposition cue, Experiment 2.

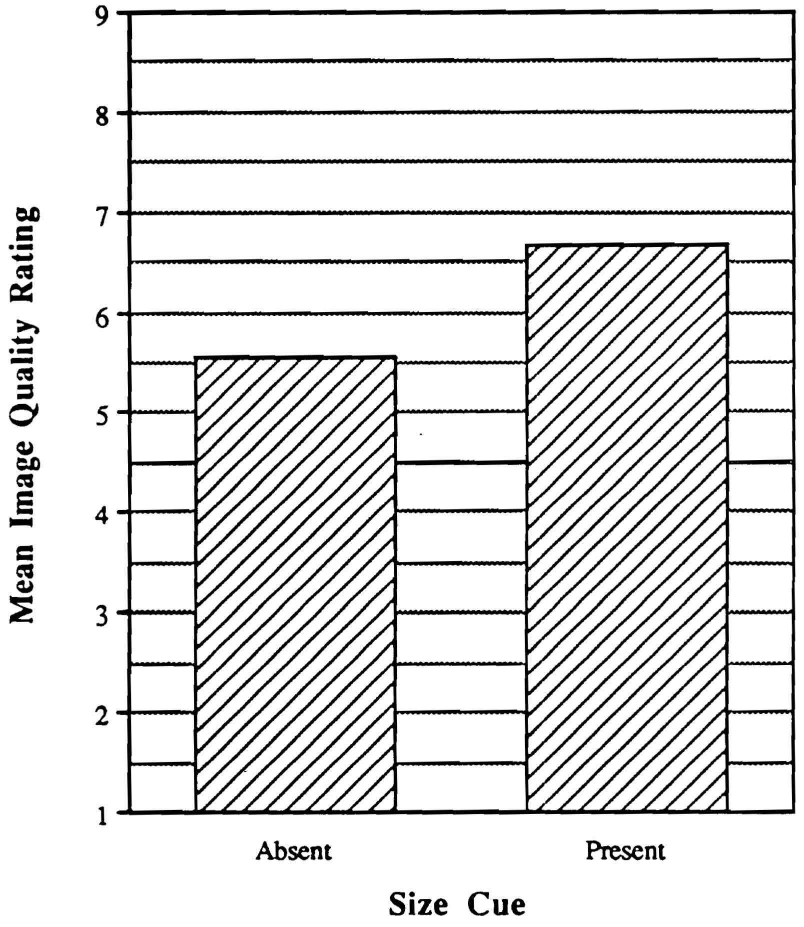


Figure 34. Mean image quality rating as a function of Size cue, Experiment 2.

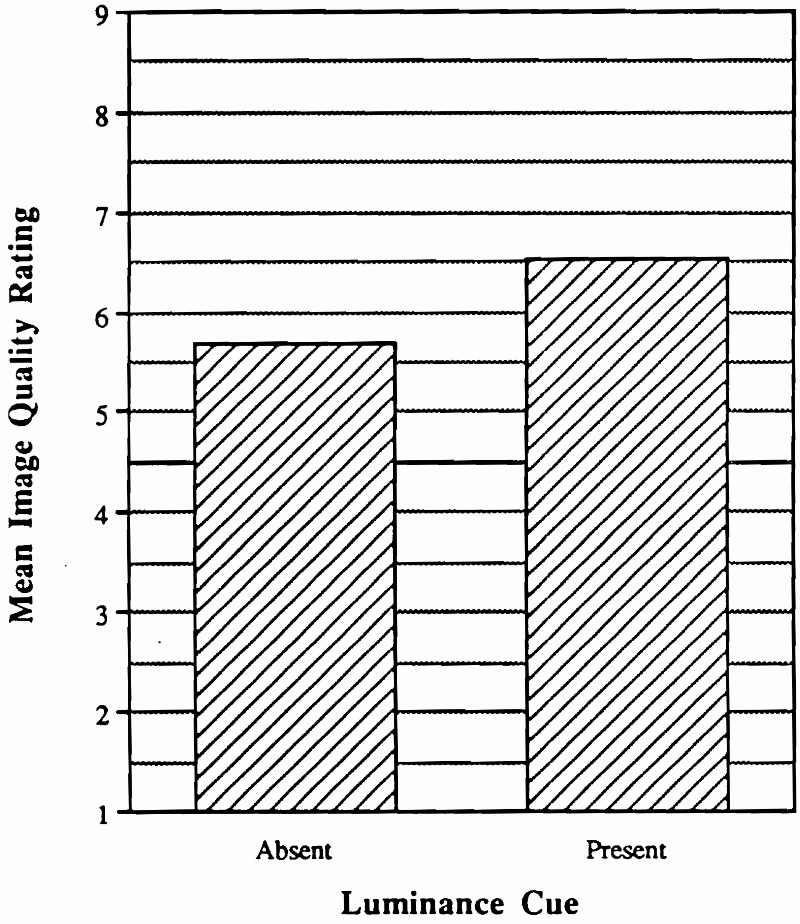


Figure 35. Mean image quality rating as a function of Luminance cue, Experiment 2.

Size x Interposition (*p* = .0351), Disparity x Interposition (*p* = .0045), and Size x Disparity (*p* < .0001). Post-hoc simple-effect F-tests on these interactions (Appendix J, Tables J-1 through J-6) revealed that participants made significantly different image quality ratings in the presence of: the Size cue, both with and without the Interposition cue (Figure 36); the Luminance cue, both with and without the Interposition cue (Figure 37); the Luminance cue, both with and without the Size cue (Figure 38); the Size cue, both with and without the Disparity cue (Figure 39); the Luminance cue, both with and without the Disparity cue (Figure 40); and the Interposition cue, both with and without the Disparity cue (Figure 41).

Three three-way interactions are statistically significant : Luminance x Interposition x Size (*p* = .0135), Luminance x Interposition x Disparity (*p* = .0203), and Luminance x Size x Disparity (*p* = .0004). Post-hoc simple-effect F-tests were performed on these interactions (Tables J-7 through J-12) to determine which elements of the interactions are statistically significant. The interaction of Luminance x Size is statistically significant only in the absence of the Interposition cue (Figure 42). Within this interaction, and in the absence of the Interposition cue, the effect of Luminance is significant both with and without the Size cue. The interaction of Luminance x Interposition is statistically significant only in the absence of the Disparity cue (Figure 43). Within this interaction, and in the absence of the Disparity cue, the effect of Luminance is significant both with and without the Interposition cue. The interaction of Luminance x Size is statistically significant only in the absence of the Disparity cue (Figure 44). Within this interaction, and in the absence of the Disparity cue, the effect of Luminance is significant both with and without the Size cue.

Finally, the four-way interaction of Luminance x Interposition x Size x Disparity (*p* = .0114) is statistically significant. Post-hoc simple-effect F-tests were performed on

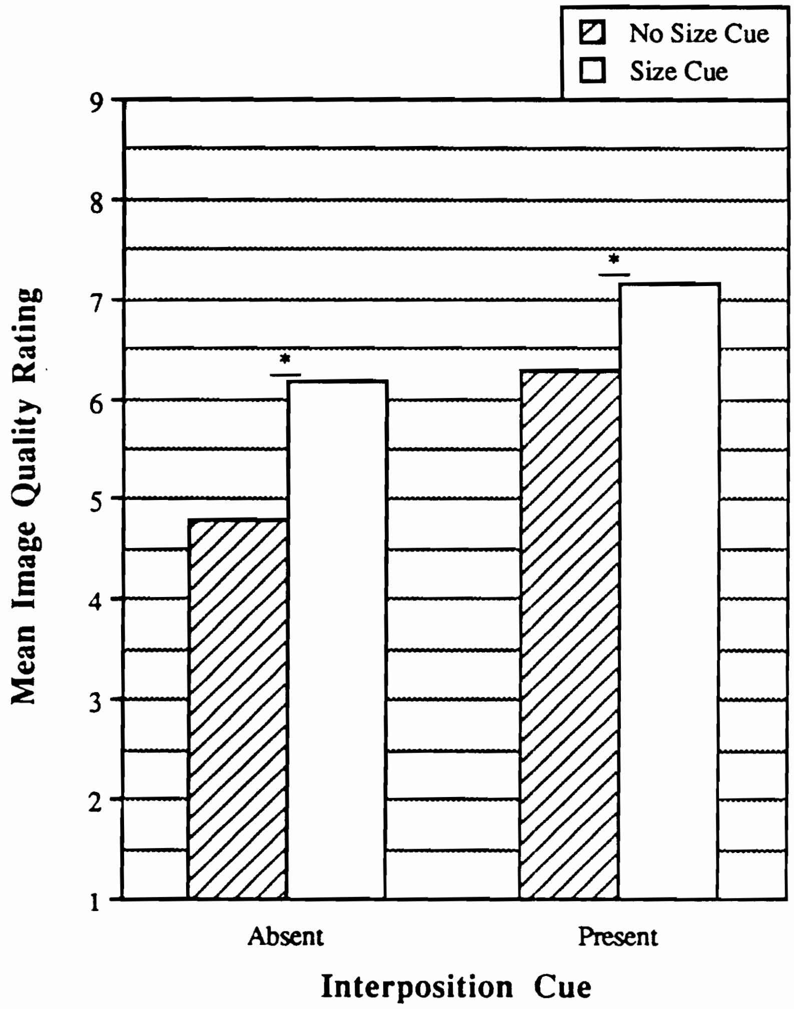


Figure 36. Mean image quality rating as a function of Interposition and Size cues, Experiment 2. Asterisk indicates mean difference at $p \leq .05$.

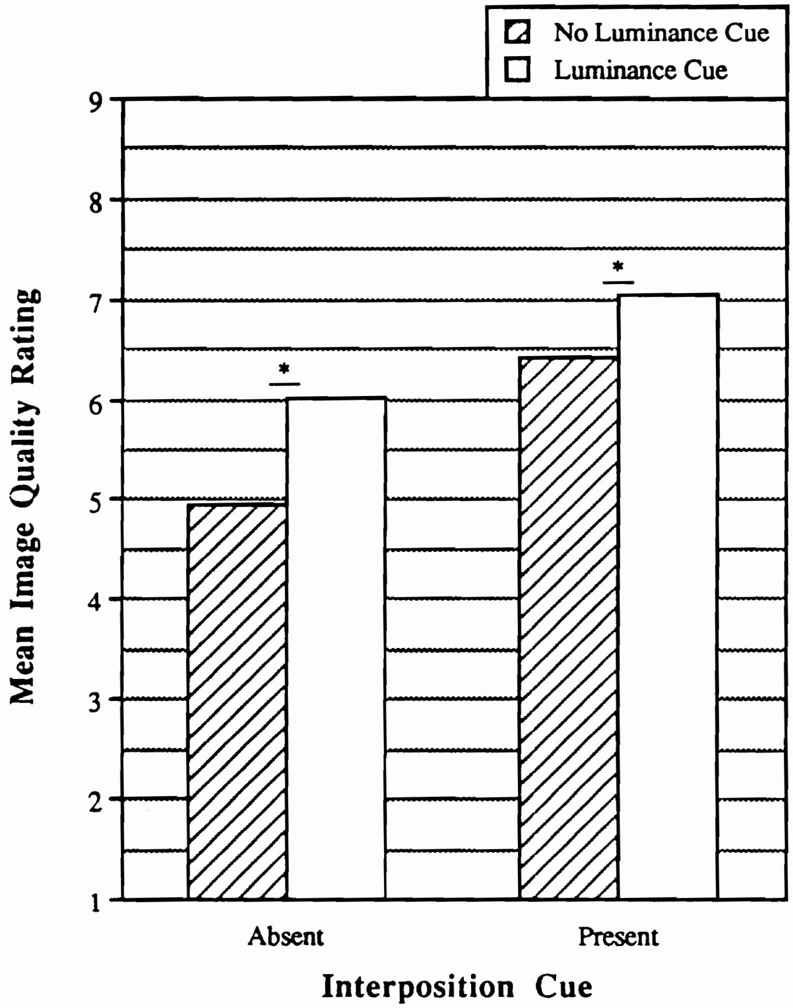


Figure 37. Mean image quality rating as a function of Interposition and Luminance cues, Experiment 2. Asterisk indicates mean difference at $p \leq .05$.

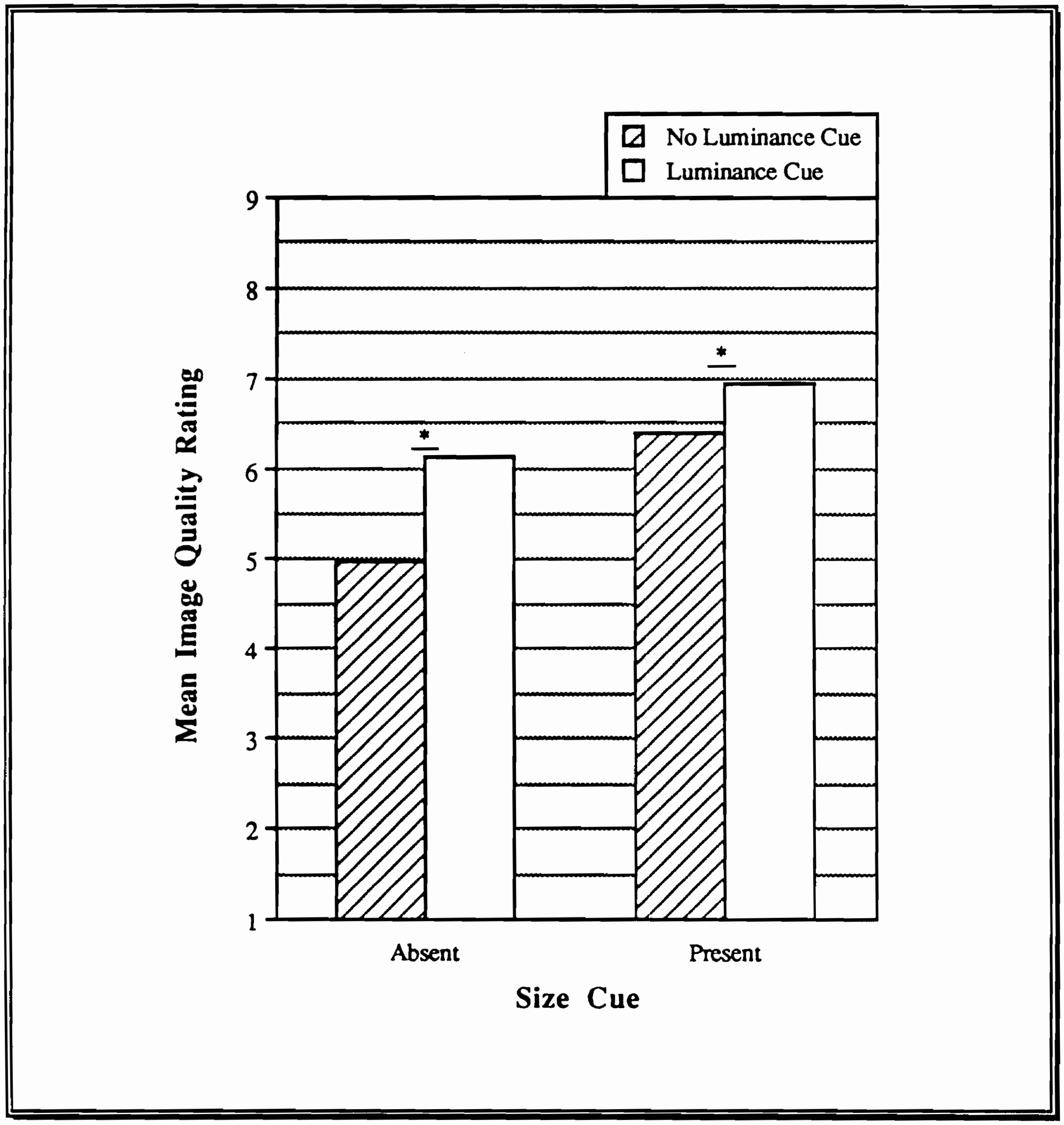


Figure 38. Mean image quality rating as a function of Size and Luminance cues, Experiment 2. Asterisk indicates mean difference at $p \leq .05$.

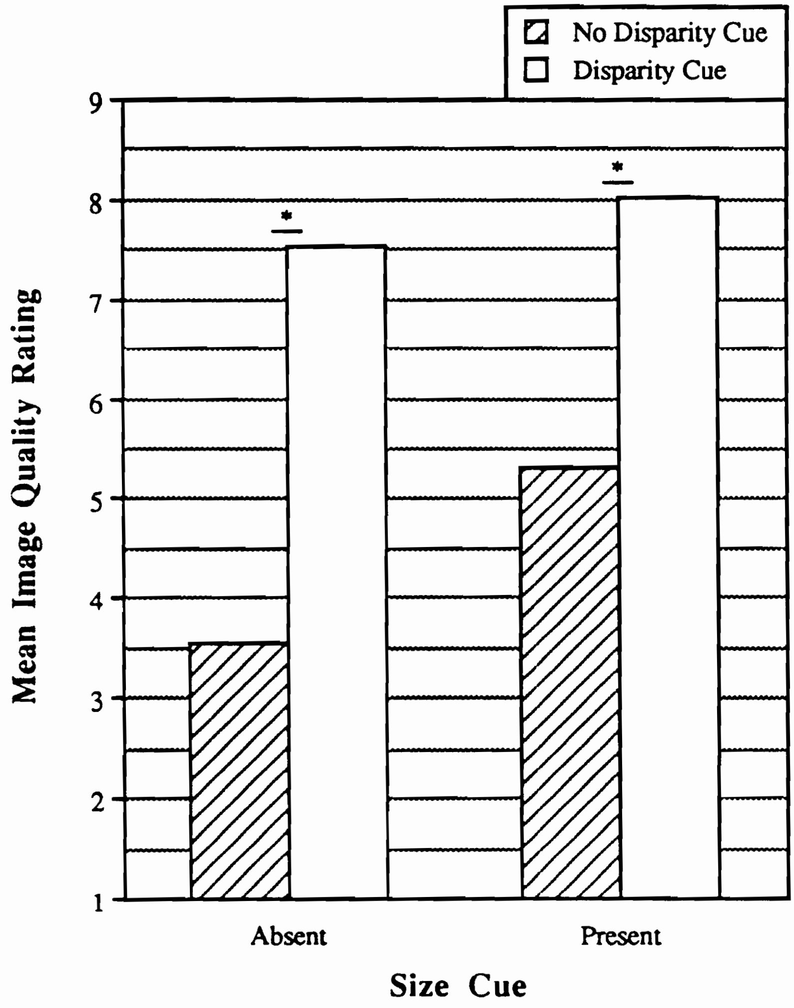


Figure 39. Mean image quality rating as a function of Size and Disparity cues, Experiment 2. Asterisk indicates mean difference at $p \leq .05$.

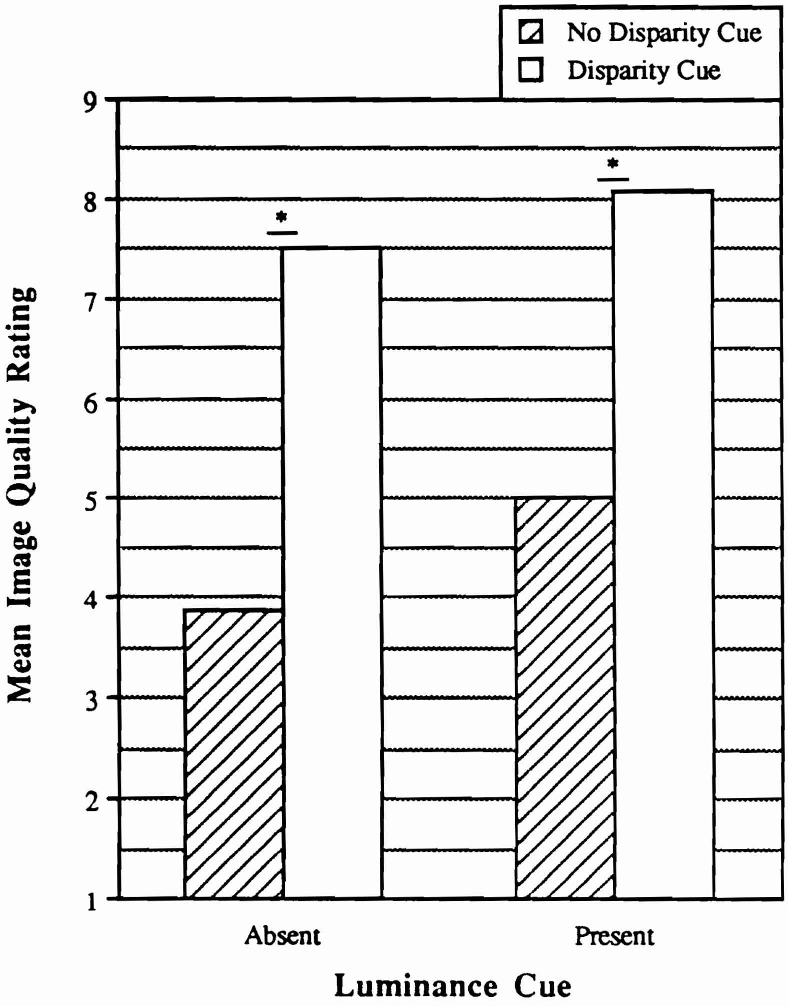


Figure 40. Mean image quality rating as a function of Luminance and Disparity cues, Experiment 2. Asterisk indicates mean difference at $p \leq .05$.

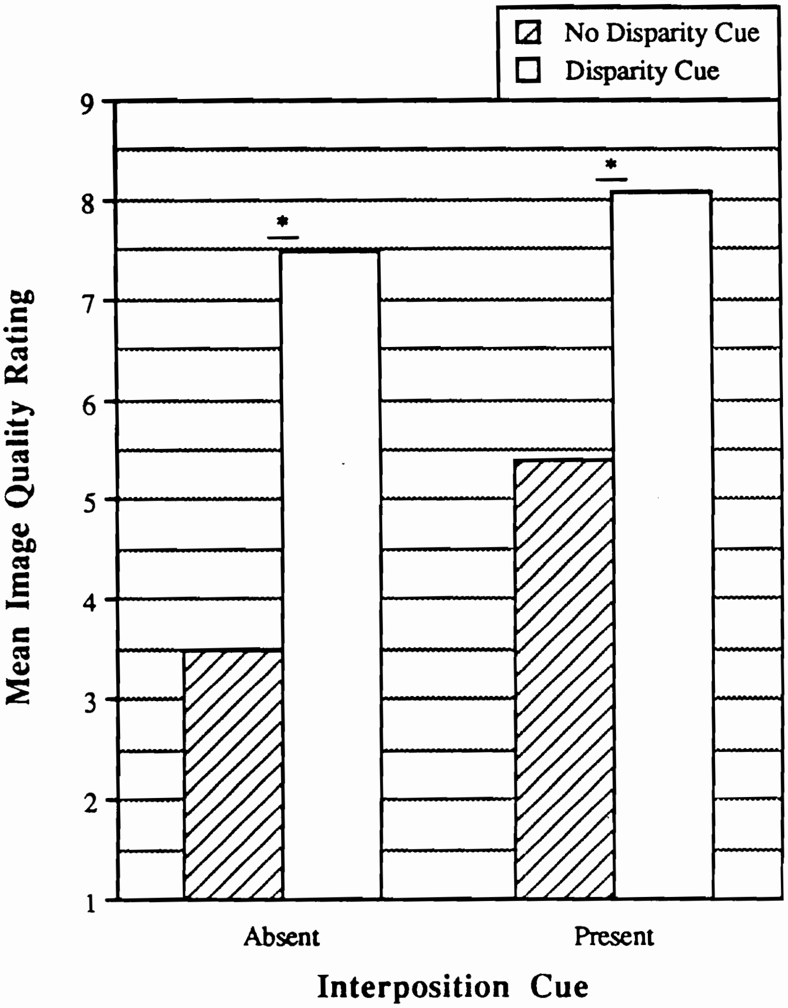


Figure 41. Mean image quality rating as a function of Interposition and Disparity cues, Experiment 2. Asterisk indicates mean difference at $p \leq .05$.

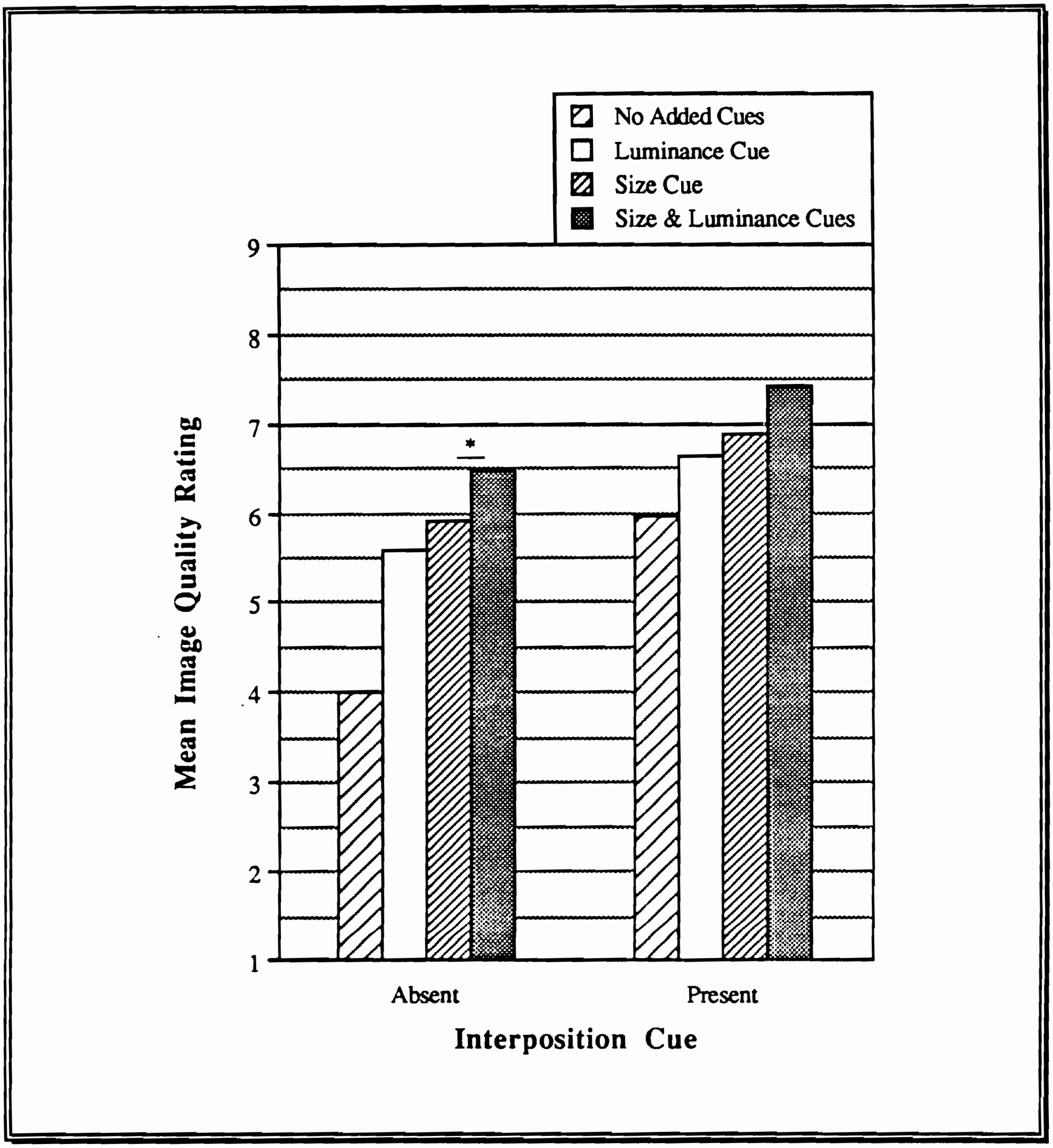


Figure 42. Mean image quality rating as a function of Interposition, Luminance, and Size cues, Experiment 2. Asterisk indicates smallest tested mean difference at $p \leq .05$.

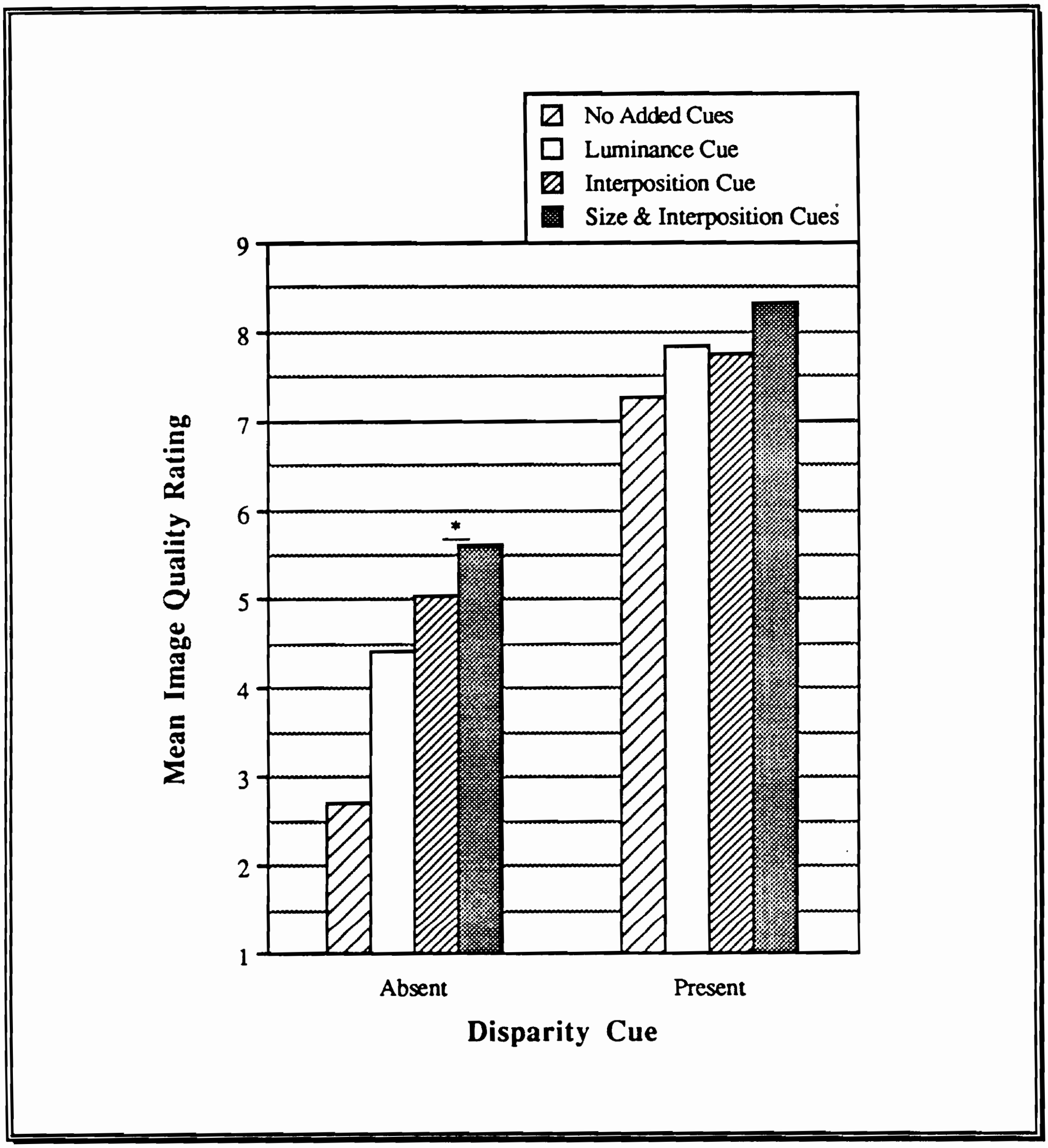


Figure 43. Mean image quality rating as a function of Disparity, Luminance, and Interposition cues, Experiment 2. Asterisk indicates smallest tested mean difference at $p \leq .05$.

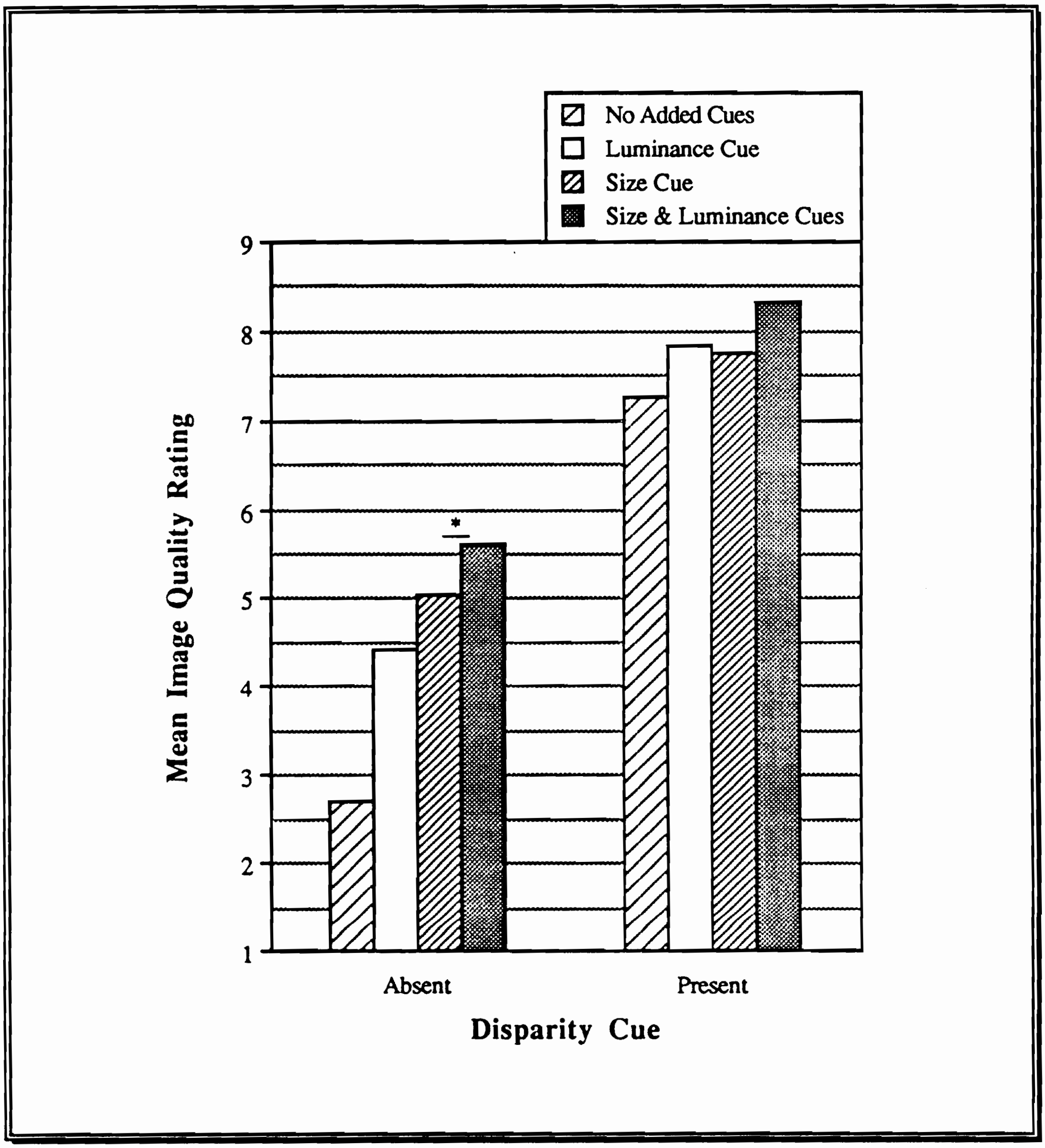


Figure 44. Mean image quality rating as a function of Disparity, Luminance, and Size cues, Experiment 2. Asterisk indicates smallest tested mean difference at $p \leq .05$.

this interaction (Tables J-13 through J-16) to determine which elements of the interaction are statistically significant. The interaction of Luminance x Interposition x Size is statistically significant only in the absence of the Disparity cue (Figure 45). Within this interaction, and in the absence of the Disparity cue, significantly different image quality ratings were made both with and without the Interposition cue. Additional post-hoc simple-effect F-tests on Luminance for each value of Size, in the absence of the Disparity and Interposition cues, revealed that significantly different image quality ratings were made both with and without the Size cue. Final post-hoc simple-effect F-tests on Luminance for each value of Size, with Interposition and without the Disparity cue, revealed that significantly different image quality ratings were made both with and without the Size cue.

3-D Questionnaire. Mean ratings were computed for questionnaire items 1(a) through 2(d). Examination of mean responses to items 1(a) through 1(f) (Table 10) reveals that participants experienced only a small amount of discomfort while viewing the display (Figure 46). Ratings of cue effectiveness were submitted to a one-way ANOVA. Ratings are significantly different ($F(3,27) = 4.68$, $p = .0093$). Examination of mean ratings (items 2(a) through 2(d), Table 10) shows Disparity to be the most highly rated depth cue (Figure 47). A Newman-Keuls post hoc means comparison showed that the rating for Disparity is significantly higher than the ratings for Luminance and Size (Table J-17).

Discussion

Subjective image quality ratings. The most informative result from this analysis is the statistically significant four-way interaction among Disparity, Interposition, Size,

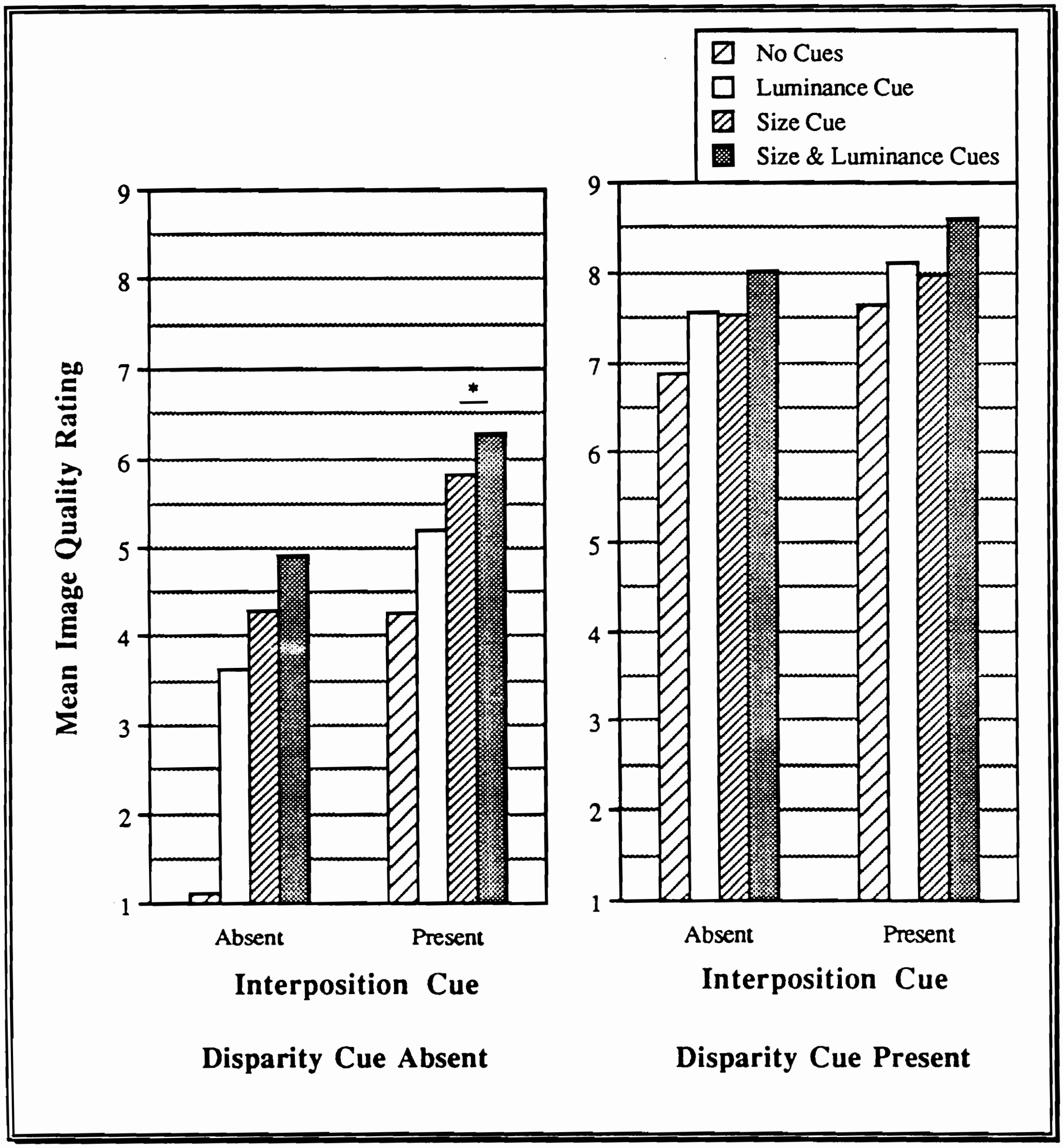


Figure 45. Mean image quality rating as a function of Disparity, Interposition, Luminance, and Size cues, Experiment 2. Asterisk indicates smallest tested mean difference at $p \leq .05$.

TABLE 10

Means, Standard Deviations, and Ranges for Questionnaire Ratings, Experiment 2

Questionnaire Item	*Mean*	*SD*	*Min*	*Max*
1(a) Headache	1.3	0.67	1	3
1(b) Eyestrain	3.0	2.26	1	9
1(c) Nausea	1.6	1.90	1	7
1(d) Blurred Vision	2.4	2.22	1	7
1(e) General Discomfort	1.9	0.74	1	3
1(f) Other	1.4	1.26	1	5
2(a) Luminance	6.4	2.32	3	9
2(b) Size	7.0	2.00	4	10
2(c) Interposition	7.9	1.73	4	10
2(d) Disparity	9.4	1.90	4	10

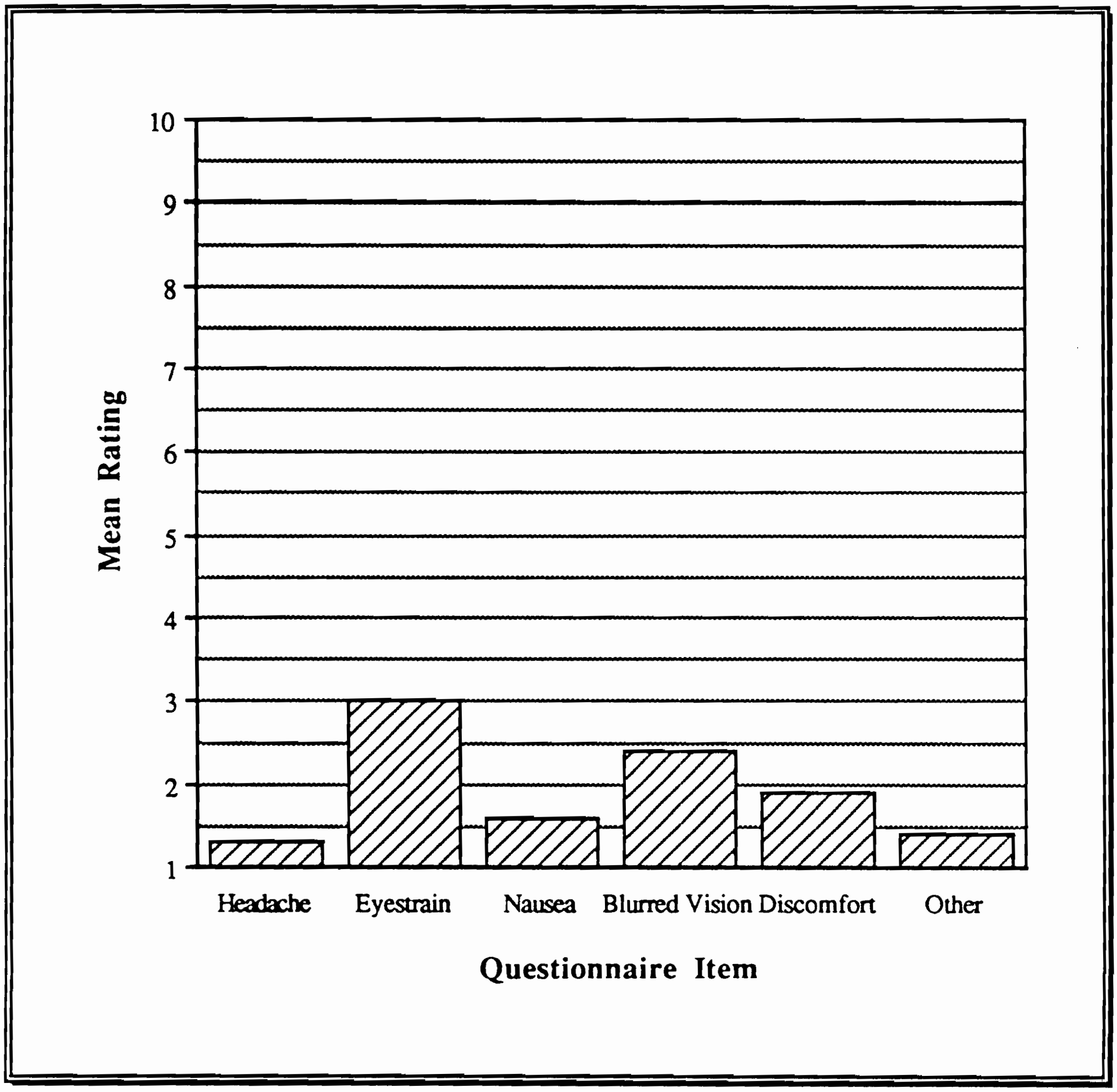


Figure 46. Mean questionnaire ratings of physical discomfort, Experiment 2.

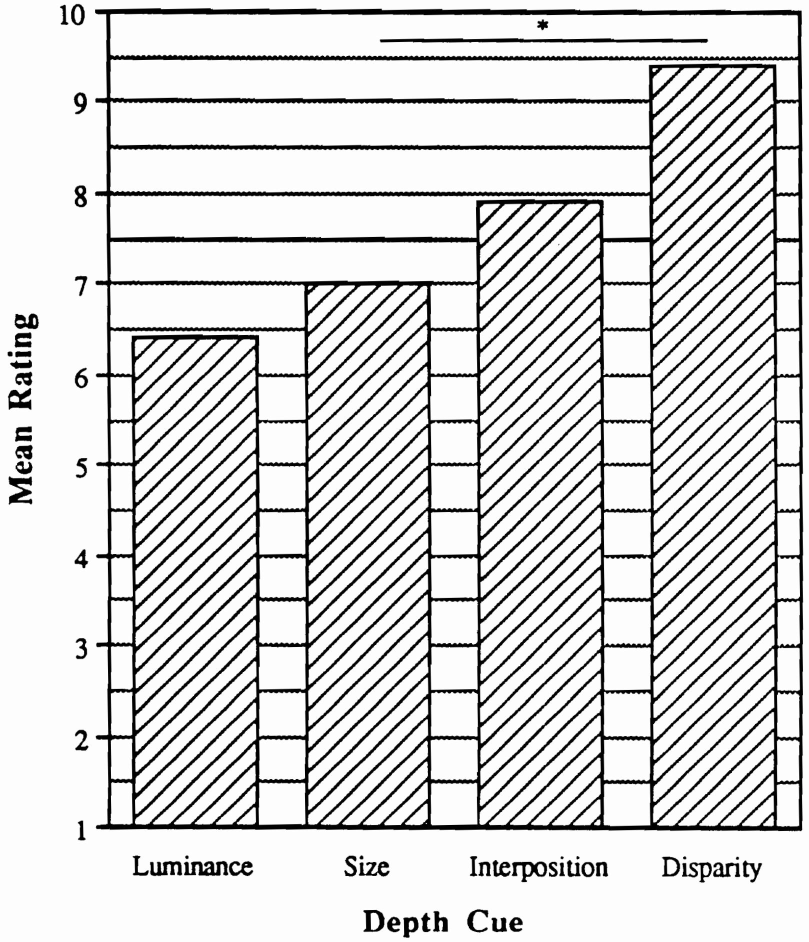


Figure 47. Mean questionnaire ratings of cue effectiveness, Experiment 2. Asterisk indicates smallest mean difference at $p \leq .05$.

and Luminance cues. Depth cue effects were complementary, with the lowest image quality ratings assigned to stimuli which incorporated no depth information, and the highest image quality ratings assigned to stimuli which contained all four depth cues. Despite the complementary nature of these depth cue effects, the relationship is clearly interactive rather than strictly additive. This interaction is illustrated in Figure 45.

Without question, Disparity dominated the image quality ratings. The addition of the Disparity cue dramatically increased image quality ratings. This is an important result which leads to three conclusions. First, although the Disparity cue was clearly not associated with any response-time benefits in Experiment 1, it is equally clear that stereoscopic presentations were associated with a highly compelling sense of apparent depth in Experiment 2. It is important to remember that the stimuli used in both experiments were identical; only the experimental tasks varied. Secondly, it seems likely that ratings of cue effectiveness for the Disparity cue in Experiment 1 may have been influenced by the compelling nature of the stereoscopic depth. Subjects may have rated Disparity as an effective cue in Experiment 1 simply because the relative depth differences among figures were so vivid. Thirdly, this result validated the saliency of depth introduced through the Disparity cue. Consequently, it is possible to rule out the possibility that the failure to demonstrate response-time advantages with stereoscopic presentations in Experiment 1 was due to an inappropriate choice of Disparity cue levels.

3-D Questionnaire . As before, ratings of participant discomfort verified that participants experienced no unusual problems, although some participants did complain of mild nausea. The highest mean rating is for the category of eyestrain, and even this rating is very low.

Relative ratings of cue effectiveness for the four depth cues are consistent with the image quality results. Disparity and Interposition cues were judged to be the most effective, followed by Size and Luminance cues. In addition, relative effectiveness ratings among the three monocular cues are consistent with those ratings reported in Experiment 1, as well as response-time effects reported in Experiment 1. The most notable rating difference between experiments occurred for the Disparity cue. Disparity supplanted Interposition as the most highly rated cue in Experiment 2. It is important to remember that the cue effectiveness ratings given in the two experiments had meanings which were task dependent. Since cue effectiveness described the degree to which each cue assisted participants in the completion of their experimental tasks, the relative rating shift can be attributed to changes in the nature of the experimental task. While participants in the first experiment used apparent depth information to make relative depth judgements, participants in the second experiment used the same information to judge image quality. Therefore, the rating shift should be interpreted as follows: participants reported that the Disparity cue had a larger influence on facilitating image quality discrimination than on aiding rapid judgements of relative depth. This rating shift is consistent with the response time data of Experiment 1 and the image quality data of Experiment 2.

EXPERIMENT 3

This experiment was designed to extend the results of Experiments 1 and 2 to include new stimulus and task dimensions. Of special interest was the clarification of the objective / subjective dissociation associated with the Disparity cue in Experiments 1 and 2. It was concluded in Experiment 1 that either the nature of the task (relative depth judgements) or stimuli (planar, simple, geometric figures) were such that stereoscopic presentation yielded no appreciable response-time benefit. It was also shown that this result was consistent with those of other researchers (i.e., Pepper and Hightower, 1984; Way, 1988). However, the results of Experiment 2 clearly showed that in an identical stimulus environment, the use of the Disparity cue had an overwhelming influence on the improvement of subjective image quality ratings. This result suggested that stereoscopic presentations may have a large subjective value which is separate in nature from performance effects.

Having demonstrated this dissociation in one stimulus environment, it was decided to test this relationship in a more complex stimulus and task environment. One contemporary use of a volumetric display which was suitable for this purpose is the horizontal situation display (HSD). More geometrically complex stimuli were developed for display in the HSD volume.

Additionally, it was of interest to explore the effects of depth cues under additional task demand. The experimental tasks included in Experiments 1 and 2 required only minimal effort, and it was desirable to consider more challenging tasks. The overall error rate in Experiment 1 was so low that very few error data existed to be considered. It was suggested that error rates might be considerably higher in more complex task environments.

Visual search and cursor positioning were identified as two tasks in the HSD environment which had potential for high task demand. There is a well established body of literature addressing the relevant parameters in 2-D visual search tasks (e.g., Treisman and Gelade, 1980; Treisman, Sykes, and Gelade, 1977). One way in which visual search may be made more difficult is by increasing the number of symbols from which the relevant information must be extracted. Response times in 2-D visual search tasks tend to increase in a linear fashion as a function of the number of distractor elements present. For example, Staller, Lappin, and Fox (1980) noted that response times for identification of random dot stereogram targets increased as a function of target set sizes, where set sizes of 1, 2, 3, and 4 items were used. However, Nakayama and Silverman (1986) reported that visual searches of greater than 25 objects which incorporated a stereo coding dimension were more efficient than searches not incorporating stereoscopic coding. Similarly, Zenyuh et al. (1988) found a visual search accuracy advantage for stereoscopic display, but only when medium and high display densities were used. One of the objectives of Experiment 3 was the investigation of map complexity on visual search performance in the 3-D HSD environment.

Regarding the effects of stereoscopic and other depth presentations on cursor positioning speed and accuracy, much less is known. Indeed, with the exception of the research of Beaton et al. (1987; 1988), few empirical investigations have been conducted to address these issues. Cursor positioning tasks clearly are of a qualitatively different nature than the judgement tasks incorporated in Experiments 1 and 2, since they involve direct spatial manipulation. Consequently, an additional objective of Experiment 3 was the investigation of depth cue manipulation on cursor positioning measures. While cursor positioning accuracy in the Z dimension would be expected to improve with more veridical and salient representations of depth, there was no reason to believe that positioning accuracy on the X-Y plane or positioning times should be affected.

In order for the tasks of visual search and cursor positioning to be meaningfully implemented, it was necessary to portray a display volume with sufficient depth. For example, cursor positioning on the Z or depth axis would be uninformative if only two discrete depth planes were portrayed in the volume. In Experiment 3, 11 discrete depth planes were portrayed in the HSD volume.

An additional objective of Experiment 3 concerned cue additivity effects. Cue additivity has been suggested in some of the literature (e.g., Dosher et al., 1986; Vlahos, 1965; Wickens, in press) but it is likely influenced by the nature of the stimuli and task. In the first two experiments, suprathreshold values were used for depth cue manipulations to ensure salience of all stimulus changes. Cue interaction, rather than additivity, was demonstrated for response times in Experiment 1 and image quality ratings in Experiment 2. This complementary interaction of depth cues was least pronounced in Experiment 1, where the use of suprathreshold cue levels may have produced a ceiling on cue effects. In Experiment 3, cue salience was manipulated at increments which approached threshold values. It was anticipated that if a cue additivity effect existed in this experimental context, the use of cue manipulations at a level closer to threshold should highlight such effects by reducing the probability of a ceiling effect.

Finally, the relationship of spatial ability to task performance was of interest in Experiment 3. In Experiment 1, faster response times were associated with superior spatial ability. This result was consistent with those of McGuinness and Brabyn (1984). Because no evidence was found for gender-related differences in MRT (spatial ability) scores or performance in Experiments 1 and 2, gender was not included in the main analyses of Experiment 3.

The specific hypotheses tested in this experiment were:

1. The individual use of Luminance, Size, and Disparity cues should have allowed faster target identification with fewer search errors, as well as higher image quality ratings, relative to display conditions which contained no depth information;
2. The use of multiple depth cues should have produced complementary effects. For example, the fastest search times and the most error-free performance should have occurred in responses to stimuli which incorporated all three depth cues;
3. Faster search times and fewer search errors should have been associated with increased cue salience and lower map complexity;
4. Higher image quality ratings should have been associated with the use of depth cues and increases in depth cue salience, but should have been unrelated to map complexity;
5. Cursor positioning times should have been constant among display conditions;
6. Cursor positioning errors in the Z dimension should have been lowest in the presence of one or more depth cues and increased depth cue salience;
7. MRT scores could have been correlated with search time and search errors; and
8. MRT scores should have been superior for male participants.

Method

Subjects. Twenty subjects (ten males and ten females, 18 to 29 years of age) participated in this experiment. As in the previous two experiments, young subjects were recruited since these participants were most likely to meet the visual screening criteria.

Subjects were recruited through campus flyers and were paid $30.00 for participation in the experiment. Prior to visual screening, participants were screened for prior experience with stereoscopic display devices and trackball controllers; subjects with previous stereo viewing experience or regular trackball use were not permitted to participate.

All participants were required to pass the same Ortho-Rater screening procedure described in Experiment 1. Informal observations suggested the possibility that the wearing of the stereoscopic polarizing glasses could impair visual acuity. To test this hypothesis, the Ortho-Rater acuity test was conducted twice for all participants in the screening process; once without the glasses and once while wearing the glasses. In addition, an Ortho-Rater test for color deficiency with pseudoisochromatic plates was included. This color test was included since discrimination of near-threshold changes in luminance which were required in the experiment could have been influenced by an inability of some subjects to discriminate differences in hue. Participants were not screened for contrast sensitivity since this procedure was found to be redundant with the Ortho-Rater procedure in Experiments 1 and 2 (no participants who passed the Ortho-Rater criteria in the first two experiments failed to meet the contrast sensitivity criteria).

Previous difficulties with stereoscopic training experienced by the three subjects in Experiment 1 might have been avoided had an appropriate stereoscopic screening device been used. Screening for stereoscopic acuity for this research was problematic for a variety of reasons. First, most standard tests of stereoscopic acuity (including the standard Ortho-Rater stereo test) incorporate stereo disparities of much smaller magnitudes than are possible to display on a stereoscopic CRT, due to limitations imposed by the spatial resolution and addressability of the CRT. For example, standard test disparities range from 2 arcsec to 2 arcmin. Unfortunately, the disparity range used among the three experiments in this research was from 2 to 10 arcmin.

In addition, informal observations for pilot research suggest that field-sequential stereoscopic presentations may involve a qualitatively different perception of depth than the space-multiplexing techniques used in standard stereoscopic tests. For example, one participant who was unable to fuse Ortho-Rater phoria images (and who also reported having a history of fusion problems) was nevertheless able to achieve stereoscopic fusion when viewing the CRT images. These two observations suggested that the most appropriate stereoscopic screening tool for use in this research would be presented with the stereoscopic CRT itself. Unfortunately, no such tool existed prior to the initiation of this research.

RDSs were generated on the stereoscopic CRT for screening purposes. These RDSs were of similar nature to those described by Julesz (1971; 1977). The RDS makes an ideal stereoscopic screening stimulus, since in the absence of stereopsis there are no obvious contours visible in the left and right image fields. The RDSs were generated using the same computer software compiler and hardware described elsewhere in this dissertation. After generating frames filled with random dots, stereoscopic figures were created by introducing lateral disparity among pixels in the center of each stereoscopic field. A series of 18 RDSs were used as test stimuli, two RDSs at each of nine values of crossed and nine values of uncrossed disparity. The range of disparities represented by these RDSs were from 1 pixel (two arcmin) to 9 pixels (18 arcmin) in both crossed and uncrossed disparities. Subjects were required to identify the orientations of virtual Landolt rings imbedded in the RDSs, as well as the direction of the apparent depth (i.e., in front of the screen or behind the screen). The rings subtended approximately 100 arcmin, while the frame of each stereogram subtended approximately 200 arcmin. The Landolt rings were 18 arcmin wide, with gaps subtending 34 arcmin. The RDSs were filled with pixel dots with a 50% dot density. Due to the novelty of this screening device, no validation information was available. Consequently, this instrument was included in Experiment 3 solely for the purpose of describing the distribution of scores for use in subsequent research. Screening profiles were recorded for all participants, and no participants were rejected on the basis of RDS screening scores (that is, no screening criteria were implemented).

A final component of the visual screening profile was the estimation of interpupillary distance (IPD). Although the effects of IPD variance on apparent depth were mediated through the use of a repeated measures research design, it was of interest to compare these measures with previously published population means. IPDs (the horizontal distance between the centers of each pupil) were estimated with a ruler as participants viewed a distant object.

Experimental task. The basic stimulus environment consisted of a 3-D HSD with eleven discrete apparent depth planes in the displayed volume. These apparent depth planes corresponded to the discrete stimulus levels associated with each depth cue (described below). A 2-D, 5 x 5 grid pattern was displayed on the X-Y plane. This grid pattern served as a reference point in the apparent volume, with the grid always being displayed on the center depth plane. Within this volume, three classes of symbols were displayed. Symbols were always centered within the grid squares. In addition, since the results of McCann (1979) suggest that spatial proximity may affect the accuracy and speed of relative stereoscopic depth judgements, the positions of these symbols within the overall grid structure were randomized. Only one symbol was displayed at one time in any given grid square.

One symbol was a square frame with a cross-hair in the center. This was the *cursor* (Figure 48, center), the symbol which participants moved through the display volume. Another symbol class was the *background* symbol (Figure 48, bottom right). Background

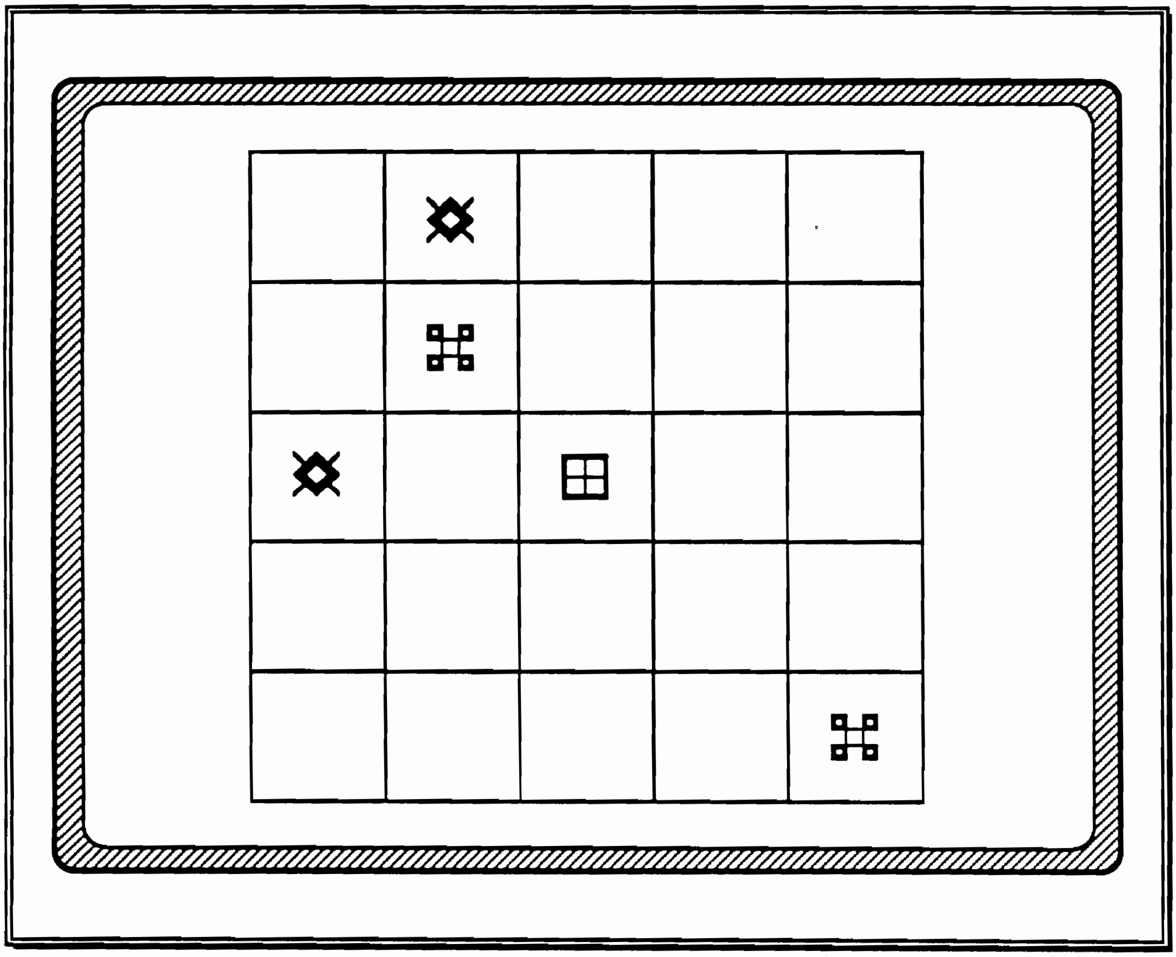


Figure 48. Horizontal situation display, Experiment 3. In this scene, no depth cues have been applied.

symbols were always displayed in the apparent depth plane farthest from the viewer. Background symbols were included to provide points of reference for the far boundary on the depth axis, as well as to create a visually enriched background. The third symbol class was the *foreground* symbol (Figure 48, far left). Foreground symbols were distributed throughout the display volume. All foreground symbols were displayed on the same apparent depth plane, with the exception of one symbol which was displayed at a different apparent depth. This foreground symbol was referred to as the *target* symbol.

The experimental task was composed of three components. Subjects first searched for the target. Having identified the target, subjects next moved the cursor to the same 3-D location as the target. Following cursor positioning, subjects rated the image quality of the scene.

Design. The experimental design was a 4 x 2 x 2 x 2 x 3 full-factorial design and all independent variables were within-subjects variables. In addition, there were three replications of each of the 96 experimental conditions. Presentation of experimental conditions was randomized within replications, with each subject contributing a total of 288 observations over a three day period (96 trials per day, in addition to one day of practice). The following independent variables were included in the design.

(1) Separation (four levels). The apparent depth separation among target and foreground symbols was varied to change the salience of the target/foreground depth differences in the scene. Targets were displaced in apparent depth from the other foreground symbols by either one, two, three, or four depth planes. These apparent depth planes corresponded to to the discrete stimulus manipulations indicated below (i.e., changes in stimulus sizes, luminance, and disparity).

(2) Size (two levels). The display did or did not incorporate relative size cues for indication of depth. In the Size condition, closer figures were appropriately larger in

angular subtense. The Size cue was implemented by developing separate symbol sets to represent each of the eleven apparent depth planes. That is, larger symbols were used to indicate a position on the depth axis closer to the viewer. Symbol sizes ranged from a 17 x 17 pixel matrix to a 37 x 37 pixel matrix, with 2-pixel increments among levels. For the viewing distance used, a 2-pixel increment was equal to approximately 4 min of visual arc. Using the method of limits with ascending and descending trials, difference thresholds were determined for two symbols placed within one degree of each other. Differences of four arcmin were discriminable over 75% of the time. The lower bound of the size range was selected to ensure stimulus detectability. All symbols were designed such that between 49% and 53% of the pixels in the symbol matrix were active.

(3) Luminance (two levels). The displayed image did or did not incorporate luminance cues for indication of apparent depth. In the Luminance condition, closer figures had a proportionally greater luminance. Eleven luminance values were used, corresponding to the eleven apparent depth planes represented in the display volume. Using the method of limits with ascending and descending trials, difference thresholds were determined for two symbols placed within one degree of each other. Luminance increments of approximately 18% were discriminable greater than 75% of the time. Consequently, luminance increments of 18% were used. The luminance values ranged from 0.3 to 1.9 cd/m^2 (at the eye of the observer). This range was determined by subtracting from the maximum achievable luminance for the red CRT electron gun. As previously discussed, the red CRT electron gun was used in exclusion of the blue and green guns to minimize perceptible ghosting. Since the display hardware used six-bit digital to analog converters (DACs) for each CRT electron gun, the luminance increments were limited in resolution to six bits. The luminance output at the center of the CRT screen was plotted as a function of the red gun DAC value in Figure 49.

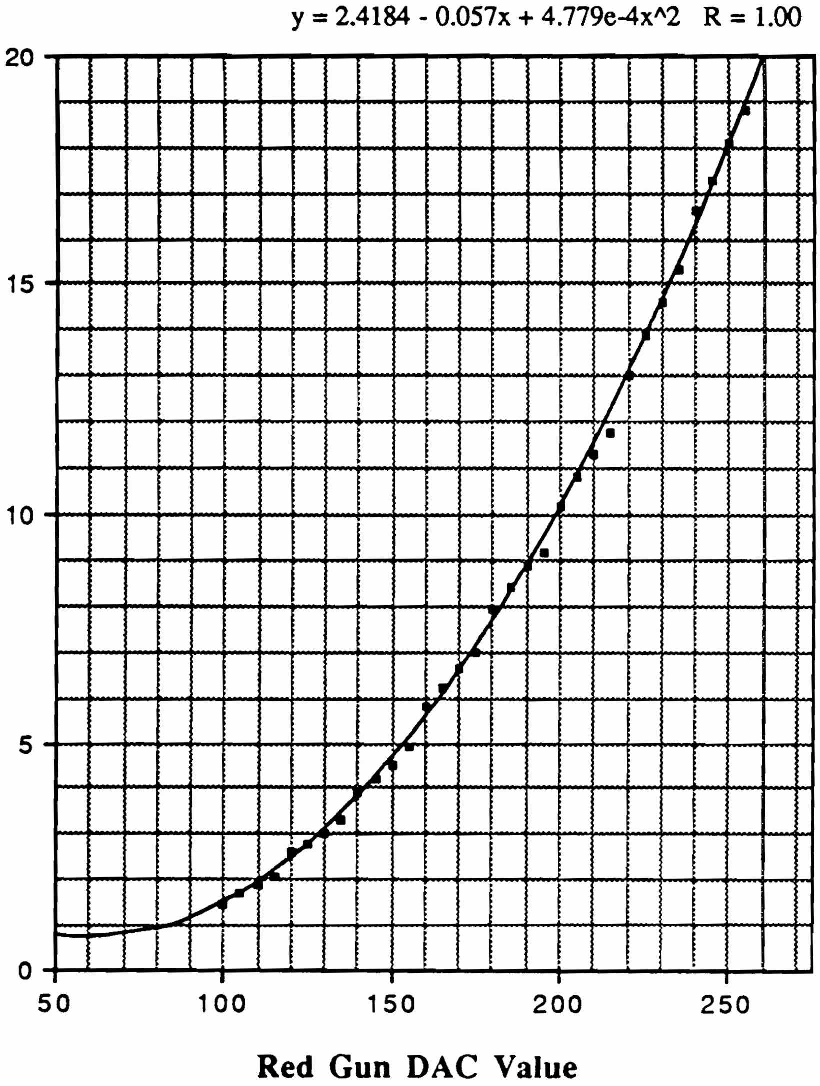


Figure 49. CRT luminance as a function of red gun DAC value. Measurements were taken at the center of the screen. Luminance values do not reflect the subsequent loss in luminance associated with the LC shutter and polarizing glasses.

Measures of CRT luminance uniformity indicated that for any given DAC value, measured luminances were up to 15% dimmer near the edges of the CRT screen than luminance values measured at the center of the screen. Such luminance nonuniformity is typical for a CRT. However, it was important that changes in use of the Luminance cue not be confounded with the position of symbols on the screen. In order to control for this luminance nonuniformity, an empirically derived correction was applied to DAC levels as a function of grid position. The correction reduced luminance differences to approximately four percent.

(4) Binocular disparity (two levels). The display did or did not incorporate binocular disparity cues for indication of apparent depth. Eleven discrete disparity values were used, each level corresponding to one of the 11 apparent depth planes represented in the display volume. Using the method of limits with ascending and descending trials, difference thresholds were determined for two symbols placed within one degree of each other. The resolution and addressability of the CRT limited the disparity resolution to approximately two-arcmin steps at the viewing distance selected. Since these steps were discriminable more than 75% of the time, the smallest increments possible (two arcmin) were used in the experiment. Disparity values ranged from 10 arcmin of crossed disparity to 10 arcmin of uncrossed disparity. This disparity range was well within the limits of comfortable fusion for all participants (as determined by the RDS screening procedure). This disparity range produced satisfactory apparent depth without exacerbating ghosting problems. The center depth plane was portrayed with no disparity.

(5) Complexity (three levels). Foreground and background symbols were present in three different densities (two, four, or six of each symbol class). For example, at the four symbol density level there were four non-target foreground symbols and four

background symbols. In all cases, only one cursor and one target was displayed. These levels were selected to allow a comparison with existing visual search literature.

Dependent variables. Dependent variables in Experiment 3 included:

1. Search time (the total elapsed time between stimulus presentation and the initiation of cursor movement);
2. Total search errors (the number of incorrectly identified targets, determined by the final position of the cursor);
3. Cursor positioning time (the total elapsed time between initiation and completion of cursor movement to the target);
4. Magnitude of X-Y positioning errors in addressable pixels from the center of the cursor to the center of the target $((\Delta X^2 + \Delta Y^2)^{1/2})$;
5. Magnitude of Z (depth) positioning errors (the total number of apparent depth planes over which the cursor was displaced from the target position); and
6. Image quality rating (using the same nine-point image quality scale as was used in Experiment 2).

Procedure. (1) Informed consent. All participants read and signed informed consent forms which outlined the benefits, risks, and rights associated with participation in the screening procedure and the experiment (e.g., Appendix A).

(2) Training. All participants received approximately 45 min of practice on representative tasks. Training was conducted on a separate day from the experimental trials and commenced no later than two weeks following administration of the visual screening procedure. All instructions (Appendix K) were read aloud by the experimenter as the participant read along. During the initial training, participants viewed representative HSDs for each experimental depth cue. Participants were given detailed explanations of the

meaning of the symbols and each of the three depth cues. For each trial, the relationship between the input device and cursor movement was illustrated and participants practiced cursor movement. This phase of the training was informational only, and no responses were recorded.

During the second and final training phase, participants initiated trial presentation by pressing and releasing the middle button on the pointing device. After releasing the button, the HSD was displayed and participants searched for the target. Once the target was identified, participants moved the cursor to the 3-D position of the target. Because search times were terminated when cursor movements began, participants were instructed to not initiate cursor movement until they had identified the target. When the participant was satisfied that the cursor was correctly positioned, the middle button was again pressed and released to terminate accumulation of positioning time. Participants were instructed to respond as quickly as possible without making an erroneous response.

At this time, the image quality rating scale was displayed in the upper left corner of the display. Participants rated the image quality of the display by moving a highlighted field among the ratings with the trackball. The trial was terminated by pressing and releasing the center button a final time. During this final phase of training, participants were provided with detailed feedback following any error. Forty-eight representative practice trials were presented. Participants received one five-min break after completing 24 of the practice trials. After completion of the full 48 trials, participants were dismissed for the day.

(3) Experimental trials. The first of three experimental trial sessions commenced on the day following practice, with each of the three replications completed on consecutive days. Therefore, each subject participated for a total of four consecutive days. The

experimental trials proceeded in the same manner as the second portion of training, with the following exceptions.

1. No feedback was given during the experimental trials.
2. The experimental trials were preceded by a five-min visual adaptation phase, during which participants viewed an empty grid, presented at the median experimental luminance value.
3. The first 10 trials were counted as practice trials and were not included in the analyses.
4. Subjects completed an additional 96 trials, with a five-min rest break following completion of the first 48 trials. Each experimental session lasted approximately 60 min.

(4) 3-D Questionnaire. On the last day of the experiment (Day 4), participants completed the 3-D Questionnaire (as reported in Experiment 1, Experiment 2, and Appendix C).

(5) Mental Rotations Test. On the last day of the experiment (Day 4), participants completed the MRT (as reported in Experiment 1 and Appendix D).

Results

Due to the large number of dependent variables included in Experiment 3, over 70 statistically significant effects were found in the analyses. Upon examination of these effects it was seen that the low interpretability of the five-way interactions and many of the four-way interactions prevented a meaningful discussion of these effects. Therefore, only select four-way interactions which are associated with meaningful interpretations are included in this text. For the interested reader, tables of means for the five-way interactions in these analyses are presented in Appendix L (Tables L-1 through L-6). From these tables, any four-way interactions can also be reconstructed.

Of the statistically significant two- and three-way interactions, those which were seen as contributing to the discussion of the objectives of this research receive detailed attention in the text. In particular, many of those effects which are included in significant higher-order interactions are not given detailed attention. Illustrations of the significant two- and three-way interactions not discussed in the text are included in Appendix M. All significant main effects are included in the main text.

Finally, while an alpha level of .05 was used as the criterion for statistical significance in the following analyses, it was recognized that those effects which approached this level without reaching it (i.e., $.05 < p \leq .10$) might be of interest to some readers. While these effects are not discussed in the text, illustrations of these effects are included in Appendix M.

Search time. Search time data were collapsed across replications and submitted to a five-factor ANOVA (Luminance x Size x Disparity x Complexity x Separation). Five main effects are statistically significant (Table 11): Luminance ($p < .0001$), Size ($p < .0001$), Disparity ($p < .0001$), Complexity ($p < .0001$), and Separation ($p < .0001$). In general, searches were faster in the presence of Luminance (Figure 50), Size (Figure 51), and Disparity cues (Figure 52). In addition, searches were faster with lower values of Complexity (smaller numbers of foreground and background symbols, Figure 53) and with higher values of Separation (larger numbers of apparent depth planes separating targets from foreground symbols, Figure 54). Newman-Keuls post-hoc comparisons of the means from these last two main effects (Appendix N, Tables N-1 and N-2) showed that search times are significantly different among all three levels of Complexity. However,

TABLE 11

ANOVA Summary Table for Search Time (s), Experiment 3

Source	*df*	*MS*	*F*	*p*
Subjects (Sub)	19	612.6781		
Luminance (L)	1	5221.4310	44.14	< .0001
L * Sub	19	118.2955		
Size (Sz)	1	9187.6050	38.29	< .0001
Sz * Sub	19	239.9782		
Disparity (D)	1	9808.0867	41.10	< .0001
D * Sub	19	238.6192		
Complexity (C)	2	1229.0705	75.96	< .0001
C * Sub	38	16.1797		
Separation (Sp)	3	3300.8204	65.59	< .0001
Sp * Sub	57	50.3253		
L * Sz	1	2348.9199	28.55	< .0001
L * Sz * Sub	19	82.2607		
L * D	1	3113.9384	28.67	< .0001
L * D * Sub	19	108.5954		
L * C	2	99.3649	12.52	< .0001
L * C * Sub	38	7.9364		
L * Sp	3	83.6661	11.32	< .0001
L * Sp * Sub	57	7.3882		
Sz * D	1	4435.6174	22.03	.0002
Sz * D * Sub	19	201.3192		
Sz * C	2	187.4867	16.49	< .0001
Sz * C * Sub	38	11.3701		
Sz * Sp	3	2.8640	0.32	.8115
Sz * Sp * Sub	57	8.9738		
D * C	2	430.0869	28.27	< .0001
D * C * Sub	38	15.2110		

TABLE 11 (continued)

ANOVA Summary Table for Search Time (s), Experiment 3

Source	*df*	*MS*	*F*	*p*
D * Sp	3	45.1552	4.76	.0050
D * Sp * Sub	57	9.4832		
C * Sp	6	99.0148	13.93	< .0001
C * Sp * Sub	114	7.1059		
L * Sz * D	1	2014.9962	21.55	.0002
L * Sz * D * Sub	19	93.4861		
L * Sz * C	2	26.9580	4.63	.0159
L * Sz * C * Sub	38	5.8228		
L * Sz * Sp	3	317.8664	30.00	< .0001
L * Sz * Sp * Sub	57	10.5947		
L * D * C	2	51.0251	10.81	.0002
L * D * C * Sub	38	4.7193		
L * D * Sp	3	160.1852	15.31	< .0001
L * D * Sp * Sub	57	10.4621		
L * C * Sp	6	5.5676	0.86	.5300
L * C * Sp * Sub	114	6.5079		
Sz * D * C	2	192.4860	11.61	< .0001
Sz * D * C * Sub	38	16.5754		
Sz * D * Sp	3	103.0836	9.14	< .0001
Sz * D * Sp * Sub	57	11.2792		
Sz * C * Sp	6	3.0936	0.44	.8513
Sz * C * Sp * Sub	114	7.0452		
D * C * Sp	6	21.6296	3.67	.0023
D * C * Sp * Sub	114	5.8939		
L * Sz * D * C	2	13.9808	3.19	.0523
L * Sz * D * C * Sub	38	4.3807		
L * Sz * D * Sp	3	204.7050	22.15	< .0001
L * Sz * D * Sp * Sub	57	9.2430		

TABLE 11 (continued)

ANOVA Summary Table for Search Time (s), Experiment 3

Source	*df*	*MS*	*F*	*p*
L * Sz * C * Sp	6	23.0511	3.61	.0026
L * Sz * C * Sp * Sub	114	6.3870		
L * D * C * Sp	6	14.3837	2.68	.0180
L * D * C * Sp * Sub	114	5.3635		
Sz * D * C * Sp	6	4.5870	0.57	.7531
Sz * D * C * Sp * Sub	114	8.0406		
L * Sz * D * C * Sp	6	19.7596	3.68	.0022
L * Sz * D * C * Sp * Sub	114	5.3631		
Total	1919			

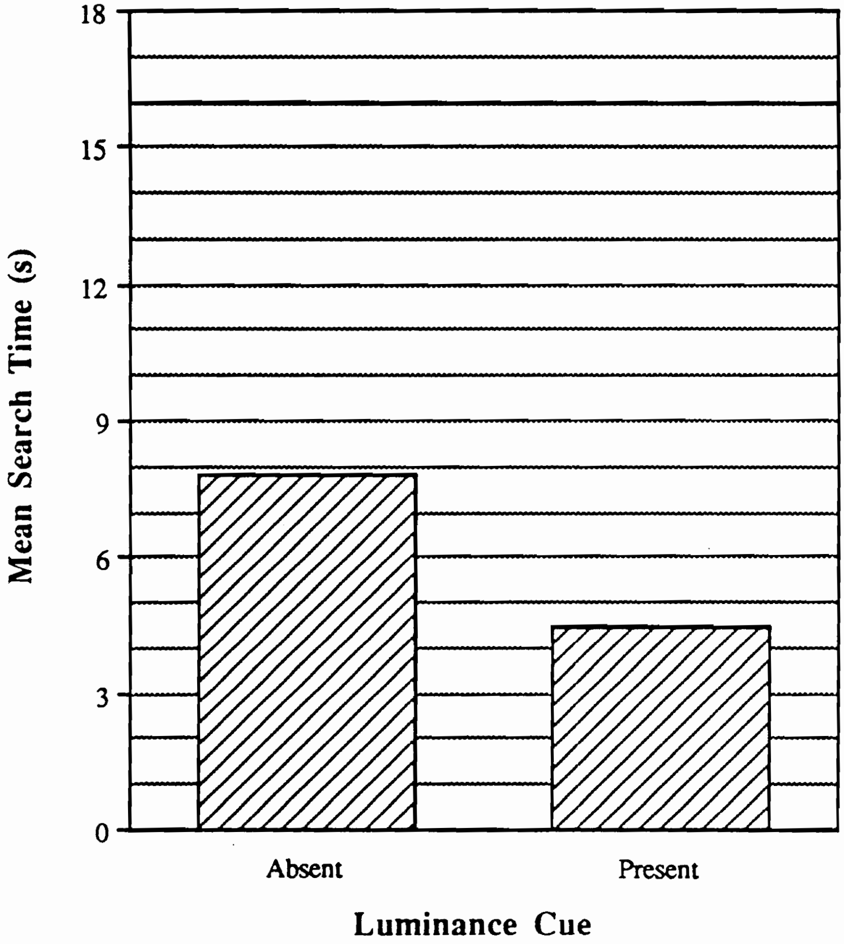


Figure 50. Mean search time as a function of Luminance cue, Experiment 3.

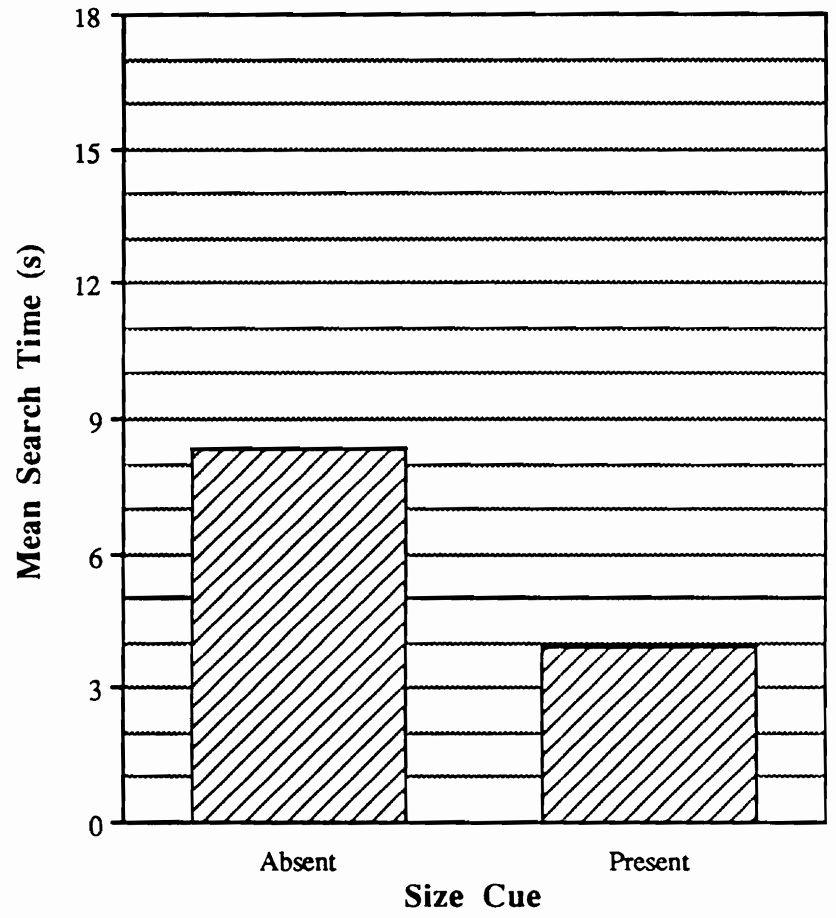


Figure 51. Mean search time as a function of Size cue, Experiment 3.

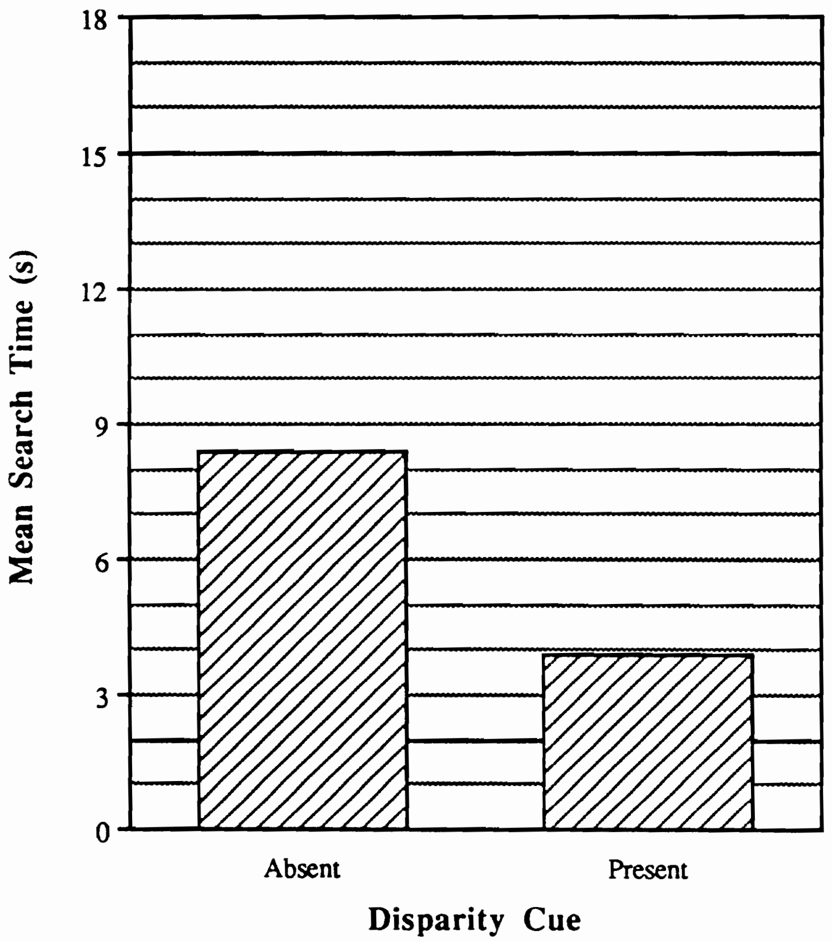


Figure 52. Mean search time as a function of Disparity cue, Experiment 3.

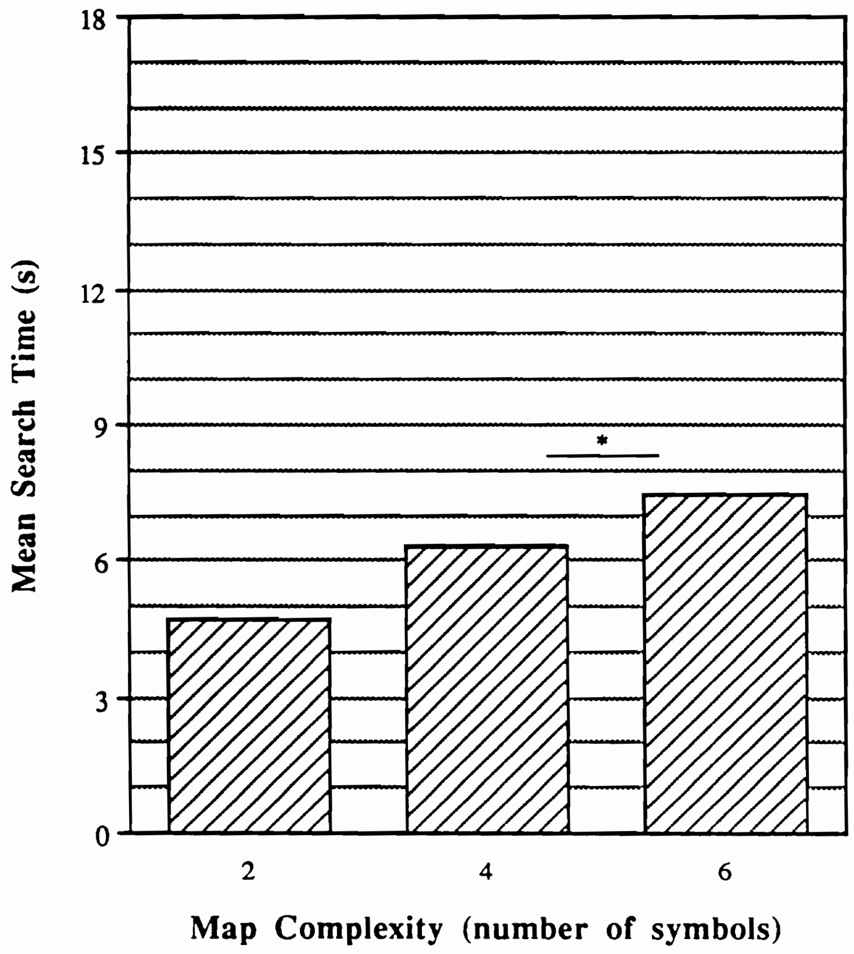


Figure 53. Mean search time as a function of Complexity, Experiment 3. Asterisk indicates smallest mean difference at $p \leq .05$.

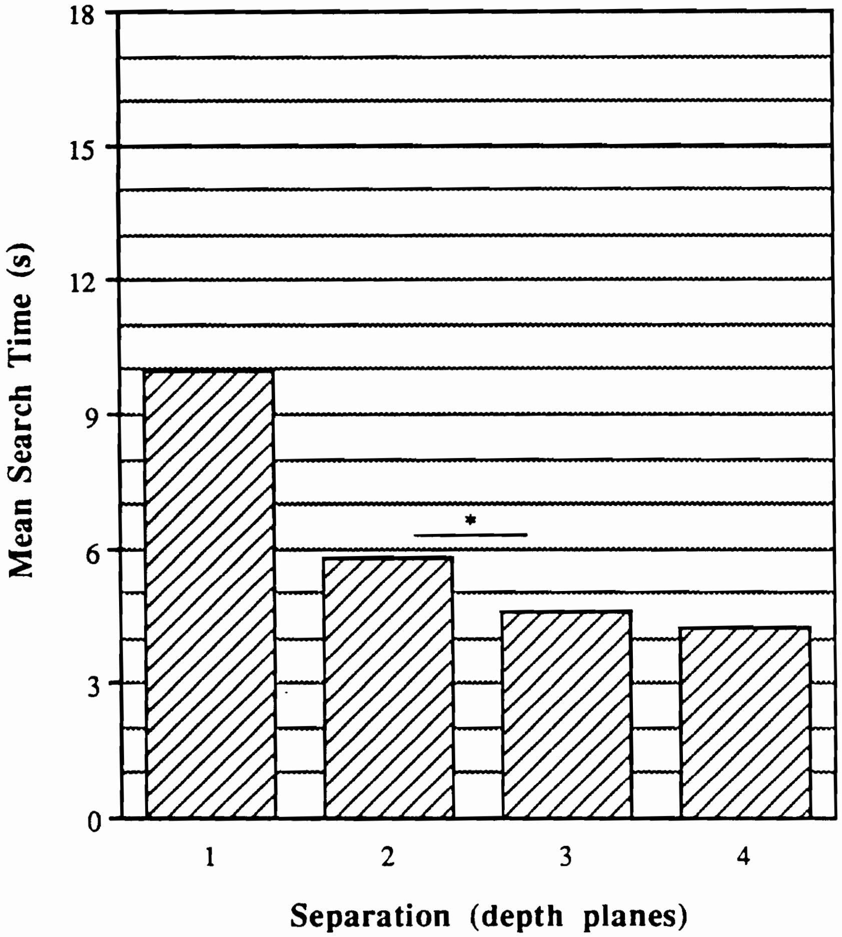


Figure 54. Mean search time as a function of Separation, Experiment 3. Asterisk indicates smallest mean difference at $p \leq .05$.

search times at 3 depth planes of Separation are not significantly different than search times at 4 depth planes of Separation.

There were 21 statistically significant interaction effects found in this analysis. Of these interactions, 16 are presented in Appendix M (Figures M-1 through M-16) and three are derivable from Table L-1. These effects are not included in the text for reasons discussed above (many of the interactions are included in the four-way interaction discussed here). Those interaction effects presented here in detail include Complexity x Separation ($p < .0001$) and Luminance x Size x Disparity x Separation ($p < .0001$). Post-hoc simple-effect F-tests and Newman-Keuls tests were conducted to determine where the significance is located in these interactions (Tables N-3 through N-14). Search times are significantly different as a function of Complexity, at all levels of Separation (Figure 55). The interaction of Luminance x Size x Disparity is statistically significant at 2, 3, and 4 depth planes of Separation (Figure 56). The interaction of Luminance x Size is statistically significant at each of these three levels, but only in the absence of the Disparity cue. Finally, searches were significantly faster in the presence of the Luminance cue, but only in the absence of Size and Disparity cues at 3 and 4 depth planes of Separation. At 2 depth planes of separation and in the absence of the Disparity cue, searches were significantly faster as a function of the Luminance cue, both with and without the Size cue.

Search errors. The overall search error rate is 14.9%. Although this appears to be an order of magnitude higher than the error rate reported for Experiment 1, there is an important difference. In both experiments, some of the trials were presented with no depth cues (due to the factorial nature of the designs). In Experiment 1, participants were allowed a response option of "no depth cues." Consequently, the error rate reported for Experiment 1 can be considered an accurate reflection of total errors. However, participants were allowed no such response option in Experiment 3. Instead, subjects were

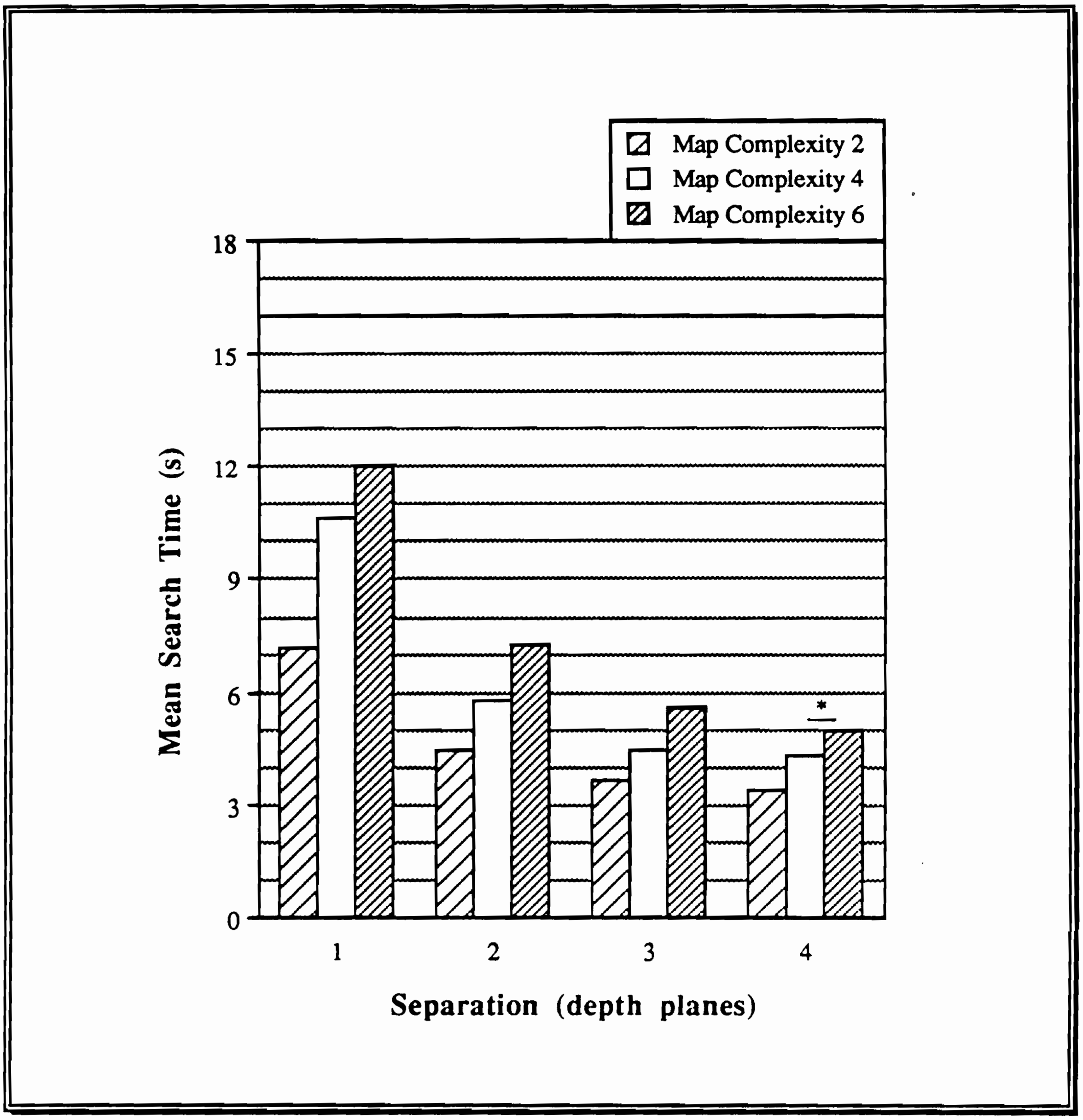


Figure 55. Mean search time as a function of Separation and Complexity, Experiment 3. Asterisk indicates smallest tested mean difference at $p \leq .05$.

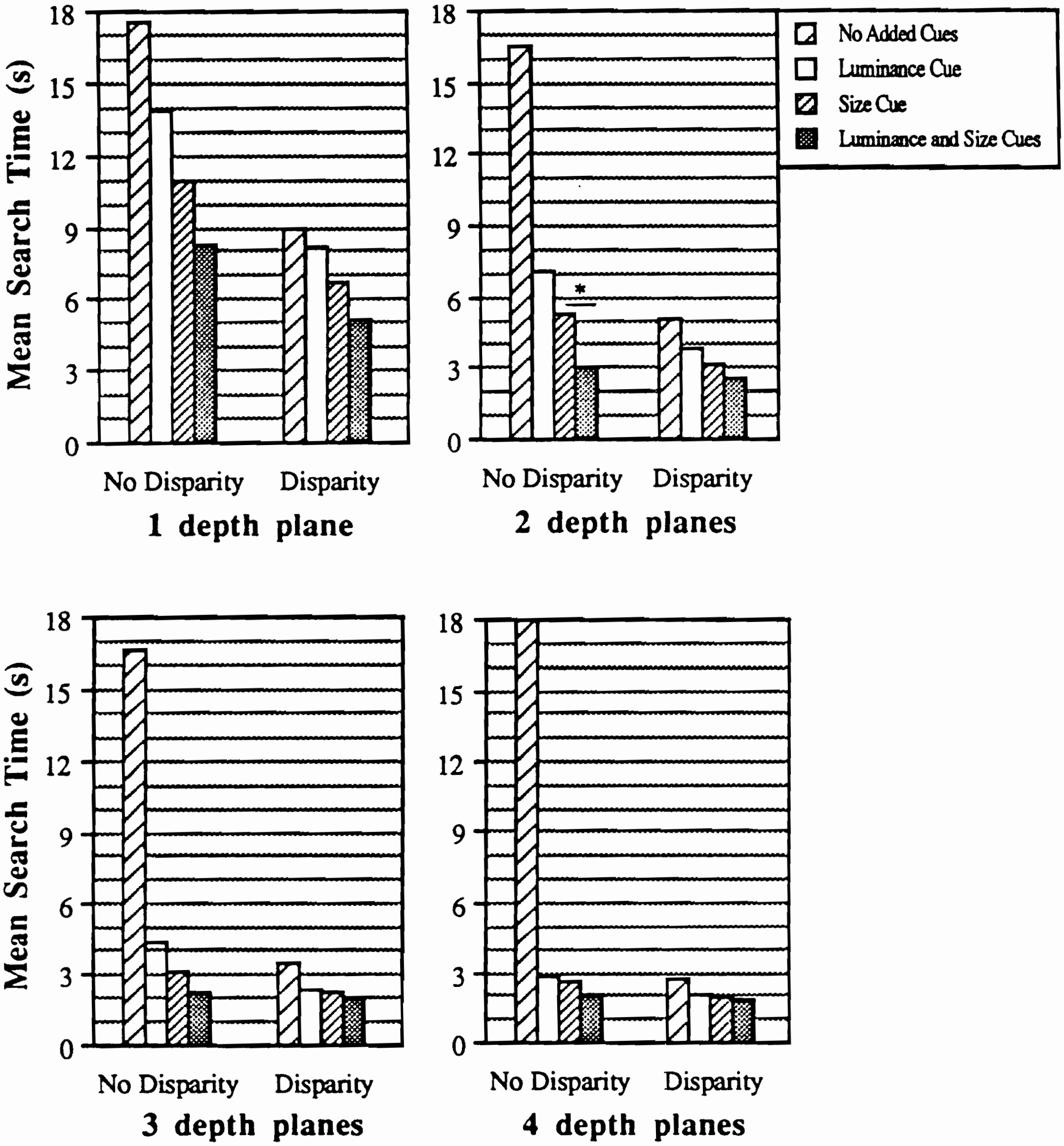


Figure 56. Mean search time as a function of Luminance, Size, and Disparity cues, and Separation, Experiment 3. Asterisk indicates smallest tested mean difference at $p \leq .05$.

told that for some of the trials, the depth differences would be very small. If they were unable to locate the target after a reasonable amount of time, they were to make their best guess. It was felt that this form of instruction would encourage increased search effort and would result in clearer differences in search times. Consequently, the error rate of 14.9% for Experiment 3 actually is composed of true errors plus the errors committed as a result of no depth information being present in the trial. If the proportion of trials containing no depth information (12.5%) is removed from the overall error rate, the true error rate can be estimated to be approximately 2.4%. Since the true error rate is representative of such a small proportion of the total experimental trials, only the main effects from the search error analysis are presented in detail here. Illustrations of the remaining significant effects from this analysis are included in Appendix M (Figures M-17 through M-31).

Search error data were collapsed across replications and submitted to a five-factor ANOVA (Luminance x Size x Disparity x Complexity x Separation). Five main effects are statistically significant (Table 12): Luminance ($p < .0001$), Size ($p < .0001$), Disparity ($p < .0001$), Complexity ($p = .0037$), and Separation ($p < .0001$). In general, fewer search errors were made in the presence of Luminance (Figure 57), Size (Figure 58), and Disparity cues (Figure 59). In addition, fewer search errors were committed with less Complexity (Figure 60) and with greater Separation (Figure 61). Newman-Keuls post-hoc comparisons of the means from these last two main effects (Tables N-15 and N-16) showed that search errors are not significantly different as a function of Complexity for 2 and 4 symbols. Search errors at 1 depth plane of Separation are significantly different from search errors at 2, 3, and 4 depth planes of Separation. Search errors at 2 depth planes of Separation are not significantly different than Search errors at 3 depth planes of Separation. Search errors at 4 depth planes of Separation are not significantly different than search errors at 3 depth planes of Separation.

TABLE 12

ANOVA Summary Table for Total Search Errors, Experiment 3

Source	*df*	*MS*	*F*	*p*
Subjects (Sub)	19	0.7909		
Luminance (L)	1	128.6505	1017.82	< .0001
L * Sub	19	0.1264		
Size (Sz)	1	223.4505	479.64	< .0001
Sz * Sub	19	0.4659		
Disparity (D)	1	198.2755	1227.82	< .0001
D * Sub	19	0.1615		
Complexity (C)	2	0.9005	6.53	.0037
C * Sub	38	0.1379		
Separation (Sp)	3	24.2227	83.74	< .0001
Sp * Sub	57	0.2893		
L * Sz	1	107.8255	504.62	< .0001
L * Sz * Sub	19	0.2137		
L * D	1	103.1380	324.49	< .0001
L * D * Sub	19	0.3178		
L * C	2	0.2224	1.62	.2116
L * C * Sub	38	0.1374		
L * Sp	3	1.0227	4.45	.0070
L * Sp * Sub	57	0.2296		
Sz * D	1	151.3130	527.77	< .0001
Sz * D * Sub	19	0.2867		
Sz * C	2	0.7255	3.63	.0360
Sz * C * Sub	38	0.1998		
Sz * Sp	3	3.9283	14.33	< .0001
Sz * Sp * Sub	57	0.2741		
D * C	2	4.1099	26.45	< .0001
D * C * Sub	38	0.1554		

TABLE 12 (continued)

ANOVA Summary Table for Total Search Errors, Experiment 3

Source	*df*	*MS*	*F*	*p*
D * Sp	3	2.0061	11.42	< .0001
D * Sp * Sub	57	0.1757		
C * Sp	6	0.2248	1.15	.3379
C * Sp * Sub	114	0.1954		
L * Sz * D	1	86.2755	303.47	< .0001
L * Sz * D * Sub	19	0.2843		
L * Sz * C	2	0.3849	3.39	.0442
L * Sz * C * Sub	38	0.1135		
L * Sz * Sp	3	1.8727	7.60	.0002
L * Sz * Sp * Sub	57	0.2463		
L * D * C	2	1.1880	5.79	.0064
L * D * C * Sub	38	0.2050		
L * D * Sp	3	1.0991	7.46	.0003
L * D * Sp * Sub	57	0.1474		
L * C * Sp	6	0.2009	0.98	.4402
L * C * Sp * Sub	114	0.2044		
Sz * D * C	2	3.3349	14.84	< .0001
Sz * D * C * Sub	38	0.2247		
Sz * D * Sp	3	0.1186	0.50	.6856
Sz * D * Sp * Sub	57	0.2385		
Sz * C * Sp	6	0.2470	1.30	.2623
Sz * C * Sp * Sub	114	0.1898		
D * C * Sp	6	0.2925	1.84	.0973
D * C * Sp * Sub	114	0.1589		
L * Sz * D * C	2	1.2630	7.82	.0014
L * Sz * D * C * Sub	38	0.1616		
L * Sz * D * Sp	3	3.0172	18.14	< .0001
L * Sz * D * Sp * Sub	57	0.1663		

TABLE 12 (continued)

ANOVA Summary Table for Total Search Errors, Experiment 3

Source	*df*	*MS*	*F*	*p*
L * Sz * C * Sp	6	0.5884	4.27	.0006
L * Sz * C * Sp * Sub	114	0.1379		
L * D * C * Sp	6	0.3137	1.67	.1354
L * D * C * Sp * Sub	114	0.1882		
Sz * D * C * Sp	6	0.1675	1.06	.3885
Sz * D * C * Sp * Sub	114	0.1575		
L * Sz * D * C * Sp	6	0.1109	0.77	.5917
L * Sz * D * C * Sp * Sub	114	0.1433		
Total	1919			

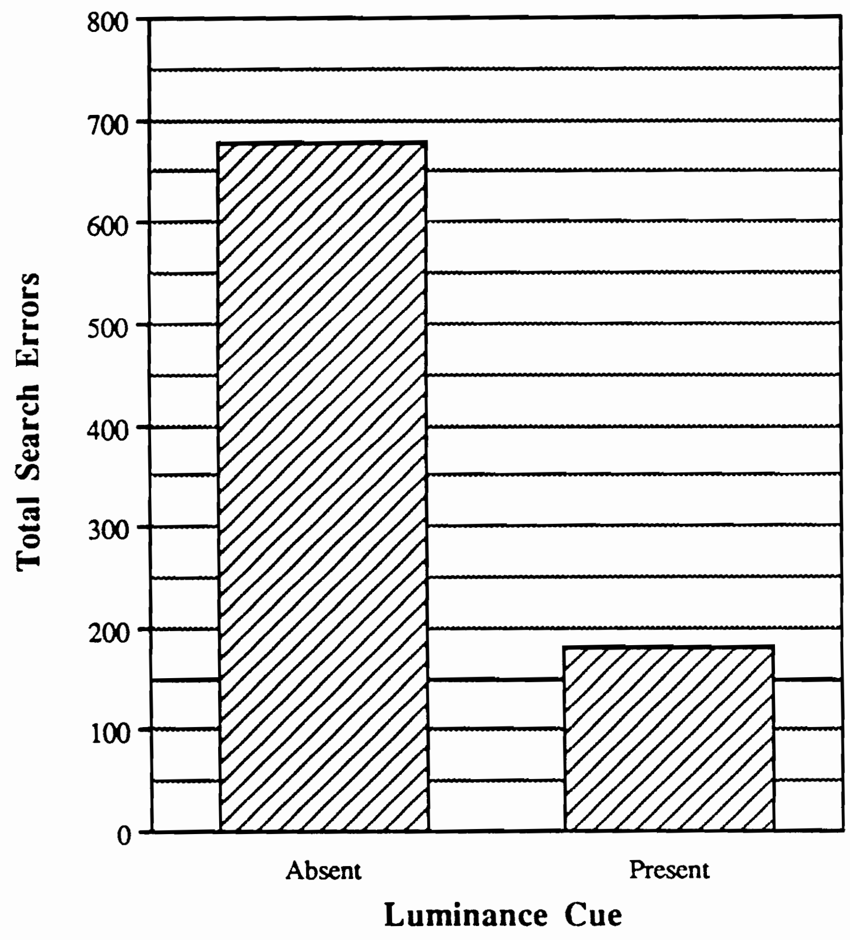


Figure 57. Total search errors as a function of Luminance cue, Experiment 3.

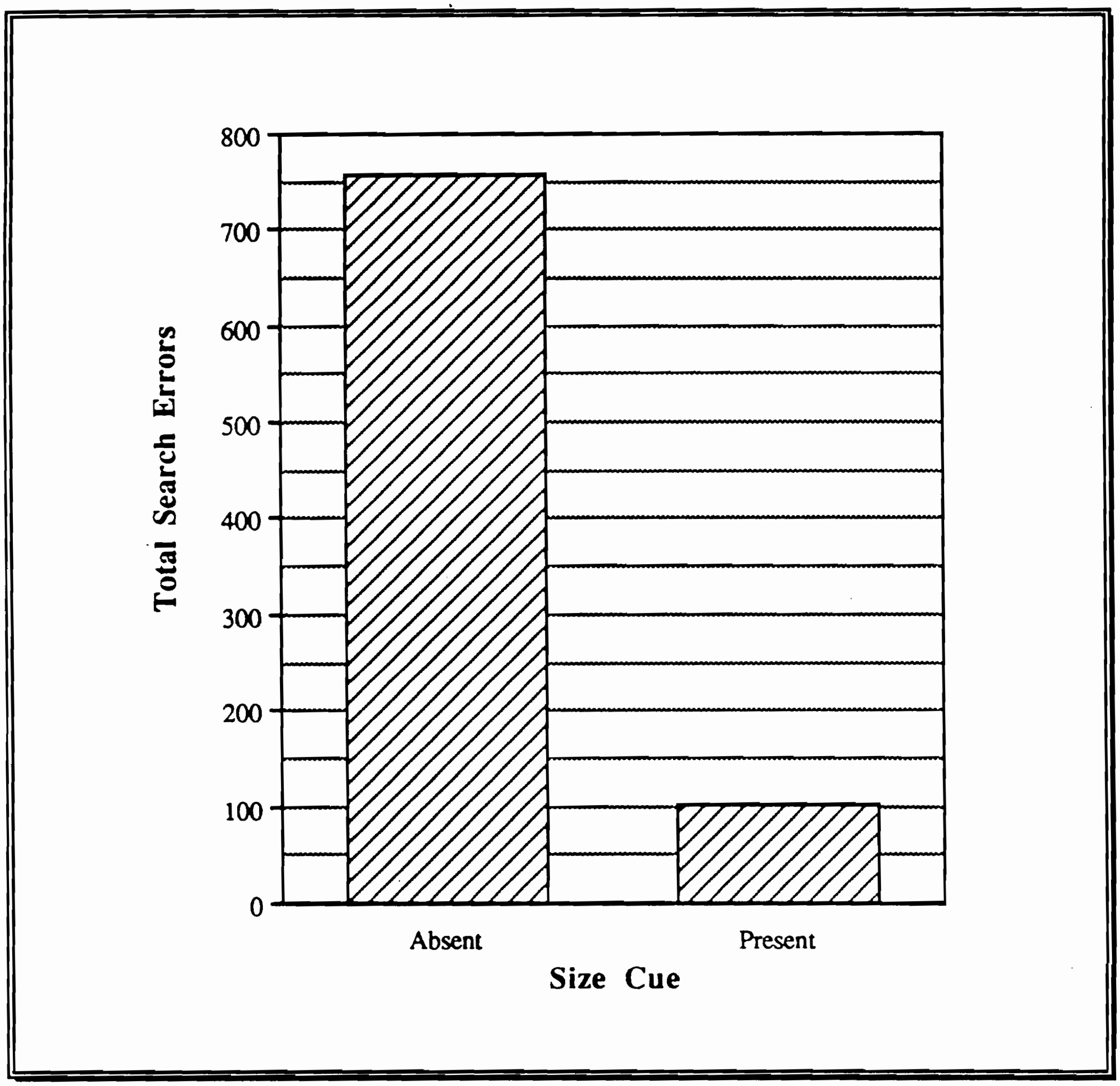


Figure 58. Total search errors as a function of Size cue, Experiment 3.

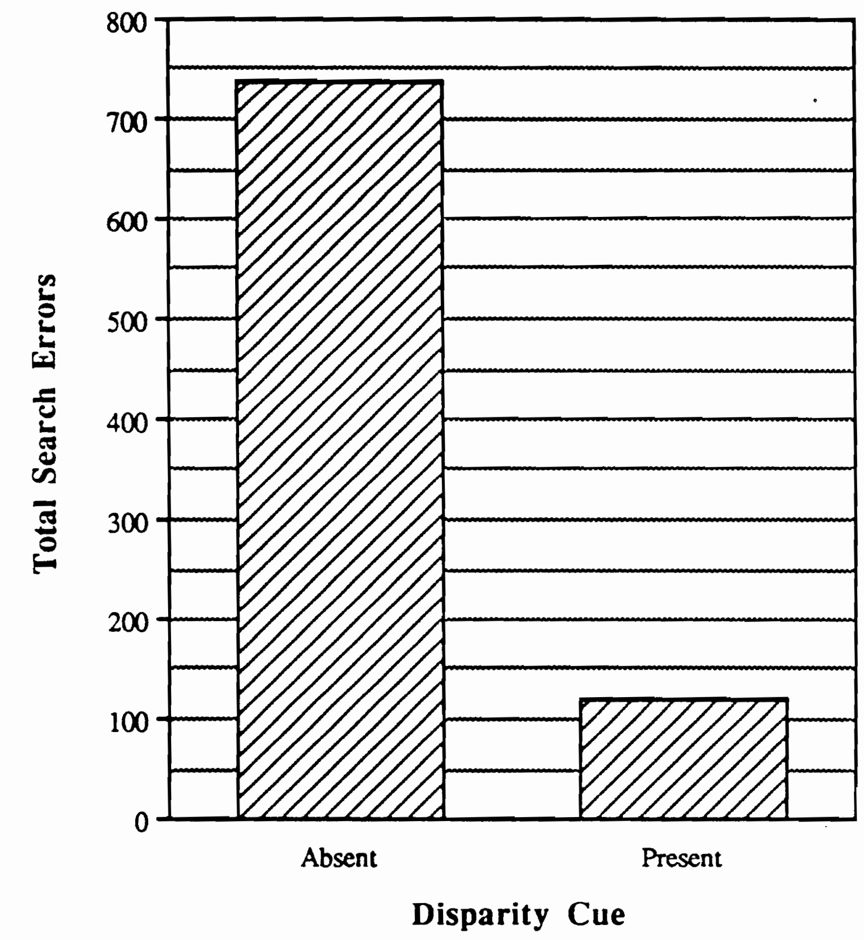


Figure 59. Total search errors as a function of Disparity cue, Experiment 3.

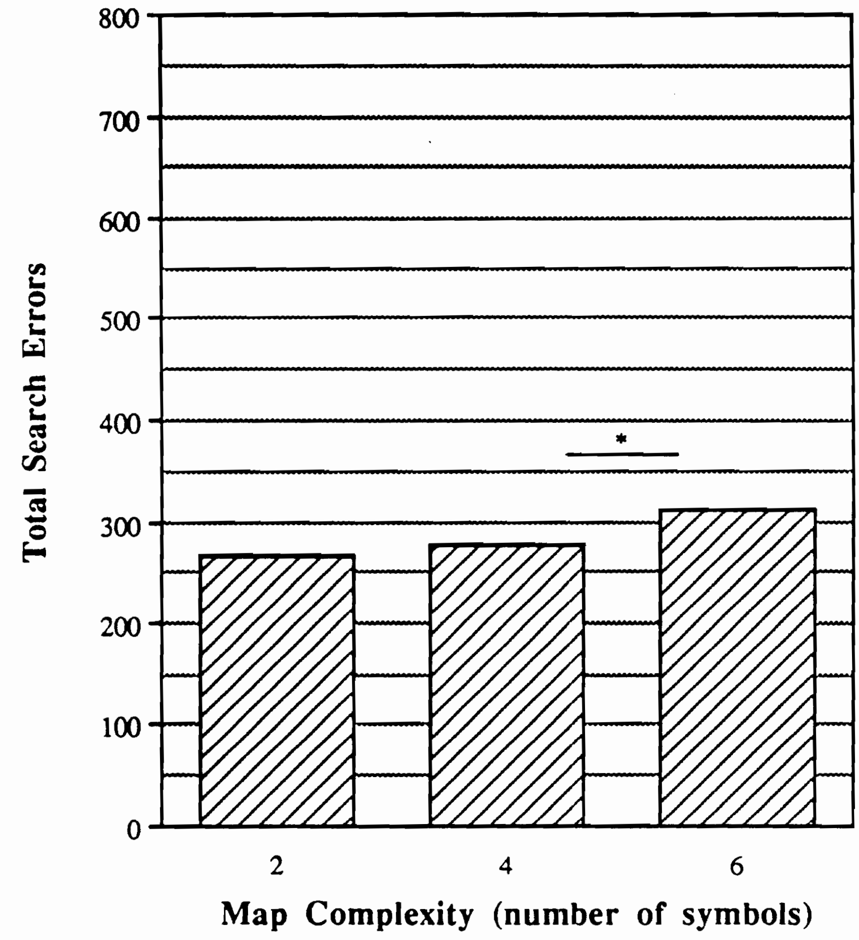


Figure 60. Total search errors as a function of Complexity, Experiment 3. Asterisk indicates smallest mean difference at $p \leq .05$.

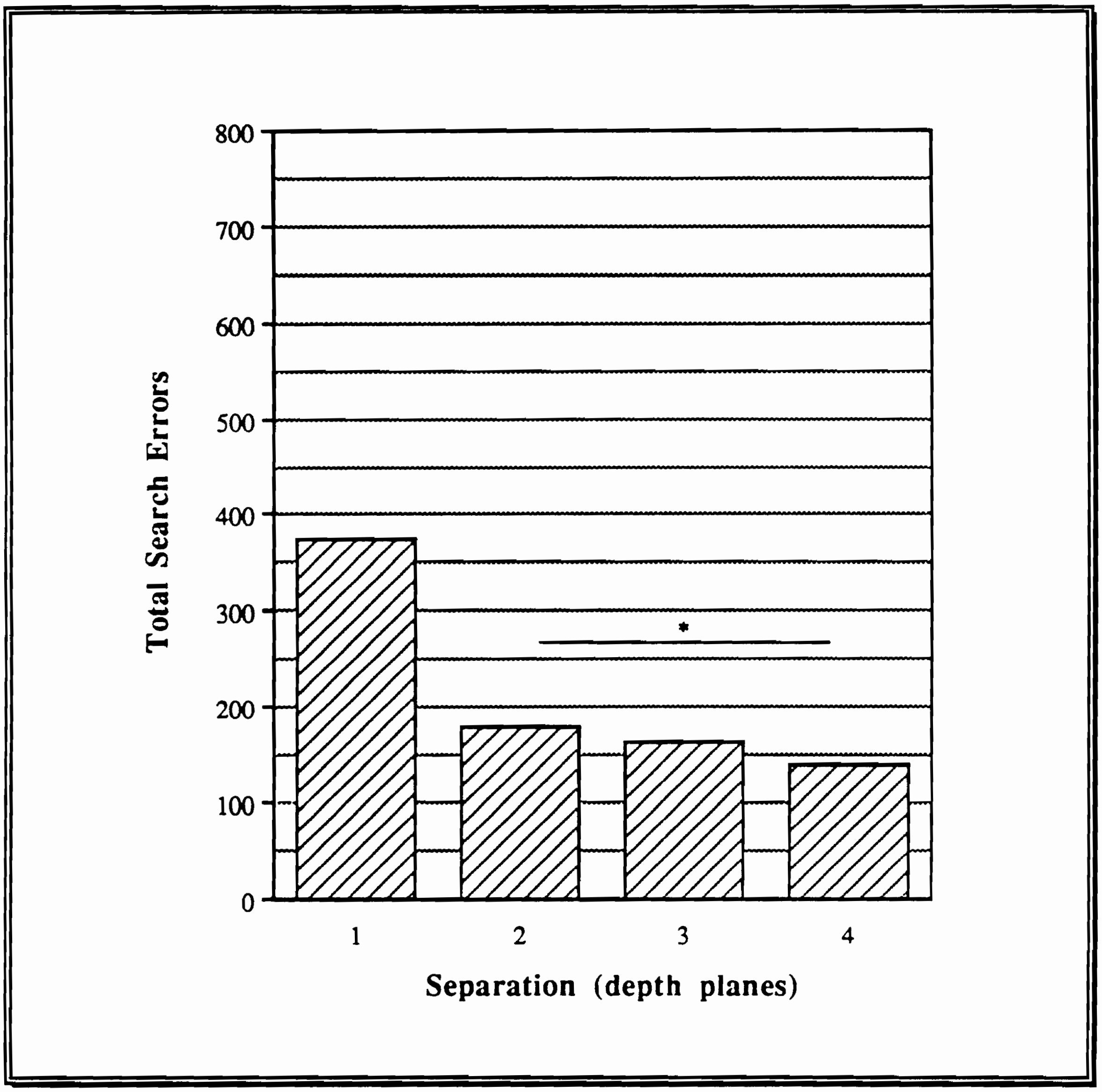


Figure 61. Total search errors as a function of Separation, Experiment 3. Asterisk indicates smallest mean difference at $p \leq .05$.

Cursor positioning time. The cursor positioning variables used in Experiment 3 (i.e., cursor positioning time, cursor positioning error (X-Y), and cursor positioning error (Z)) are logically related to search errors. That is, in instances where search errors were committed, cursor positioning errors were necessarily committed as well. Since it was desirable to consider the cursor positioning measures independently from the effects of search errors, analyses of cursor positioning data used only those trials which were not associated with search errors.

Because the exclusion of search error trials created an unbalanced design (i.e., an unequal number of observations per experimental condition), an attempt was made to use a general linear model (GLM) technique for the ANOVAs and post-hoc analyses. Due to the large size of the model used and the relative inefficiency of the GLM procedure, an insufficient amount of virtual memory was available to accomplish these analyses. Nor was it possible to conduct analyses of covariance using the complete data set, for the same reasons. Therefore, it was necessary to balance the design and use a standard ANOVA procedure. Balancing was accomplished by collapsing data across subjects. The highest order interaction term (Luminance x Size x Disparity x Complexity x Separation) was used as the denominator when computing F-ratios.

Positioning time data (excluding trials for which search errors had been committed) were collapsed across replications and across subjects and submitted to a five-factor ANOVA (Luminance x Size x Disparity x Complexity x Separation). One main effect is statistically significant (Table 13). In general, positioning times were faster in the presence of the Disparity cue ($p = .0214$, Figure 62). Three additional positioning time effects are significant at the $p \leq .10$ level. These three effects are illustrated in Appendix M (Figures M-32 through M-34).

TABLE 13

ANOVA Summary Table for Positioning Time (s), Experiment 3

Source	*df*	*MS*	*F*	*p*
Luminance (L)	1	0.2424	0.23	.6510
Size (Sz)	1	0.1601	0.15	.7123
Disparity (D)	1	10.2176	9.54	.0214
Complexity (C)	2	0.3230	0.30	.7501
Separation (Sp)	3	4.1782	3.90	.0734
L * Sz	1	2.9809	2.78	.1462
L * D	1	5.6510	5.28	.0613
L * C	2	0.5535	0.52	.6206
L * Sp	3	0.8920	0.83	.5226
Sz * D	1	0.8675	0.81	.4027
Sz * C	2	0.7052	0.66	.5513
Sz * Sp	3	0.6011	0.56	.6599
D * C	2	0.3234	0.30	.7499
D * Sp	3	0.1807	0.17	.9136
C * Sp	6	0.7275	0.68	.6745
L * Sz * D	1	4.8470	4.53	.0774
L * Sz * C	2	0.0339	0.03	.9690
L * Sz * Sp	3	1.2967	1.21	.3834
L * D * C	2	0.5838	0.55	.6059
L * D * Sp	3	0.8087	0.76	.5584
L * C * Sp	6	1.2478	1.17	.4286

TABLE 13 (continued)

ANOVA Summary Table for Positioning Time (s), Experiment 3

Source	*df*	*MS*	*F*	*p*
Sz * D * C	2	0.0045	0.00	.9958
Sz * D * Sp	3	0.1469	0.14	.9342
Sz * C * Sp	6	0.4461	0.42	.8446
D * C * Sp	6	0.1988	0.19	.9700
L * Sz * D * C	2	0.0117	0.01	.9892
L * Sz * D * Sp	3	1.0736	1.00	.4536
L * Sz * C * Sp	6	0.7080	0.66	.6858
L * D * C * Sp	6	0.2681	0.25	.9419
Sz * D * C * Sp	6	0.4201	0.39	.8601
L * Sz * D * C * Sp	6	1.0705		
Total	95			

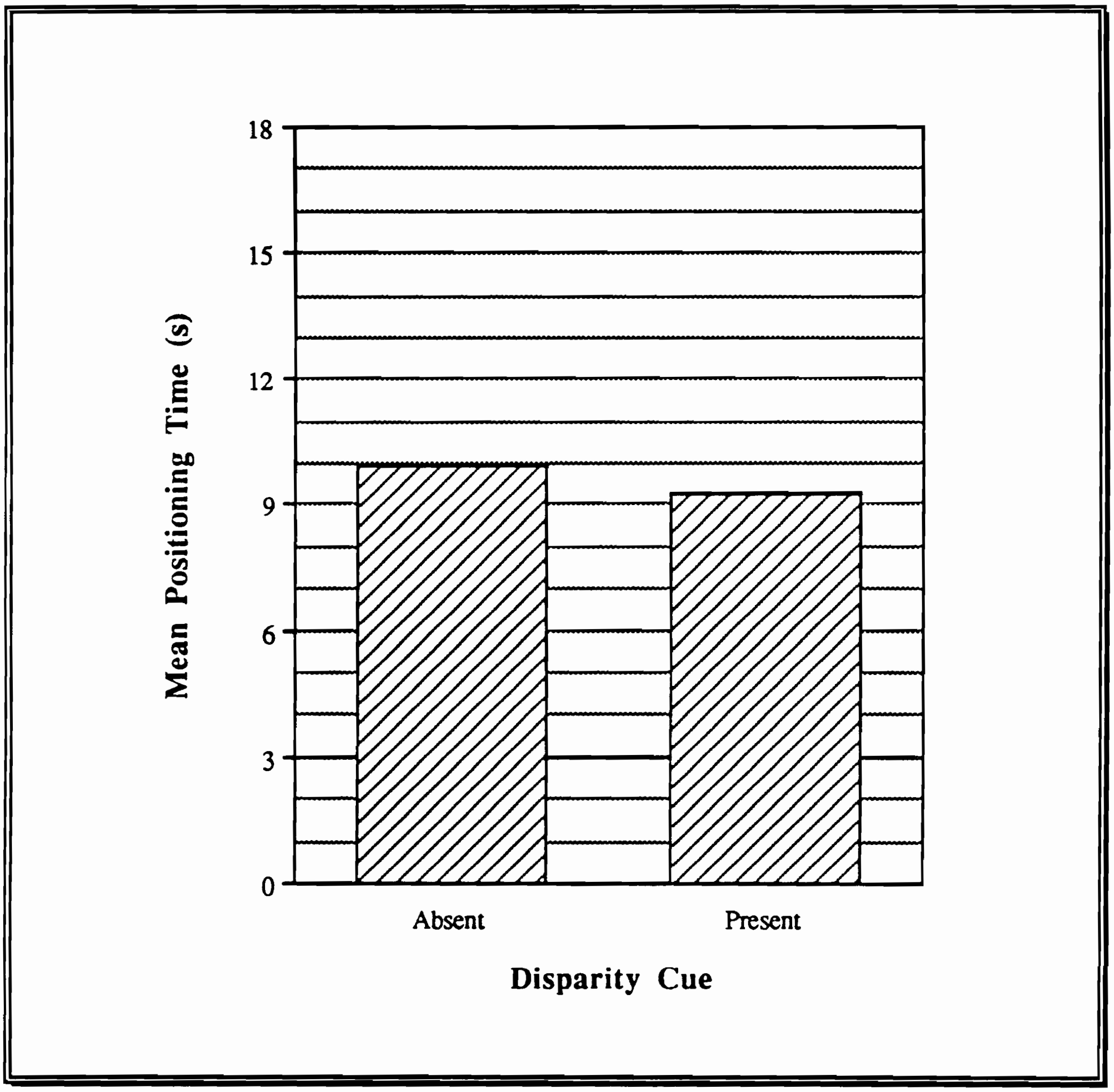


Figure 62. Mean positioning time as a function of Disparity cue, Experiment 3.

Cursor Positioning Errors (X-Y). Positioning error data from the X-Y plane (excluding trials for which search errors had been committed) were collapsed across replications and across subjects and submitted to a five-factor ANOVA (Luminance x Size x Disparity x Complexity x Separation). One main effect is statistically significant (Table 14). In general, smaller X-Y positioning errors were made in the absence of the Disparity cue ($p = .0041$, Figure 63). One statistically significant interaction was found in this analysis (Size x Disparity x Separation, $p = .0226$). Since this effect does not appear to add meaning to the interpretation of the analysis, it is not considered in detail here. Illustrations of this interaction and those of three additional effects significant at the $p \leq .10$ level are included in Appendix M (Figures M-35 through M-38).

Cursor Positioning Errors (Z). Depth positioning error data (excluding trials for which search errors had been committed) were collapsed across replications and across subjects and submitted to a five-factor ANOVA (Luminance x Size x Disparity x Complexity x Separation). Three main effects are statistically significant (Table 15): Luminance ($p = .0002$), Size ($p < .0001$), and Disparity ($p < .0001$). In general, smaller positioning errors were made in the presence of Luminance (Figure 64), Size (Figure 65), and Disparity cues (Figure 66).

There were four statistically significant interaction effects found in this analysis. Since three of these interactions are included in the fourth interaction, the highest-order interaction is presented here in detail: Luminance x Size x Disparity ($p = .0006$). Post-hoc simple-effect F-tests were conducted to determine where the significance is located in this interaction (Tables N-17 and N-18). The interaction of Luminance x Size is statistically significant only in the absence of the Disparity cue (Figure 67). Positioning errors in depth were significantly smaller in the presence of the Luminance cue when both Size and

TABLE 14

ANOVA Summary Table for X-Y Positioning Error (pixels), Experiment 3

Source	*df*	*MS*	*F*	*p*
Luminance (L)	1	0.0143	1.59	.2535
Size (Sz)	1	0.0226	2.52	.1632
Disparity (D)	1	0.1823	20.34	.0041
Complexity (C)	2	0.0224	2.50	.1623
Separation (Sp)	3	0.0101	1.13	.4084
L * Sz	1	0.0366	4.09	.0897
L * D	1	0.0003	0.03	.8587
L * C	2	0.0064	0.71	.5273
L * Sp	3	0.0065	0.73	.5716
Sz * D	1	0.0150	1.68	.2431
Sz * C	2	0.0011	0.12	.8850
Sz * Sp	3	0.0030	0.33	.8042
D * C	2	0.0010	0.11	.8971
D * Sp	3	0.0102	1.14	.4054
C * Sp	6	0.0158	1.76	.2550
L * Sz * D	1	0.0212	2.36	.1752
L * Sz * C	2	0.0202	2.25	.1865
L * Sz * Sp	3	0.0219	2.45	.1615
L * D * C	2	0.0440	4.91	.0545
L * D * Sp	3	0.0110	1.23	.3790
L * C * Sp	6	0.0200	2.24	.1751

TABLE 14 (continued)

ANOVA Summary Table for X-Y Positioning Error (pixels), Experiment 3

Source	*df*	*MS*	*F*	*p*
Sz * D * C	2	0.0425	4.75	.0581
Sz * D * Sp	3	0.0226	2.52	.0226
Sz * C * Sp	6	0.0186	2.07	.1986
D * C * Sp	6	0.0113	1.27	.3912
L * Sz * D * C	2	0.0067	0.75	.5108
L * Sz * D * Sp	3	0.0078	0.87	.5046
L * Sz * C * Sp	6	0.0185	2.07	.1989
L * D * C * Sp	6	0.0175	1.95	.2187
Sz * D * C * Sp	6	0.0199	2.22	.1770
L * Sz * D * C * Sp	6	0.0090		
Total	95			

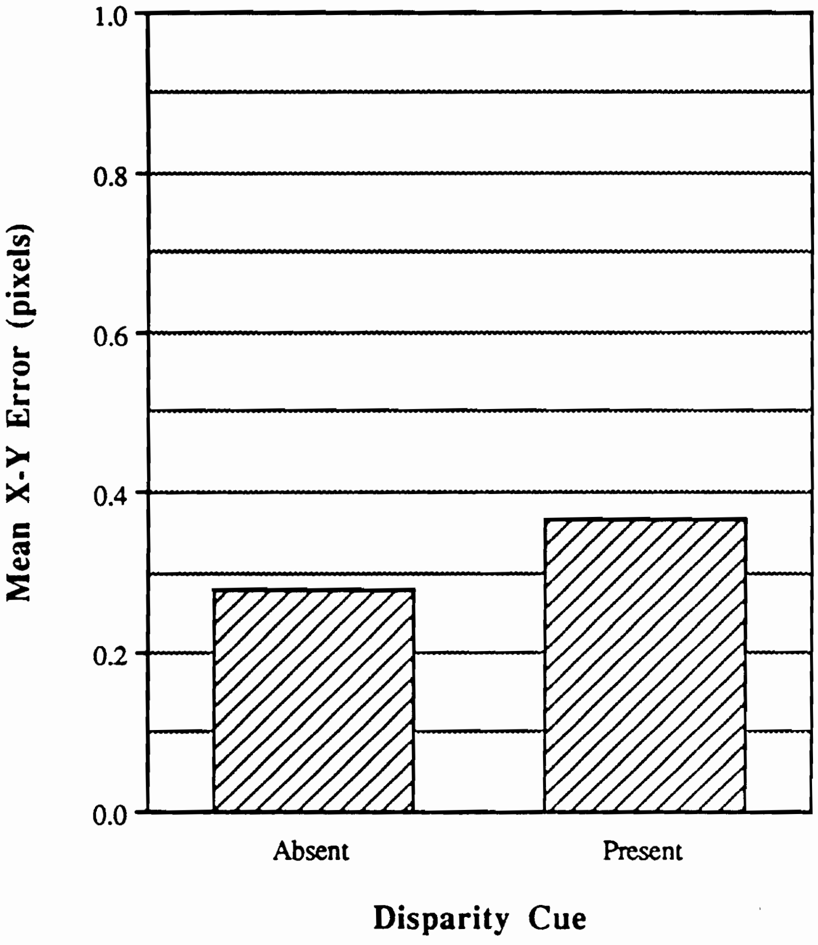


Figure 63. Mean positioning error (X-Y) as a function of Disparity cue, Experiment 3.

TABLE 15

ANOVA Summary Table for Z Positioning Error (apparent depth planes), Experiment 3

Source	*df*	*MS*	*F*	*p*
Luminance (L)	1	8.5615	65.99	.0002
Size (Sz)	1	9.8246	75.72	< .0001
Disparity (D)	1	13.3990	103.27	< .0001
Complexity (C)	2	0.0016	0.01	.9877
Separation (Sp)	3	0.0317	0.24	.8627
L * Sz	1	6.4828	49.97	.0004
L * D	1	7.4585	57.49	.0003
L * C	2	0.0037	0.03	.9720
L * Sp	3	0.0409	0.31	.8146
Sz * D	1	7.9469	61.25	.0002
Sz * C	2	0.0008	0.01	.9940
Sz * Sp	3	0.0225	0.17	.9105
D * C	2	0.0042	0.03	.9681
D * Sp	3	0.0312	0.24	.8653
C * Sp	6	0.1752	1.35	.3622
L * Sz * D	1	5.6573	43.60	.0006
L * Sz * C	2	0.0088	0.07	.9353
L * Sz * Sp	3	0.0184	0.14	.9310
L * D * C	2	0.0081	0.06	.9400
L * D * Sp	3	0.0377	0.29	.8313

TABLE 15 (continued)

ANOVA Summary Table for Z Positioning Error (apparent depth planes), Experiment 3

Source	*df*	*MS*	*F*	*p*
L * C * Sp	6	0.1654	1.27	.3879
Sz * D * C	2	0.0030	0.02	.9769
Sz * D * Sp	3	0.0147	0.11	.9490
Sz * C * Sp	6	0.1555	1.20	.4160
D * C * Sp	6	0.1765	1.36	.3590
L * Sz * D * C	2	0.0227	0.18	.8436
L * Sz * D * Sp	3	0.0175	0.14	.9355
L * Sz * C * Sp	6	0.1263	0.97	.5125
L * D * C * Sp	6	0.1655	1.28	.3875
Sz * D * C * Sp	6	0.1606	1.24	.4011
L * Sz * D * C * Sp	6	0.1297		
Total	95			

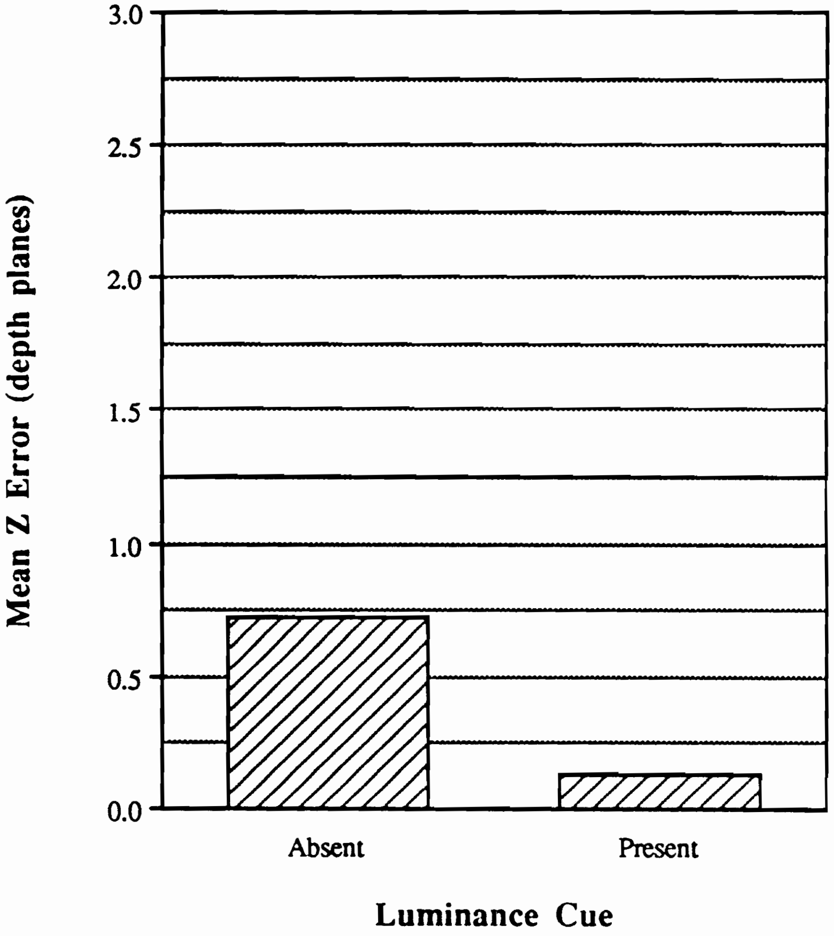


Figure 64. Mean positioning error (Z) as a function of Luminance cue, Experiment 3.

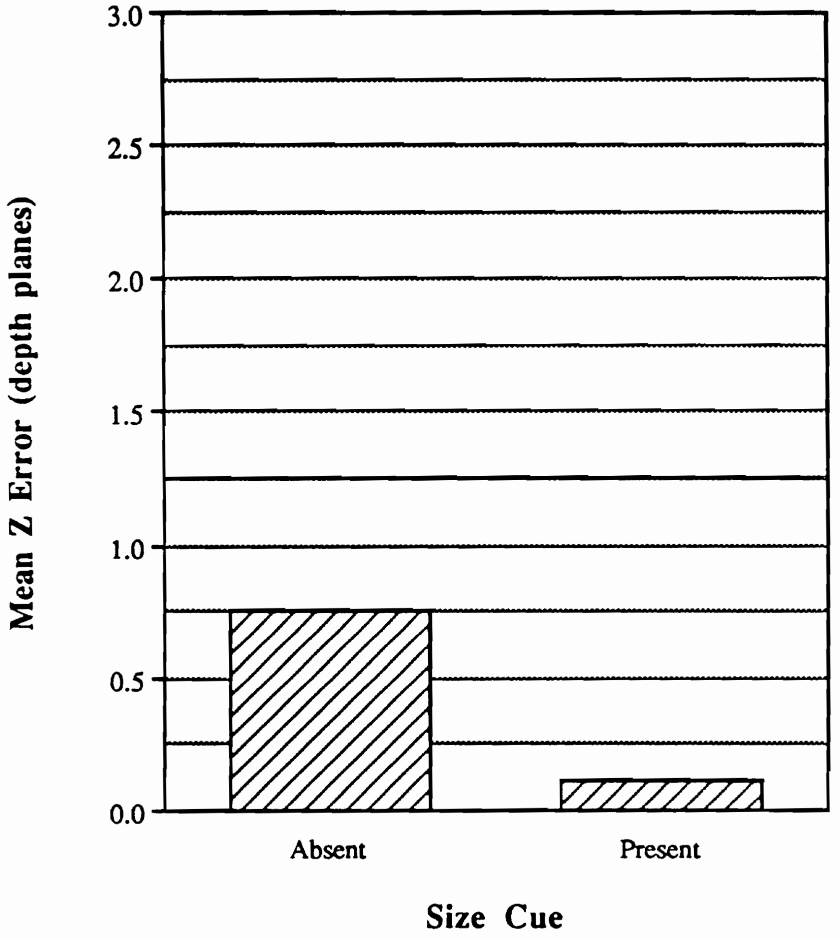


Figure 65. Mean positioning error (Z) as a function of Size cue, Experiment 3.

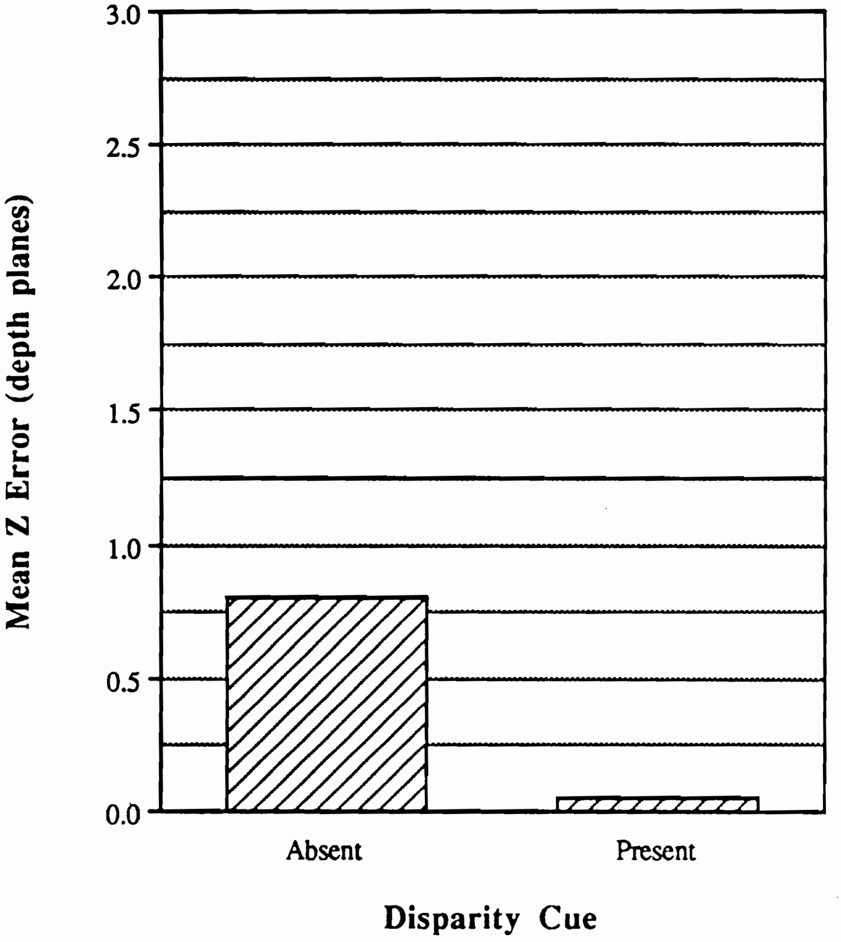


Figure 66. Mean positioning error (Z) as a function of Disparity cue, Experiment 3.

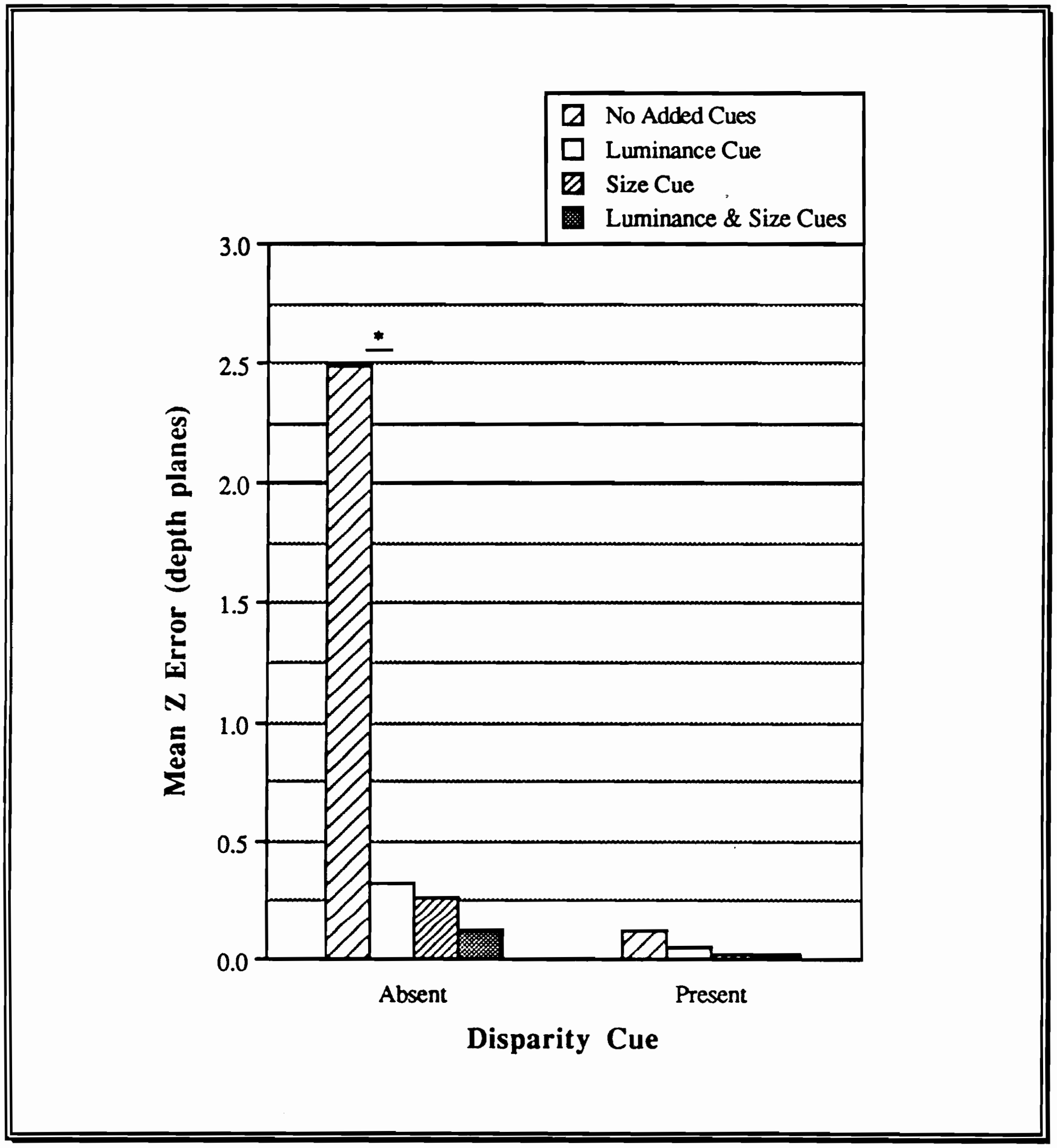


Figure 67. Mean positioning error (Z) as a function of Luminance, Size, and Disparity cues, Experiment 3. Asterisk indicates smallest tested mean difference at $p \leq .05$.

Disparity cues were absent. Illustrations of the remaining interaction effects are presented in Appendix M (Figures M-39 through M-41).

Subjective Image Quality. Image quality ratings were collapsed across replications and submitted to a five-factor ANOVA (Luminance x Size x Disparity x Complexity x Separation). Five main effects are statistically significant (Table 16): Luminance ($p < .0001$), Size ($p < .0001$), Disparity ($p < .0001$), Complexity ($p = .0003$), and Separation ($p < .0001$). In general, higher ratings of image quality were made in the presence of Luminance (Figure 68), Size (Figure 69), and Disparity cues (Figure 70). In addition, higher ratings of image quality were made with lower Complexity (Figure 71) and with greater Separation (Figure 72). Newman-Keuls post-hoc comparisons of the means from these last two main effects (Tables N-19 and N-20) showed that ratings of image quality made with 4 and 6 symbols (medium and high Complexity) are significantly different from ratings made with 2 symbols (low Complexity), but that the mean rating made with 4 symbols is not different from the mean rating made with 6 symbols. Ratings of image quality are significantly different among 1, 2, 3, and 4 depth planes of Separation.

There are 12 statistically significant interactions in this analysis. Most of these interactions are included in the interaction of Luminance x Size x Disparity x Separation ($p < .0001$), which is considered in greater detail here. Post-hoc Simple-Effects F-Tests were conducted to determine where the significance is located in this interaction (Tables N-21 through N-29). The interaction of Luminance x Size x Disparity is statistically significant at all Separations (Figure 73). The interaction of Luminance x Size is statistically significant at each of these four levels, but for 1 depth plane of Separation, this interaction is statistically significant only in the presence of the Disparity cue. At 2, 3, and 4 depth planes of Separation, this interaction is statistically significant only in the absence

TABLE 16

ANOVA Summary Table for Image Quality Ratings, Experiment 3

Source	*df*	*MS*	*F*	*p*
Subjects (Sub)	19	29.1387		
Luminance (L)	1	448.8556	193.71	< .0001
L * Sub	19	2.3171		
Size (Sz)	1	1116.8083	183.43	< .0001
Sz * Sub	19	6.0886		
Disparity (D)	1	2831.5987	86.26	< .0001
D * Sub	19	32.8263		
Complexity (C)	2	9.9693	10.08	.0003
C * Sub	38	0.9892		
Separation (Sp)	3	447.5479	91.18	< .0001
Sp * Sub	57	4.9084		
L * Sz	1	97.0501	57.40	< .0001
L * Sz * Sub	19	1.6907		
L * D	1	178.6487	162.09	< .0001
L * D * Sub	19	1.1021		
L * C	2	0.3924	1.29	.2873
L * C * Sub	38	0.3044		
L * Sp	3	16.2937	23.03	< .0001
L * Sp * Sub	57	0.7076		
Sz * D	1	383.1209	203.11	< .0001
Sz * D * Sub	19	1.8862		
Sz * C	2	0.3084	1.15	.3280
Sz * C * Sub	38	0.2686		
Sz * Sp	3	5.7505	6.94	.0005
Sz * Sp * Sub	57	0.8282		
D * C	2	12.4292	22.05	< .0001
D * C * Sub	38	0.5638		

TABLE 16 (continued)

ANOVA Summary Table for Image Quality Ratings, Experiment 3

Source	*df*	*MS*	*F*	*p*
D * Sp	3	0.2535	0.34	.7949
D * Sp * Sub	57	0.7408		
C * Sp	6	0.6282	1.18	.3222
C * Sp * Sub	114	0.5326		
L * Sz * D	1	89.9889	139.96	< .0001
L * Sz * D * Sub	19	0.6429		
L * Sz * C	2	0.0341	0.10	.9095
L * Sz * C * Sub	38	0.3583		
L * Sz * Sp	3	17.2132	29.23	< .0001
L * Sz * Sp * Sub	57	0.5888		
L * D * C	2	1.3730	2.48	.0972
L * D * C * Sub	38	0.5536		
L * D * Sp	3	9.1960	16.59	< .0001
L * D * Sp * Sub	57	0.5545		
L * C * Sp	6	0.3481	0.70	.6485
L * C * Sp * Sub	114	0.4959		
Sz * D * C	2	1.0098	2.21	.1240
Sz * D * C * Sub	38	0.4577		
Sz * D * Sp	3	15.3717	19.53	< .0001
Sz * D * Sp * Sub	57	0.7869		
Sz * C * Sp	6	0.4311	0.96	.4552
Sz * C * Sp * Sub	114	0.4487		
D * C * Sp	6	1.0896	2.36	.0347
D * C * Sp * Sub	114	0.4617		
L * Sz * D * C	2	1.0626	2.69	.0810
L * Sz * D * C * Sub	38	0.3955		
L * Sz * D * Sp	3	8.6181	17.78	< .0001
L * Sz * D * Sp * Sub	57	0.4847		

TABLE 16 (continued)

ANOVA Summary Table for Image Quality Ratings, Experiment 3

Source	*df*	*MS*	*F*	*p*
L * Sz * C * Sp	6	0.7838	1.81	.1032
L * Sz * C * Sp * Sub	114	0.4330		
L * D * C * Sp	6	0.4458	1.07	.3824
L * D * C * Sp * Sub	114	0.4152		
Sz * D * C * Sp	6	0.1675	0.39	.8871
Sz * D * C * Sp * Sub	114	0.4347		
L * Sz * D * C * Sp	6	0.5315	1.40	.2218
L * Sz * D * C * Sp * Sub	114	0.3804		
Total	1919			

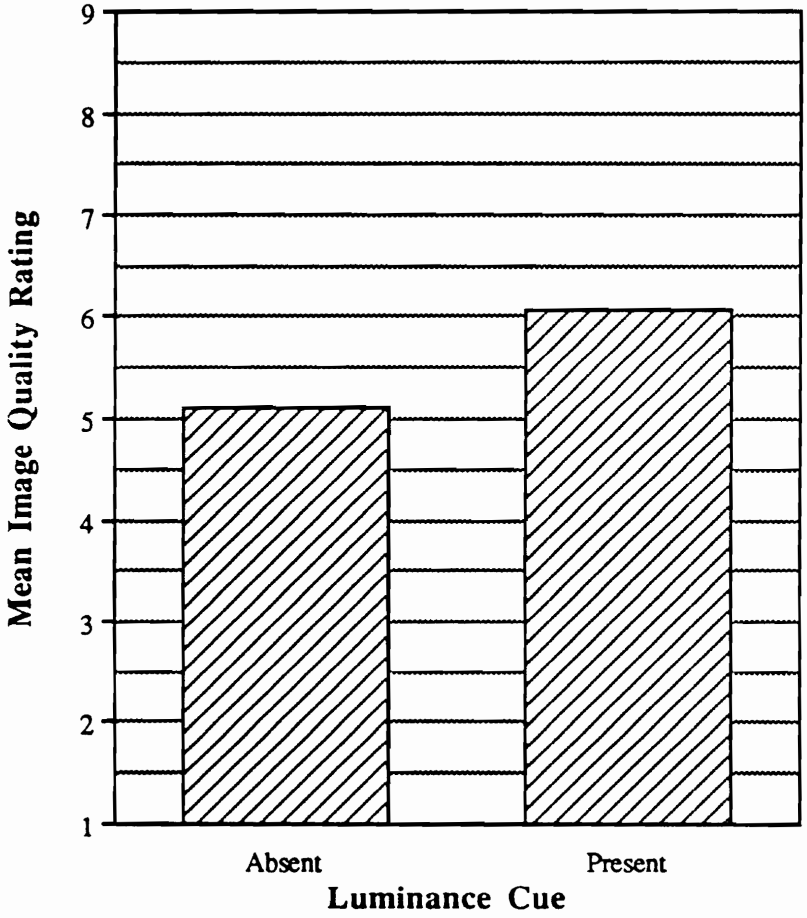


Figure 68. Mean image quality rating as a function of Luminance cue, Experiment 3.

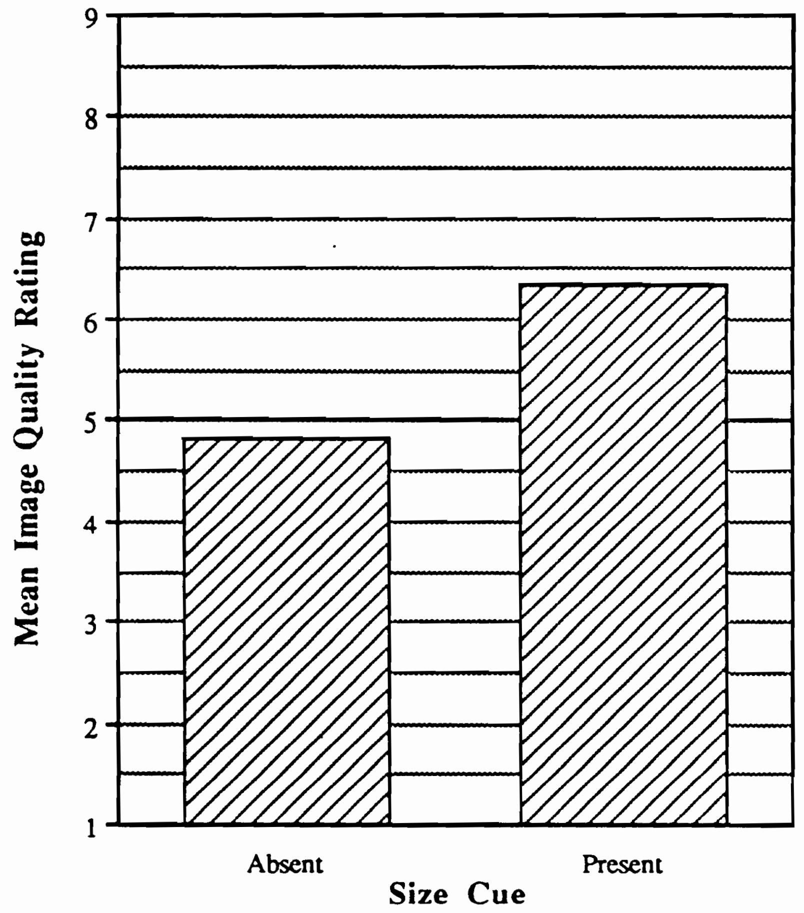


Figure 69. Mean image quality rating as a function of Size cue, Experiment 3.

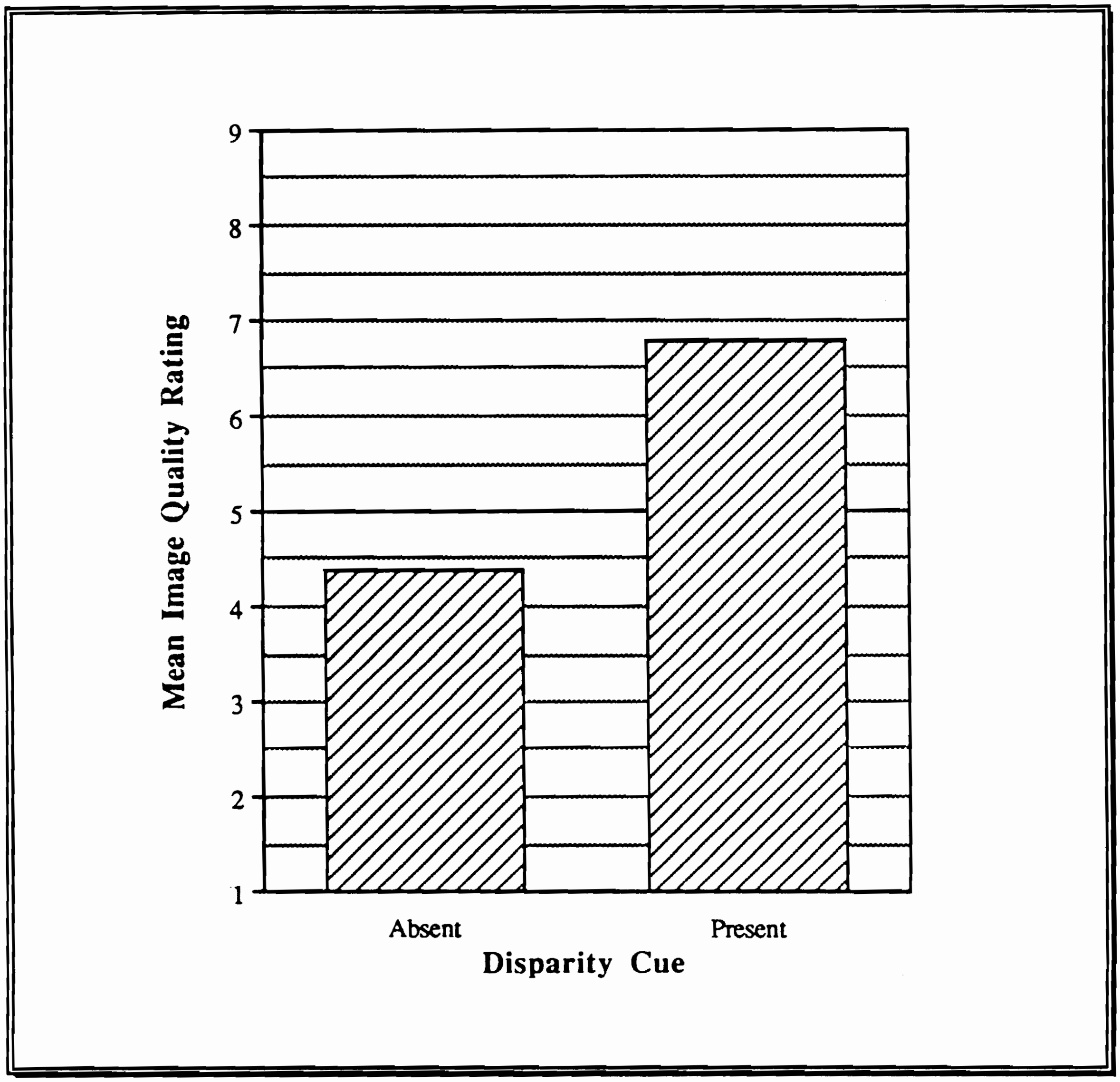


Figure 70. Mean image quality rating as a function of Disparity cue, Experiment 3.

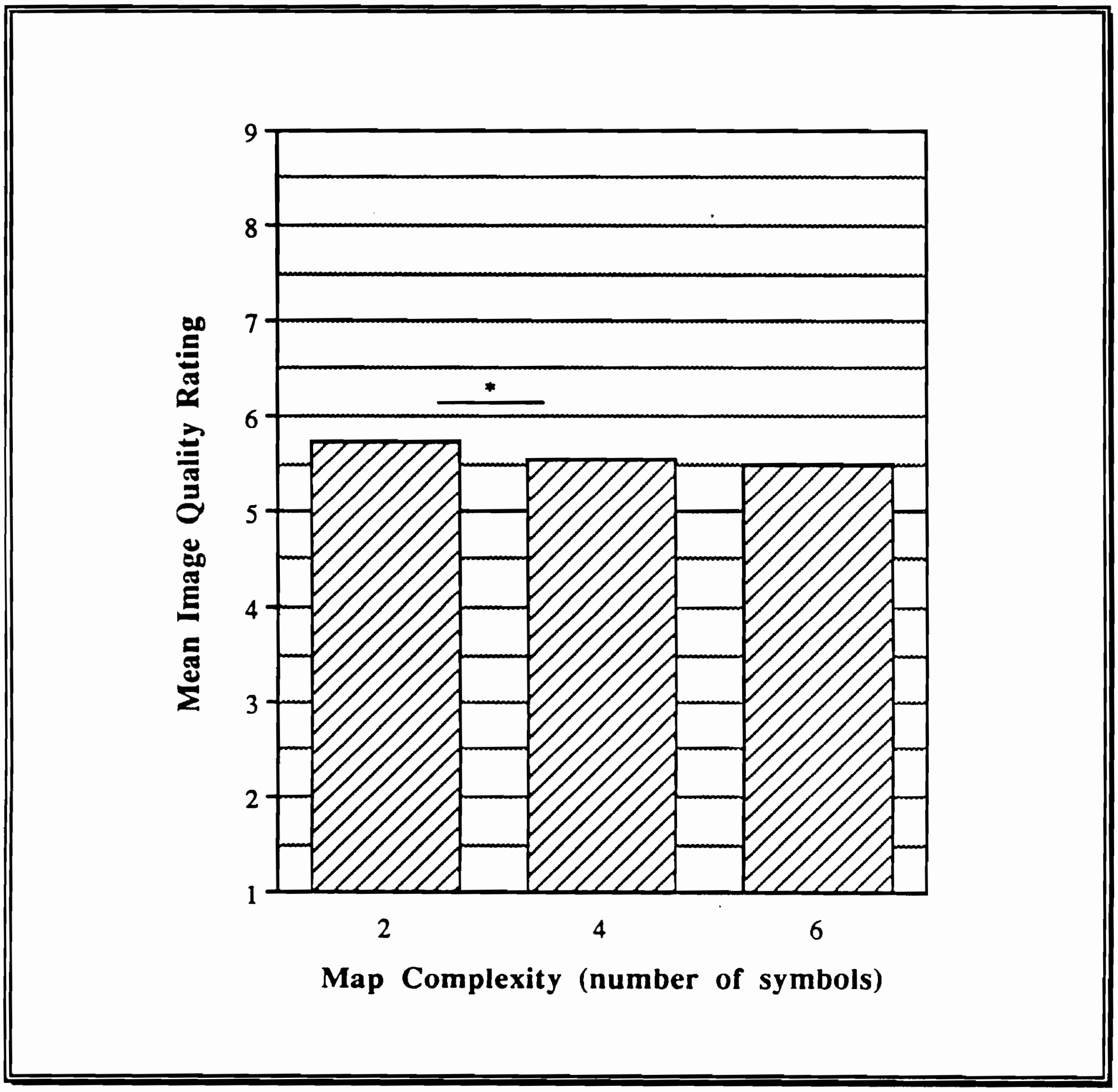


Figure 71. Mean image quality rating as a function of Complexity, Experiment 3. Asterisk indicates smallest mean difference at $p \leq .05$.

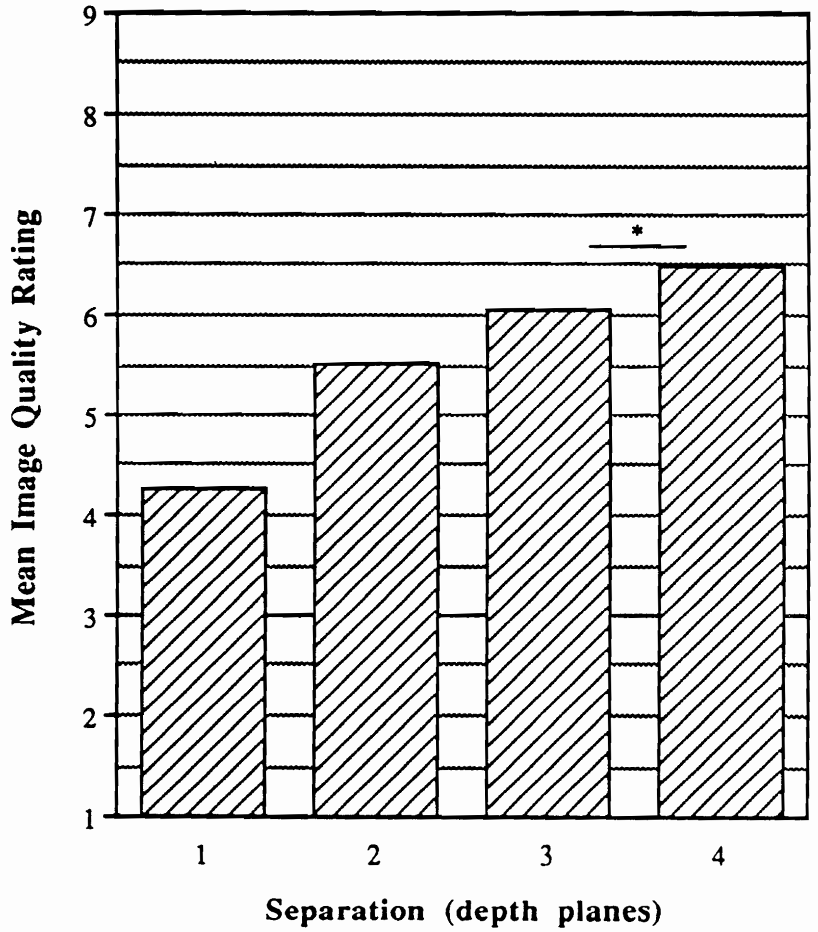


Figure 72. Mean image quality rating as a function of Separation, Experiment 3. Asterisk indicates smallest mean difference at $p \leq .05$.

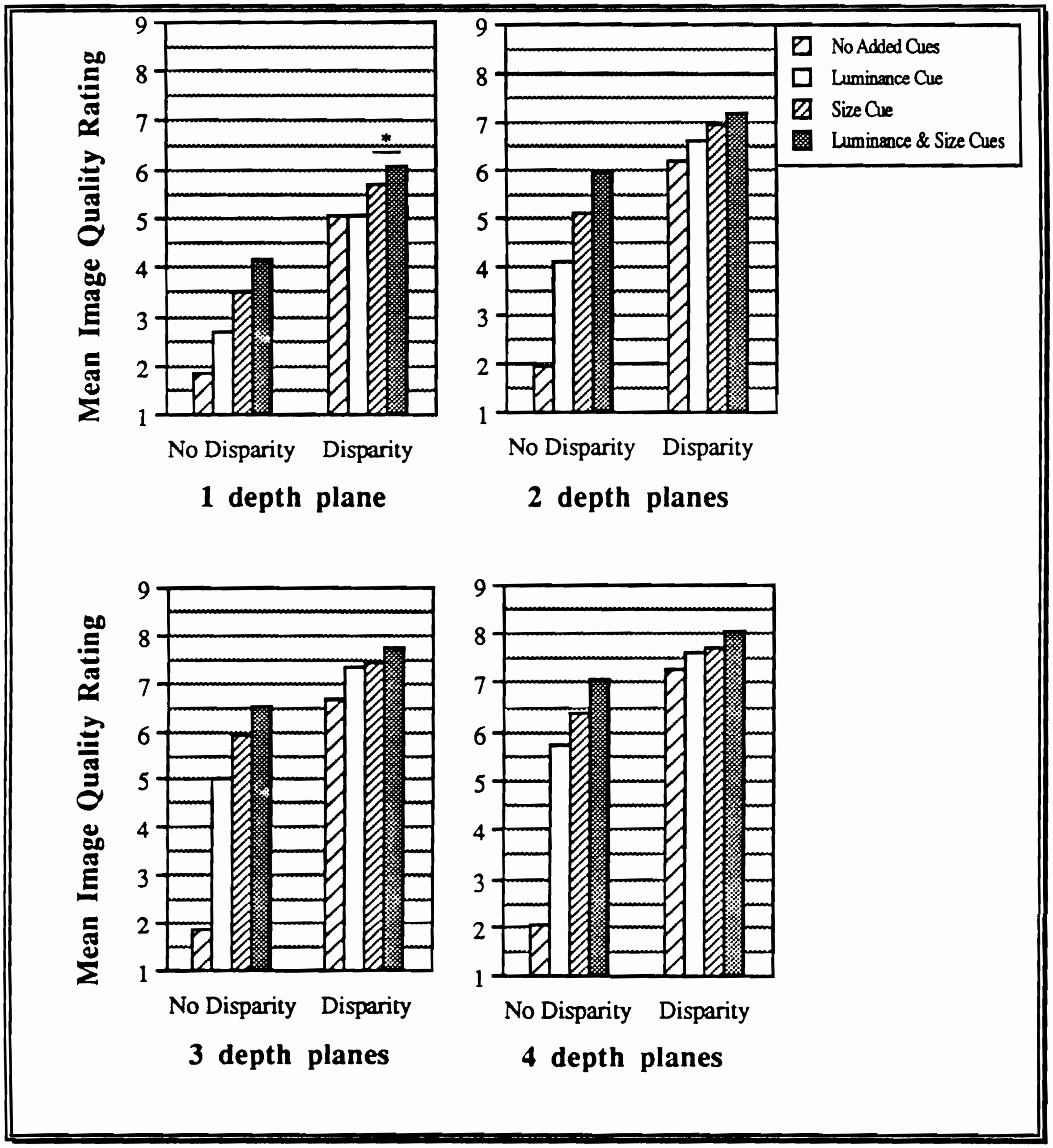


Figure 73. Mean image quality rating as a function of Luminance, Size, and Disparity cues, and Separation, Experiment 3. Asterisk indicates smallest tested mean difference at $p \leq .05$.

of the Disparity cue. Finally, image quality ratings are significantly higher in the presence of the Luminance cue, with 1 depth plane of Separation and in the presence of the Disparity cue, but only when the Size cue was present. For 2, 3, and 4 depth planes of separation and in the absence of the Disparity cue, Luminance is statistically significant in the absence or presence of the Size cue. The remaining interactions, as well as two effects which are significant at the $p \leq .10$ level, are illustrated in Appendix M (Figures M-42 through M-53).

3-D Questionnaire. Mean ratings were computed for questionnaire items 1(a) through 2(d). Inspection of mean responses to items 1(a) through 1(f) (Table 17) reveals that participants reported experiencing a moderate amount of eyestrain while viewing the display (Figure 74).

Ratings of cue effectiveness were submitted to a one-way ANOVA. Ratings are significantly different (F(2,38) = 3.98, $p = .0271$). An examination of mean ratings of cue effectiveness (items 2(a) through 2(c), Table 17) shows Disparity to be the most favored cue (Figure 75). A Newman-Keuls post-hoc means comparison (Table N-30) showed that mean ratings for the Luminance and Disparity cues are significantly different, but not different from the mean rating for the Size cue.

Mental Rotations Test. Correct MRT responses were scored as one point per correct response. Incorrect responses were scored as minus one-half point to weight the score for guessing. Pearson product-moment correlation coefficients were calculated between pairs of the following factors: MRT score, mean search time, and mean search errors (Table 18). No statistically significant correlations were found between MRT scores and performance. However, there is a statistically significant gender difference between mean MRT scores (Table 19, $t = 2.40$, $df = 18$, $p = .0274$), with males scoring higher than females.

TABLE 17

Means, Standard Deviations, and Ranges for Questionnaire Ratings, Experiment 3

Questionnaire Item	*Mean*	*SD*	*Min*	*Max*
1(a) Headache	2.6	2.03	1	8
1(b) Eyestrain	5.0	2.82	1	10
1(c) Nausea	1.1	0.22	1	2
1(d) Blurred Vision	3.3	2.39	1	9
1(e) General Discomfort	2.7	0.95	1	6
1(f) Other	2.1	2.26	1	8
2(a) Luminance	6.6	2.67	2	10
2(b) Size	7.3	1.97	4	10
2(c) Disparity	8.7	2.08	4	10

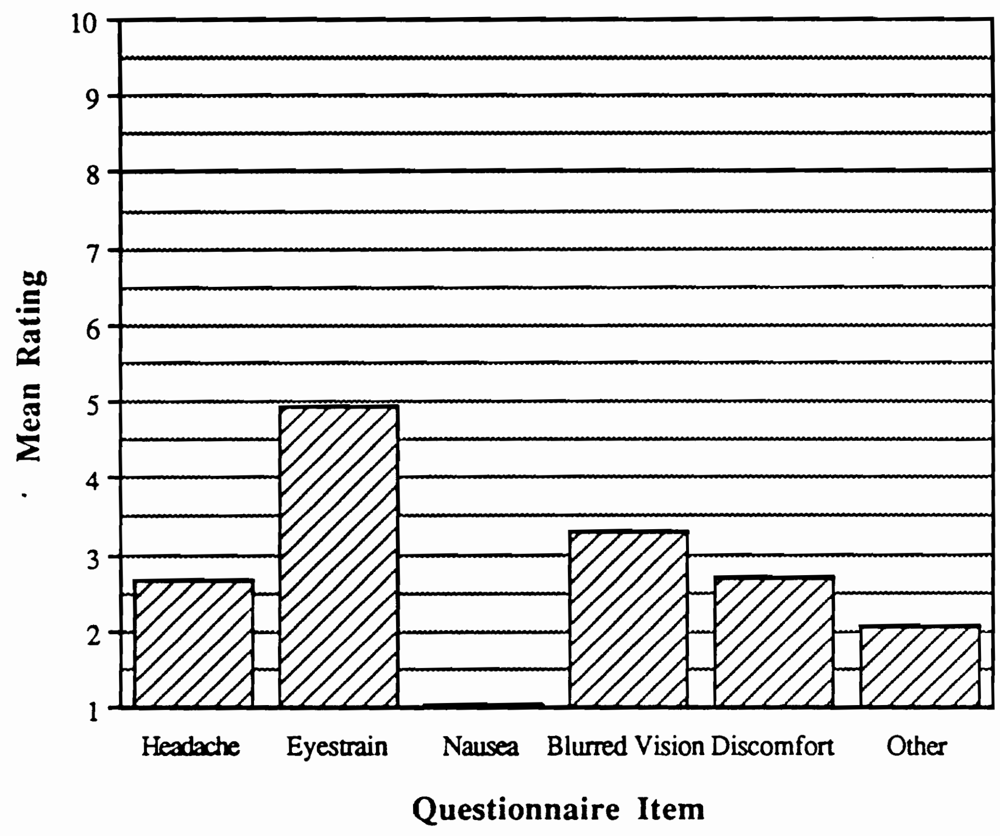


Figure 74. Mean questionnaire ratings of physical discomfort, Experiment 3.

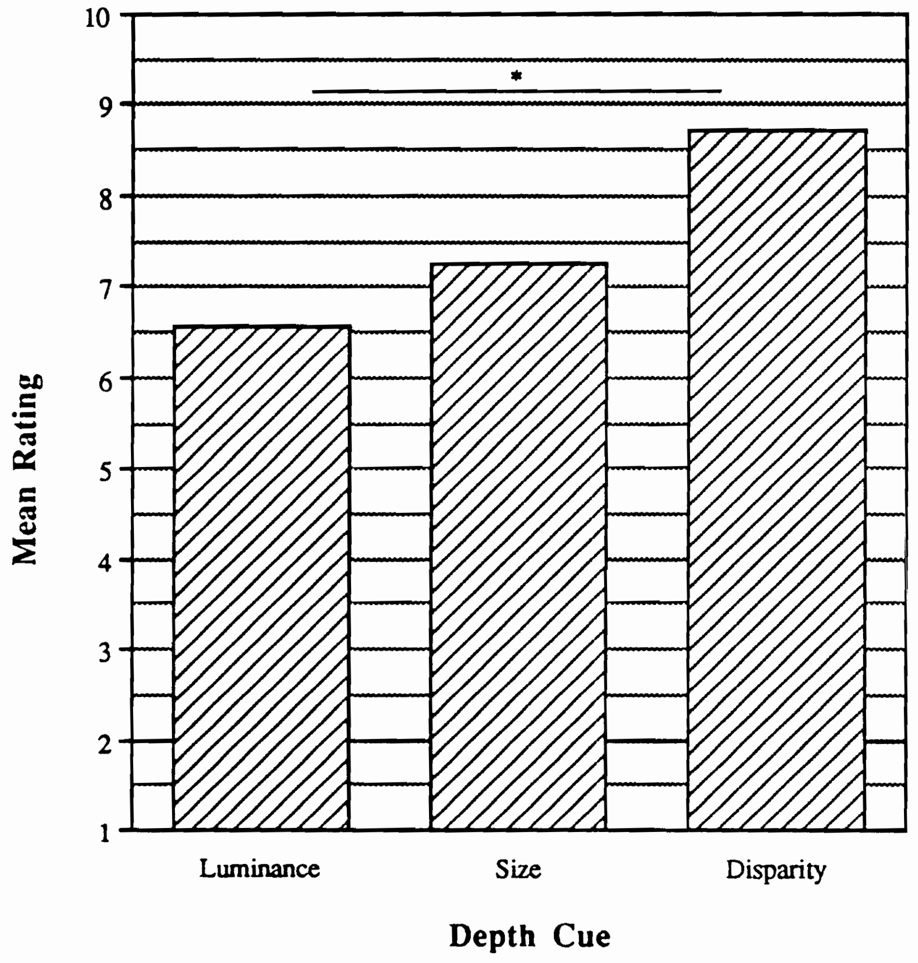


Figure 75. Mean questionnaire ratings of cue effectiveness, Experiment 3. Asterisk indicates smallest mean difference at $p \leq .05$.

TABLE 18

Pearson Product-Moment Correlation Coefficients[1] for MRT Scores[2], Mean Search Times[3], and Total Search Errors[3], Experiment 3

Compared Scores	*r*	*p*
MRT x Mean Search Time	-.16	.51
MRT x Total Search Errors	-.14	.55
Search Time x Search Errors	.34	.14

[1] Calculated with 20 data points.

[2] One observation per subject.

[3] Calculated from 288 observations per subject.

TABLE 19

Means, Standard Deviations, and Ranges for MRT Scores as a Function of Gender, Experiment 3

Gender	*Mean*	*SD*	*Min*	*Max*
Female	15.4	5.75	7.5	26.5
Male	22.4	7.20	13.0	34.5

Visual screening. Data were collected from the visual screening of 36 subjects (20 of whom subsequently participated in Experiment 3). Of these subjects, 20 were males and 16 were females. The mean age of participants in the screening procedure is 20.6 years. The mean IPD is 59.7 mm (SD = 3.19).

All participants with the exception of one red-weak male correctly identified all of the Pseudoisochromatic numerals. Ortho-Rater acuity scores were pooled for each subject into single acuity scores for the two test conditions (with or without polarizing glasses). Data pooling was accomplished by simply adding near and far phoria scores to create single composite scores. These data were submitted to a one-way ANOVA. There is no statistically significant effect of wearing the polarizing glasses on Ortho-Rater acuity ($F(1,35) = .08$, $p = .7838$).

Errors were tabulated from the RDS screening procedure. Of 1,296 observations, only 54 are errors (4.2%). Participants committed one or both of two possible errors; participants either incorrectly identified the orientation of the Landolt ring or incorrectly identified the stereoscopic direction of the image. Of the total errors, 21 (39%) are mistakes of Landolt ring orientation and 33 (61%) are mistakes of stereoscopic direction. There are only three instances of both errors being committed simultaneously. The distribution of scores by subjects is shown in Figure 76. The modal number of errors is one, and the largest number of errors is six (there were 36 errors possible per subject). The distribution of these scores was also considered as a function of horizontal disparity (Figure 77). The majority of errors (76%) are accounted for by test items including seven pixels of disparity or greater. Of these errors, most (71%) occurred for stimuli of positive (uncrossed) disparity.

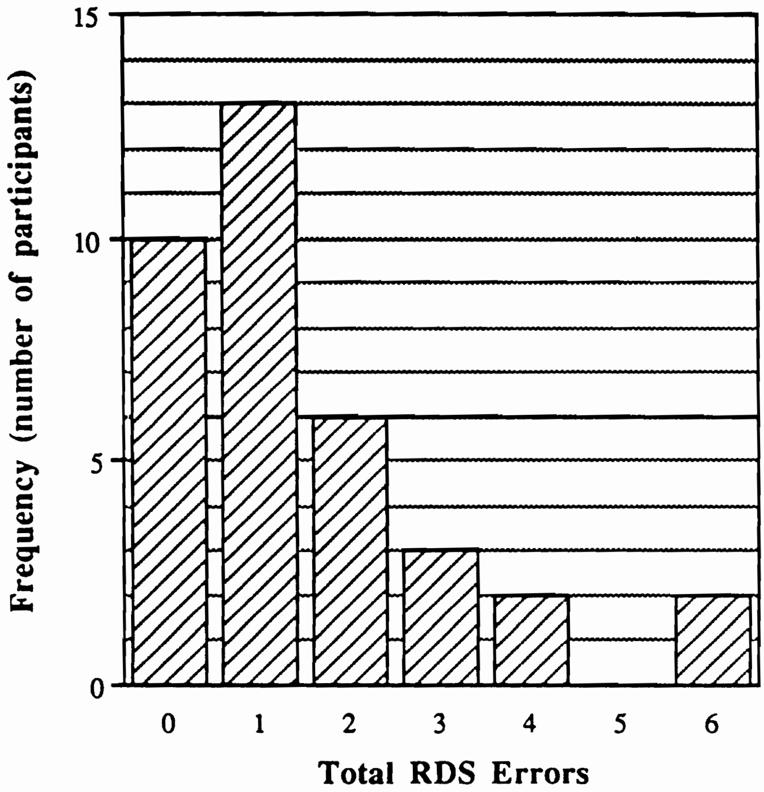


Figure 76. Frequency of RDS scores for the visual screening procedure, Experiment 3.

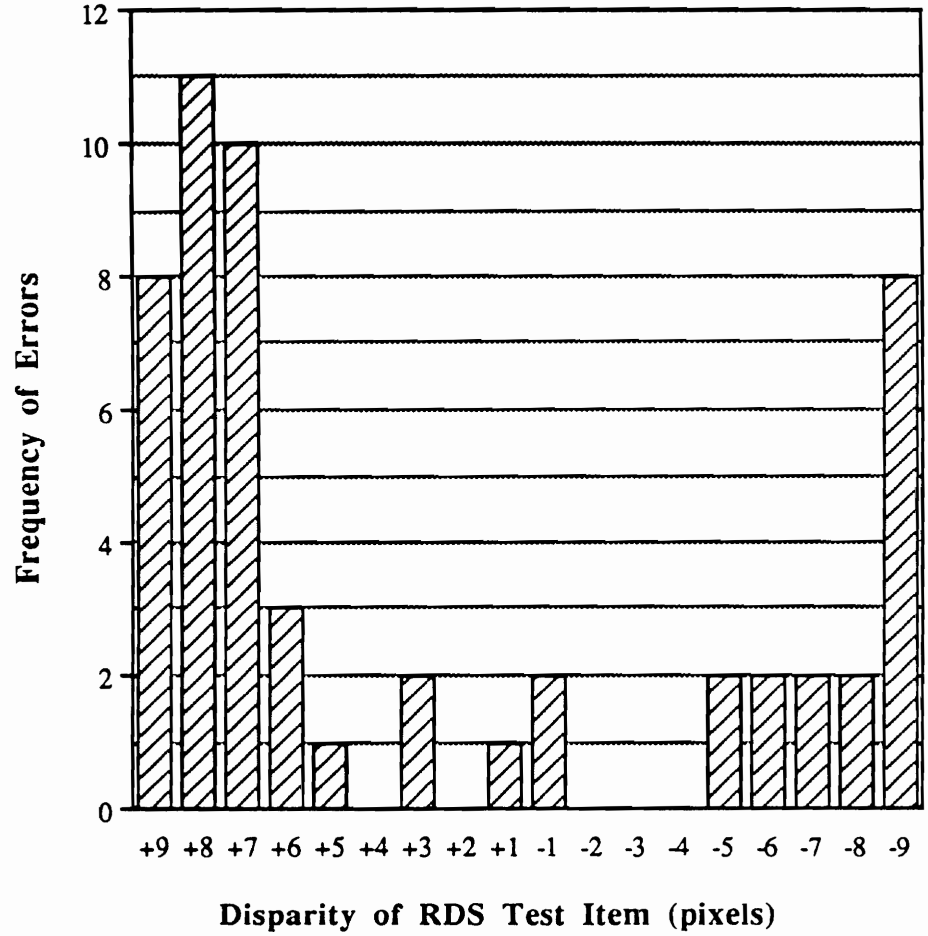


Figure 77. Frequency of RDS errors as a function of horizontal disparity for the visual screening procedure, Experiment 3.

Discussion

In order to form a coherent picture of the results from a large number of analyses, the results from Experiment 3 are discussed under the global headings of *Visual search*, *Cursor positioning*, *Image quality ratings*, *Questionnaire ratings*, *Spatial ability*, and *Visual screening*.

Visual search. As hypothesized, increased cue salience (greater Separation) and fewer distractor elements (lower Complexity) were associated with reduced search times and fewer search errors. In addition, the individual use of Luminance, Size, and Disparity cues allowed faster target identification with fewer errors. Individually, these main effects appear to have been quite strong. The use of multiple depth cues produced complementary effects, with the fastest search times occurring for stimuli incorporating multiple depth cues. Search time and search error effects were plotted as a function of the total number of depth cues present (Figures 78 and 79). While the largest performance benefits accrued from the addition of a single depth cue to scenes which contained no depth cues, the best performance occurred in the presence of all three depth cues. Figures 78 and 79 illustrate that the notion that "more is better" may to a certain extent be true. That is, the cues were additive in the sense that performance improved in the presence of greater numbers of depth cues. However, strictly speaking, these effects were interactive rather than additive. Perhaps a more accurate statement would be, "more is better, with diminishing returns with larger numbers of depth cues."

The role of Separation is of special importance here, since cue salience was of critical concern in Experiments 1 and 2 as well. Separation played a clear role in mediating all of the effects mentioned above. For example, in Figure 55, it can be seen that while search times associated with less Complexity were faster, this effect became smaller in

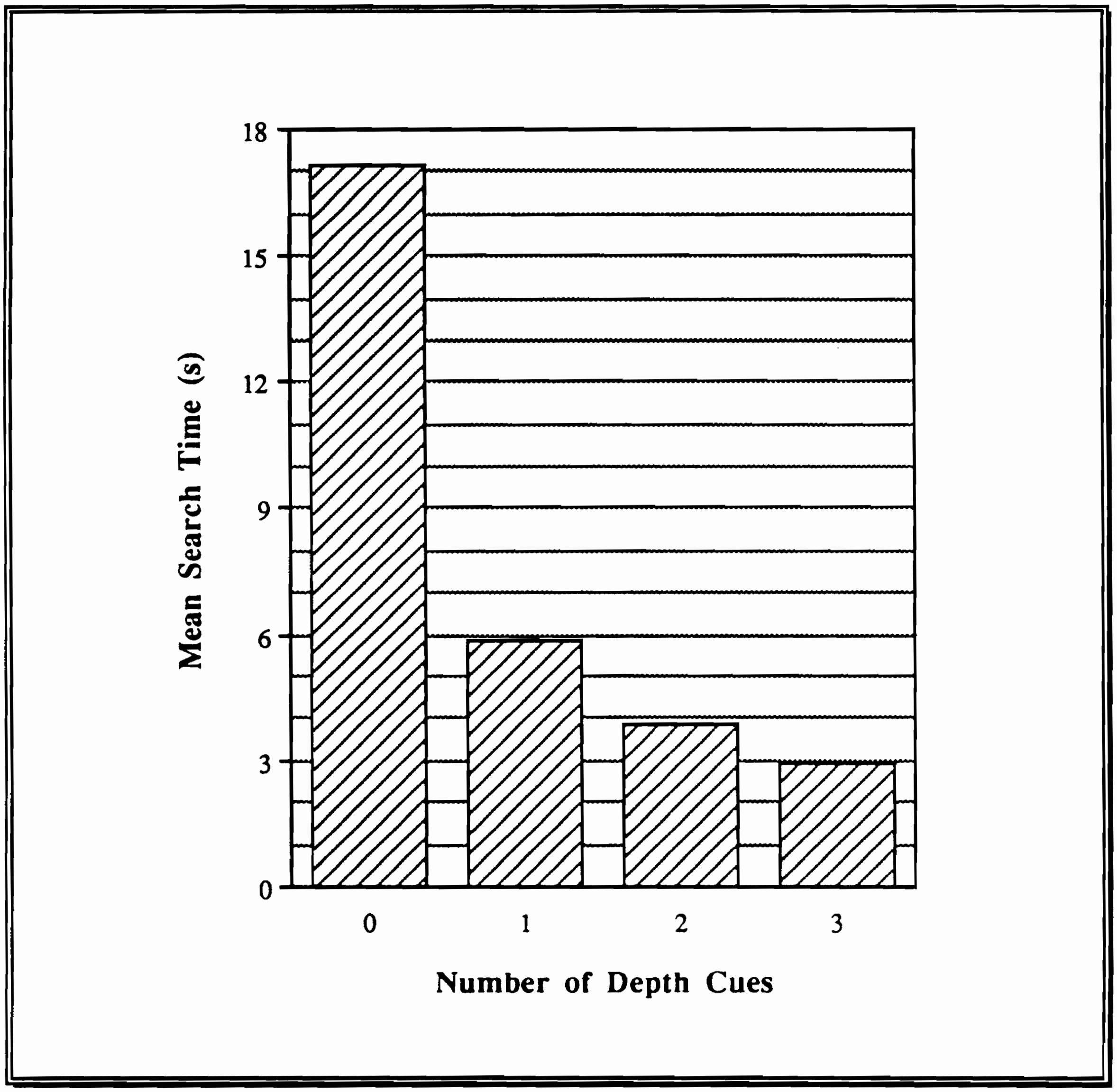


Figure 78. Mean search time as a function of the total number of depth cues present, Experiment 3.

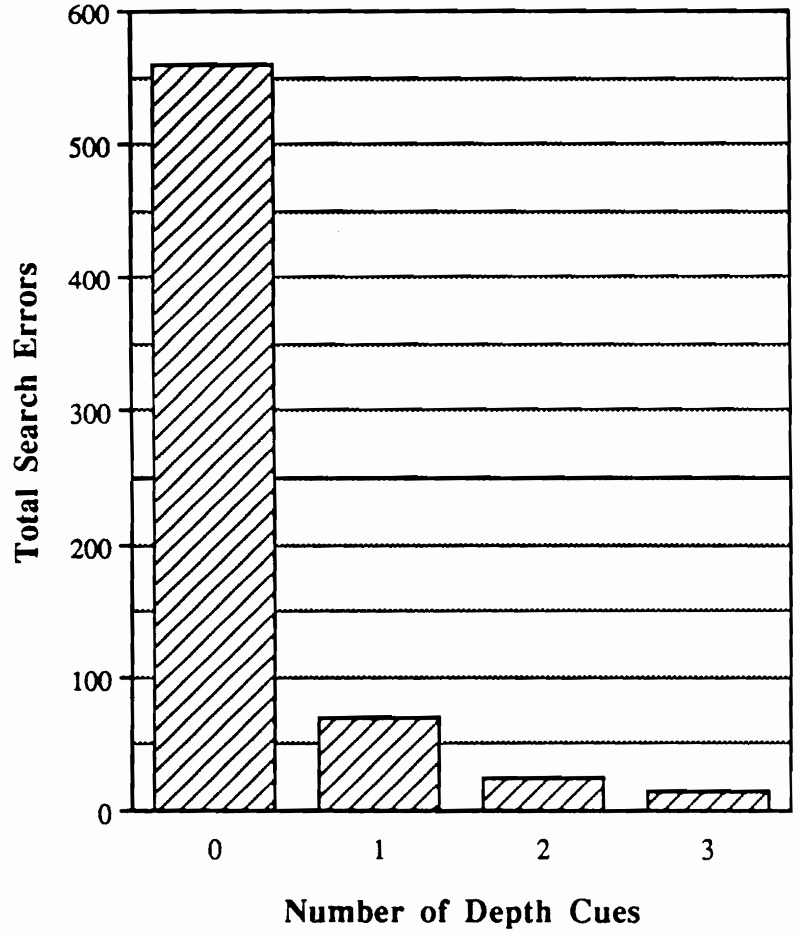


Figure 79. Total search errors as a function of the total number of depth cues present, Experiment 3.

magnitude with greater Separation. In other words, at high cue salience levels, a performance ceiling effect developed which mediated the effect of Complexity. A similar pattern is evident in Figure 56. While the use of multiple cues improved search times with small Separation, this effect was washed out by a ceiling effect at the highest levels of cue salience. It should be noted that in both cases the pattern is interactive, rather than strictly additive. This mediating role of cue salience is consistent with the pattern of performance effects reported in Experiment 1.

It was suggested earlier that the increased difficulty associated with the tasks in Experiment 3 would lead to an increased error rate, despite instruction to participants to make the same tradeoff of speed for accuracy which was used in all three experiments. Although the overall search error rate is higher, the true error rate is likely much lower, as was previously explained. The failure to produce substantially higher error rates in Experiment 3 suggests the possibility that task demand in Experiment 3 was not substantially different from that present in Experiment 1. However, an important difference in search time results is contrary to this hypothesis; while the Disparity cue was not associated with any response time benefits in Experiment 1, it played a significant role in reducing search times in Experiment 3. This result is in agreement with Merritt's (1983) suggestion that stereoscopic display advantages for response time measures are most likely to be found in task environments with a high degree of task demand. The finding of significant Disparity search time effects also lends credence to the suggestion that inadequate training did not play a major role in the mediation of stereoscopic response times in Experiment 1.

Cursor positioning. It is important to note first the differences among perceptual display space, physical display space, and addressable display space, since the distinctions among these three spaces and the units of measurement associated with each space have bearing on the interpretation of all three cursor positioning variables discussed in Experiment 3. Perceptual display space refers to the perception of 3-D space by a viewer of the 3-D display. As such, depth in perceptual space is measured in units of apparent depth, such as apparent depth planes. Positioning errors on the depth (Z) dimension in Experiment 3 were measured in units of apparent depth planes.

In contrast, physical display space is measured in physical units commensurate with the appropriate depth cue being used. For example, a luminance gradient in physical display space was used to represent depth in the Luminance condition. However, the physical display space is quantized by the limits of resolution and addressability of the physical display. Consequently, changes in display luminance were limited in addressable space by the six-bit DACs previously discussed. Similarly, changes in the relative sizes of stimuli were limited by the structure of the pixel pattern on the CRT. While size changes in physical display space would have been ideally continuous and equal in all directions, addressable size changes in Experiment 3 were unequal in physical X and Y dimensions due to an aspect ratio of X distance units to Y distance units per addressable pixel which was greater than unity. Rather than attempt to scale X-Y positioning errors in terms of this aspect ratio, X-Y positioning errors were reported in units of addressable pixels. That is, a positioning error of 1 pixel on the X dimension was numerically equivalent to a positioning error of 1 pixel on the Y dimension, despite the fact that these errors were of unequal magnitudes in terms of physical display space. Because X-Y positioning errors were measured in addressable space while Z positioning errors were measured in perceptual space, it is most meaningful to discuss these positioning errors separately, rather than as a single composite measure (i.e., as $(\Delta X^2 + \Delta Y^2)^{1/2}$ and ΔZ rather than as $(\Delta X^2 + \Delta Y^2 + \Delta Z^2)^{1/2}$).

Cursor positioning in 3-D space represented a qualitatively unique task to Experiment 3 in that cursor positioning required direct spatial manipulation. Nevertheless, it was hypothesized that cursor positioning times should not be associated with any statistically significant effects in the ANOVA. There was no a priori reason to expect differential positioning times as a function of apparent depth separation since the cursor always started at the center of the display volume for each trial. Similarly, Complexity and the three depth cues were more likely to impact visual search than positioning times. While one statistically significant effect was found in the analysis (the Disparity cue, Figure 62), the magnitude of this effect is small and it appears to be relatively unimportant in terms of describing performance in the 3-D environment. Cursor positioning time was plotted as a function of the total number of depth cues present (Figure 80). As expected, no cue additivity pattern is evident among cursor positioning times.

Similar expectations existed regarding X-Y positioning errors. These errors should have in no way been influenced by the use of the three depth cues. Nor should Complexity or cue salience have had an effect on X-Y positioning accuracy. Rather, the most important determinant of these errors should have been the accuracy with which participants initially identified the target. Once again, the presence of the Disparity cue was associated with significantly different positioning errors (Figure 63), but this effect is very small. It should be noted that the mean X-Y positioning errors plotted in Figure 63 are less than 1 pixel in magnitude (less than 1 addressable display unit). The small size of this effect removes it from the realm of practical significance.

Cursor positioning errors on the X-Y dimension were plotted as a function of the total number of depth cues present (Figure 81). Although there appears to be a small cumulative depth cue effect, the direction of this effect is such that larger positioning errors were made in the presence of larger numbers of depth cues. As discussed above, the small

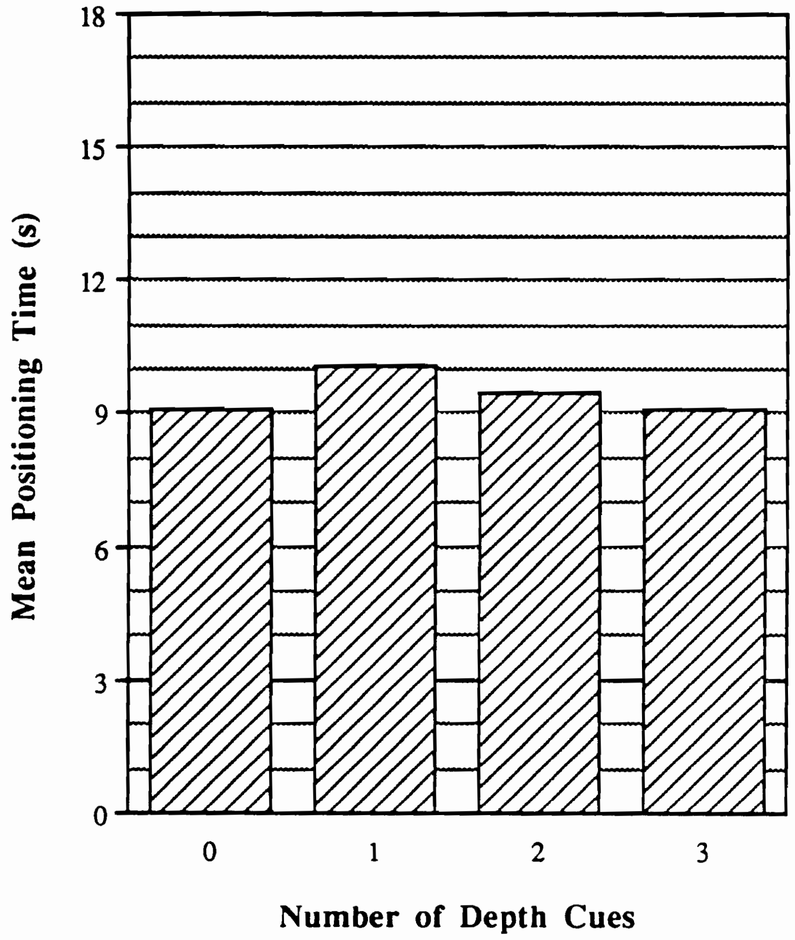


Figure 80. Mean positioning time as a function of the total number of depth cues present, Experiment 3.

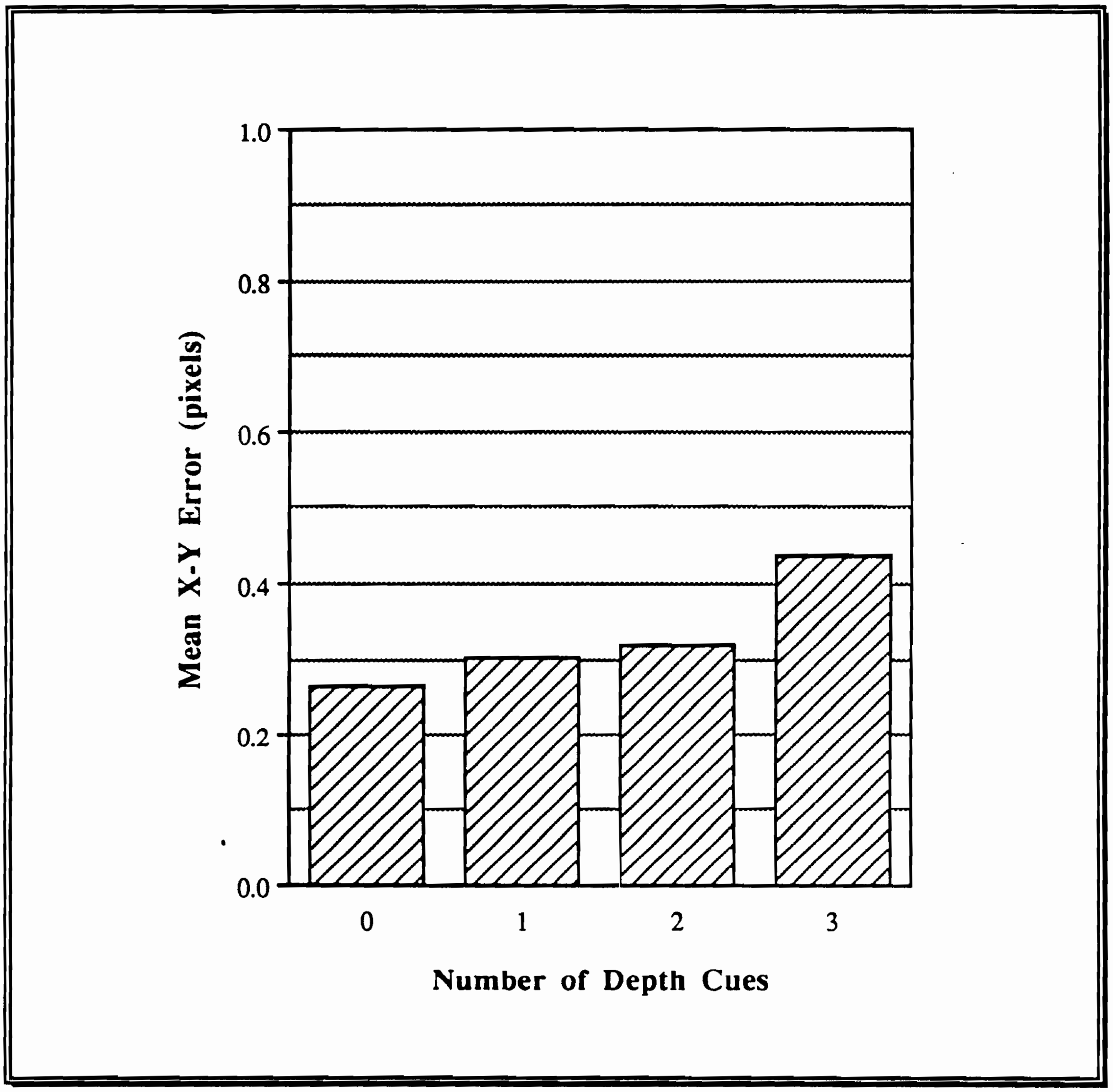


Figure 81. Mean positioning error (X-Y) as a function of the total number of depth cues present, Experiment 3.

size of the X-Y positioning effect must mediate the importance associated with the effect.

Positioning errors on the Z-dimension were expected to be influenced by those factors affecting salience of the depth dimension; Luminance, Size, Disparity, and Separation. Positioning errors should not have been associated with a Complexity effect. Such an association would have been likely only if Z-axis positioning error effects had been artifacts of visual search errors. The results are in agreement with these hypotheses, with positioning errors on the Z axis significantly smaller in the presence of each of the three depth cues. The nature of these performance effects is highly similar to those shown for the visual search measures, despite that the qualitative differences between the visual search and cursor positioning tasks. Surprisingly, cue salience (Separation) was not a statistically significant factor in this analysis. As noted for the X-Y positioning errors, the relative importance of the Z positioning errors is small since the mean depth positioning errors are mostly smaller than 1 apparent depth plane.

Cursor positioning errors on the Z-dimension were plotted as a function of the total number of depth cues present (Figure 82). Z-axis positioning errors reflected a cumulative depth cue effect. The largest performance benefit accrued from the addition of the first depth cue, with diminishing returns associated with the addition of the second and third cues. Once again, it can be seen that this effect was interactive rather than additive.

Image quality ratings. In Experiment 2, image quality ratings were not associated with the same ceiling effect as was seen for response times in Experiment 1, despite the use of the same suprathreshold cue manipulations. There was no reason to believe that this pattern of results would change in Experiment 3. In addition, increased Separations were expected to be associated with higher image quality ratings. There was no reason to believe that Complexity should have influenced image quality ratings. As hypothesized, higher image quality ratings were associated with greater depth cue salience. In addition, higher

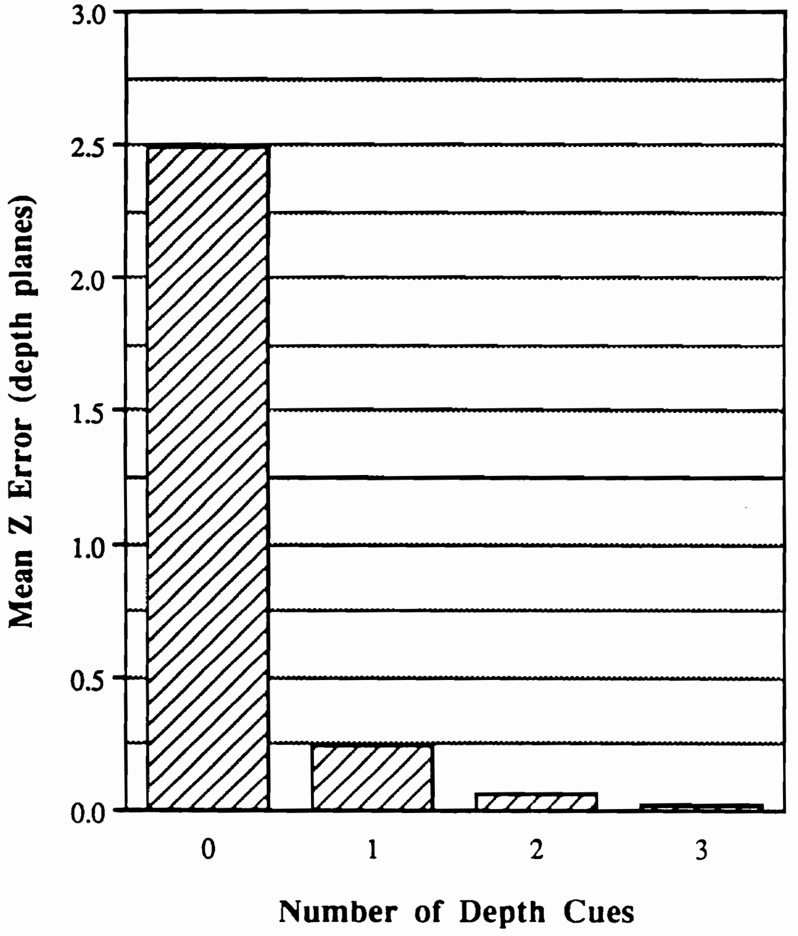


Figure 82. Mean positioning error (Z) as a function of the total number of depth cues present, Experiment 3.

image quality ratings were associated with the presence of each of the three depth cues, more so with greater depth cue salience (greater Separation). However, Complexity is also a statistically significant factor. While this effect is not robust (Figure 71), it may be reflective of a task-demand contamination in the image quality measure. That is, participants may have rated scenes as having lower image quality when they experienced more difficulty in the visual search task.

Image quality ratings reflected a cumulative depth cue effect (Figure 73). Image quality ratings were plotted as a function of the total number of depth cues present (Figure 83). The largest performance benefit accrued from the addition of the first depth cue, with diminishing returns associated with the addition of the second and third cues. The nature of this effect is clearly interactive rather than additive in the strictest sense.

Questionnaire ratings. Ratings of physical discomfort may have been expected to be slightly higher in Experiment 3 due to increases in task demand, as well as an overall increase in the required length of time during which subjects participated. Ratings for Eyestrain did indeed appear to increase, with the mean rating two points higher than was found in Experiments 1 and 2. However, with the exception of this elevated rating, there were no substantial complaints of discomfort. These data are important, since 3-D display technologies (especially anaglyph techniques) have long been plagued by problems of headaches and nausea. The data collected here suggest the use of the field-sequential stereoscopic CRT under the conditions represented in this research need not be associated with such discomfort problems.

The other issue of interest here concerns the ratings of cue effectiveness. In Experiments 1 and 2, a rating shift was found for the depth cue of Disparity. This shift is in agreement with the dependent variables used; disparity was rated more highly in Experiment 2, where it was also associated with potent effects on image quality. The

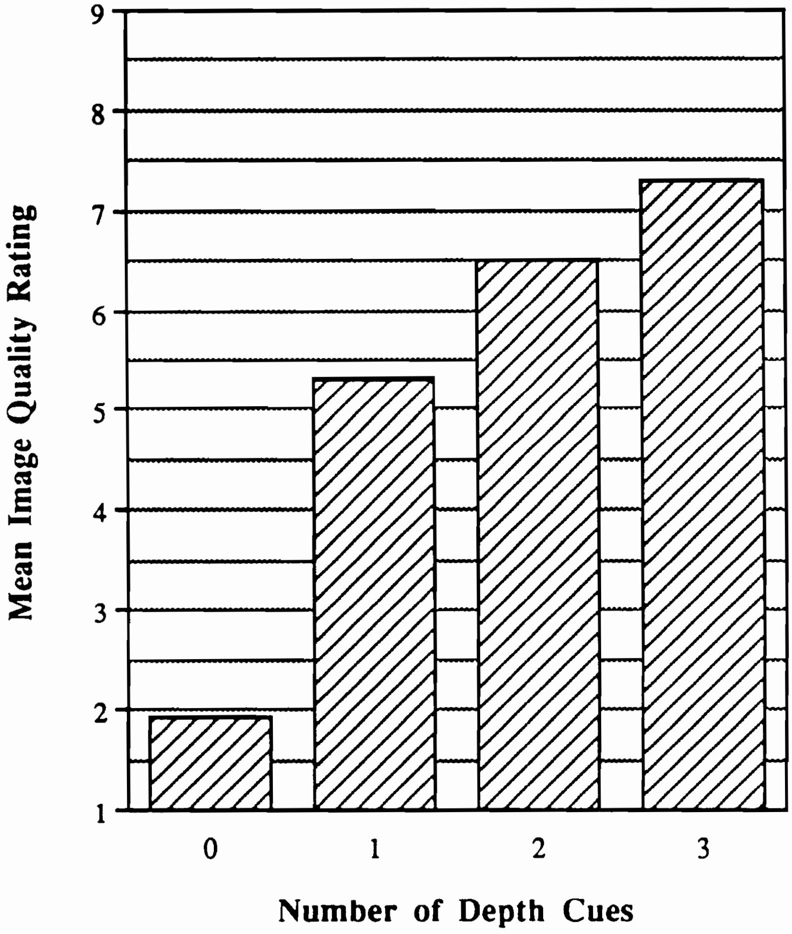


Figure 83. Mean image quality rating as a function of the total number of depth cues present, Experiment 3.

results from Experiment 3 are consistent with this trend. Disparity was found to have a significant influence on all performance measures tested. Similarly, Disparity was the most highly rated cue in Experiment 1, although the differences among these ratings are not great. In retrospect, it might have been informative to have also asked participants to rate the effects of Complexity and Separation. Exit interviews with participants suggested that perceived cue effectiveness was highly dependent on Separation.

Spatial ability. While the MRT was not used in Experiment 2, the results of Experiment 1 indicate that spatial ability may play an important role in speed of response for 3-D judgements. This hypothesis is consistent with the results of McGuinness and Brabyn (1984), who found spatial ability to be correlated with RDS fusion times. Therefore, it was expected that MRT scores might be correlated with visual search times in Experiment 3. However, no significant correlation was found between these two measures. It is reasonable to suggest that some critical task elements which were present in Experiment 1, but absent in Experiment 3, were responsible for the strong relationship with spatial ability.

The expected gender difference in MRT scores (i.e., Sanders et al., 1982; Tapley and Bryden, 1977) which was not statistically significant in Experiment 1 was demonstrated in Experiment 3. Male participants scored significantly higher on the MRT than female participants. Although approximately 40% more power existed in the test of gender difference for Experiment 3, the magnitude of the effect makes it unlikely that the increase in power alone was responsible for the difference in statistical results between Experiments 1 and 3.

Visual screening. There were several objectives for the analysis of visual screening data. One such objective was the comparison of the IPDs of participants in this experiment with those values published elsewhere. This was a relevant consideration, since IPD has a mediating effect on apparent stereoscopic depth. Estimates of mean IPD have ranged from 65 mm (Valius, 1962) to 63 mm for adult males (Woodson, 1981). The mean value of the estimates generated in this experiment is considerably lower (59.7 mm). There are two likely explanations for this difference. First, approximately one half of the participants were females. Most anthropometric values have been derived from male populations only (e.g., Webb Associates, 1978). In addition, the use of a relatively small sample as well as a relatively crude measurement technique may have introduced error into this estimate.

A second objective of this analysis was the study of possible acuity degradation associated with the stereoscopic viewing glasses. No effects were found, although only composite acuity scores were tested. It seems likely that wearing the viewing glasses during the experiments was not associated with impaired visual acuity. This is important, since it indicates that participants had operational acuities which were equivalent to those specified in the Ortho-Rater screening procedure. It also suggests that participants need not wear the glasses while completing the screening procedure

Finally, an attempt was made to develop a suitable stereoscopic screening instrument for use in the field-sequential stereoscopic CRT environment. Because this hybrid Landolt ring / RDS test had not been previously validated, an important objective of the visual screening phase of Experiment 3 was the generation of descriptive performance data. Although the overall error rate is relatively low, some salient features of the data can be used for further test development. The first important feature of the data is illustrated in Figure 81. The modal number of errors is one, with 89% of all participants scoring three or fewer errors. The second important feature in the RDS screening data is shown in Figure 82. Most errors (76%) were accounted for by test items including 7 pixels of disparity or greater, especially by those items incorporating positive disparity. Future use of this instrument as a screening device can be guided by these initial data.

SUMMARY AND RECOMMENDATIONS

Based on the work described in this dissertation, some preliminary conclusions can be made regarding the presentation of depth in the stereoscopic display environment. In addition, based on the experience of implementing these cues with a stereoscopic CRT, some of the constraints imposed by the CRT medium are discussed. To return to the framework with which this report began, these conclusions are first organized by individual depth cues. Next, the mediating factors of Separation, Complexity, and experimental task are considered. Finally, suggestions for future research are outlined.

Recommendations

Luminance cue. Although the luminance range of the display system used was constrained by light loss associated with the polarization process, variations in luminance were shown to be an effective means by which depth information can be encoded. Use of the Luminance cue was associated with improvements in response times for relative depth judgements in Experiment 1, as well as faster search times in Experiment 3. In addition, the Luminance cue was rated as fairly effective in helping viewers to complete depth judgement tasks (Experiments 1, 2, and 3) and it was associated with increases in image quality (quality of depth) in both Experiments 2 and 3.

A serious constraint exists for the use of the Luminance cue on a CRT display. This is the problem of CRT luminance roll off, or luminance nonuniformity. Luminance roll off refers to the typical reduction in luminance which occurs between measurements taken at the center of the CRT and measurements taken at an edge. As was discussed in this dissertation, luminance nonuniformities have serious consequences for the use of luminance as an information encoding dimension, since luminance will be confounded with spatial location on the CRT. In the current research, this was controlled by empirically smoothing the large area luminance profile of the CRT. This task was simplified by the use of a static display and a discrete coordinate system. Such a solution would be more computationally taxing for displays which incorporate dynamic images. In addition, since each CRT picture tube has a unique large area luminance profile, smoothing algorithms must be tailored to each CRT. If an adequate luminance range is available, the most equitable solution may be to simply use luminance manipulations of sufficiently large magnitudes such that the magnitude of the nonuniformity is proportionally small.

Size cue. Use of the Size cue was associated with the same benefits illustrated for the Luminance cue. Improvements in response times were shown for relative depth judgements in Experiment 1, as well as faster search times in Experiment 3. In addition, the Size cue was rated as fairly effective in helping viewers to complete depth judgement tasks (Experiments 1, 2, and 3) and it was associated with increases in image quality (quality of depth) in both Experiments 2 and 3.

The most serious constraint existing for the use of the Size cue on a CRT display is the spatial resolution and addressability of the display. That is, increments in stimulus sizes can only be as small as the pixel structure of the CRT. The resolution and addressability problem can be mediated, of course, by viewing distance; higher spatial frequencies can be displayed by increasing the viewing distance. However, this is not always a realistic strategy outside of the laboratory. When conducting the psychophysical evaluations of cue manipulations in Experiment 3, 2-pixel increments in symbol matrix size were used to maintain symmetrical symbols. Given the constraints of the viewing environment, these increments were clearly above threshold. A finer pixel structure may be necessary to use this depth cue in a more continuous fashion.

A related issue is that of aspect ratio. Since CRT pixels are often not symmetrical, any attempt to change the sizes of screen objects must take into account the unequal effect of adding pixels to the image. For example, increasing the matrix size of a font by 3 pixels could lead to a greater change in size in either the vertical or horizontal direction, depending on the shape of the pixel structure.

Interposition cue. This monocular depth cue has been shown in the literature to have a potent effect on depth perception. The results of Experiments 1 and 2 were in agreement with this conclusion. Use of the Interposition cue was associated with faster response times in Experiment 1, as well as increases in image quality (quality of depth) in Experiment 2. In addition, Interposition was rated as the most effective of the four depth cues in Experiment 1. While there is no doubt as to the potency of the Interposition cue as a means to encode relative depth information, there are some inherent limitations in the use of this depth cue.

The principal difficulty with the Interposition cue is that it is by definition dependent on spatial position. Consequently, display environments which do not allow constant or regular figural occlusion cannot consistently incorporate the Interposition cue. It can be seen, however, that applications such as the Macintosh windowing environment have nevertheless made good use of Interposition. Another constraint is that if overlapping objects do not have clear contours, the nature of the figural interposition will be ambiguous. This can be illustrated by considering the symbols used in the third experiment, which were unfilled line drawings without borders. The only time at which which Interposition could have had any meaning in these scenes was when the Luminance cue was used. In these cases, differences in symbol luminance could have served to create contours between interposed symbols. In all other cases, no such contours would have been present.

Disparity cue. The most unique conclusions offered here pertain to the use of the Disparity cue. The results of Experiment 1 clearly showed that the Disparity cue was of no practical benefit to viewers tasked with making rapid relative depth judgements. The absence of performance benefits associated with the Disparity cue is in sharp contrast to the response time benefits which were documented for the three monocular depth cues. However, the strengths of the Disparity cue were shown in Experiments 2 and 3. In Experiment 2, the most dramatic contribution to image quality came from the Disparity cue. In the more demanding task environment of Experiment 3, Disparity was associated with faster search times. In fact, in Experiments 2 and 3, Disparity was rated as the most effective of the depth cues presented. As with the other depth cues discussed, the use of the Disparity cue is constrained by limitations of the CRT display.

As is the case with the depth cue of Size, the most serious constraint for the use of the Disparity cue on a CRT display is the spatial resolution and addressability of the display. Because horizontal shifts between left and right stereo image fields are used to create stereoscopic depth, the resolution of this depth dimension is necessarily limited by the 2-D resolution and addressability of the CRT. These limitations can be problematic if one wishes to display continuous lines which transverse the depth planes. In such cases, jagged stereoscopic lines occur as a result of limited CRT resolution and addressability. As was previously suggested, increasing the viewing distance may be a temporary solution for some laboratory applications, although increasing viewing distance will also have an impact on apparent stereoscopic depth.

Separation. As implemented in Experiment 3, it is most useful to consider the factor of Separation as equivalent to cue salience. This factor has special importance for the consideration of cue interaction effects. The role of cue salience was well illustrated both within Experiment 3 and among the three experiments, where cue interaction rather than additivity was found. Cue salience played an important part in mediating the nature of these interactions. Performance in Experiment 1 did not show a strong pattern of cumulative depth cue facilitation, most likely because such cumulative effects were washed out by the use of highly salient cue manipulations. In contrast, image quality ratings in Experiment 2 did not appear to suffer from the same ceiling effect. When cue salience (Separation) was added as an independent variable in Experiment 3, it was clearly shown that cumulative depth cue facilitation of performance was most pronounced at near-threshold levels of cue manipulations (low salience levels). When greater salience was used, cue interactions showed ceiling effects. In contrast, no such ceiling effects were evident for subjective image quality ratings in Experiments 2 and 3.

Complexity. Complexity had a predictable effect on visual search performance; that is, visual search times increased as a function of increased Complexity. It has been well established that 2-D visual search may be made more difficult by increasing the number of symbols from which the relevant information must be extracted. The search time results of Experiment 3 are in agreement with those of Staller, Lappin, and Fox (1980). Similarly, the search error results are in agreement with those of Zenyuh et al. (1988) who found a visual search accuracy advantage for stereoscopic display, but only when medium and high display densities were used. There was no indication that the effects of Complexity were unique to any of the three depth cues.

Task. Four general classes of experimental tasks, all qualitatively different, were incorporated in this dissertation research. These tasks included relative depth judgement (Experiment 1), image quality judgement (Experiments 2 and 3), visual search (Experiment 3), and cursor positioning (Experiment 3). It was clearly demonstrated across Experiments 1, 2, and 3 that the effects of depth cues were task dependent. This task dependency was especially evident where the Disparity cue was used.

The Disparity cue was not associated with any response time advantages for the relative depth judgement task in Experiment 1, yet was associated with improved image quality ratings in Experiments 2 and 3 and faster visual searches in Experiment 3. It could be suggested that task-dependent performance differences between Experiments 1 and 3 were confounded with changes in the nature of experimental stimuli. However, it can be seen that the nature of image quality effects remained relatively unchanged between Experiments 2 and 3. This result lends support to the conclusion that performance differences in response to the presence of the Disparity cue between Experiments 1 and 3 were due to task differences rather than stimulus changes.

An additional task dependency was evident in the performance ceiling effects demonstrated in Experiments 1 and 3 where highly salient depth cue manipulations were used. No such ceiling effects were produced for image quality ratings in either Experiment 2 or Experiment 3.

Future Work

Many of the caveats raised in this dissertation could be addressed in future work. One of the principal constraints of the current work is that the results may not generalize well to dynamic imagery. The powerful effects of motion parallax and dynamic interposition have previously been demonstrated. It remains unclear, however, how such depth cues may interact with binocular disparity. For example, Wickens (in press) suggested that the presence of motion cues in a 3-D display reduces the performance utility of stereo depth. Similarly, the use of such displays for the presentation of taped or live video imagery for applications ranging from entertainment to telepresence invites a whole host of new research questions.

Another concern to be raised when interpreting these results is the relatively low task demand involved in all three experiments. Stereoscopic display advantages may be especially apparent under high workload conditions such as might be found in an air traffic control task. Research should be conducted to test the effects of alternative depth presentations on situation awareness, signal detection, and monitoring behavior in such environments.

It may also be suggested that the generalizability of these results is limited by the use of relatively simple geometric images. Within the graphic display realm, specific applications such as computer aided design and molecular modelling should be examined to determine what special limitations may be imposed in these display environments. Similarly, potential application areas beyond the current realm of use for such displays should be examined. For example, 3-D displays may be of special benefit to teachers for the display of multidimensional concepts. A related issue is the determination of how novices and experts may differ in their use of these displays. Indeed, many training questions regarding stereoscopic display in general remain unanswered.

It is clear that there are at least as many unanswered questions regarding 3-D display as there are potential applications. This dissertation was intended as a starting point in a research program to investigate some of the more fundamental questions.

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APPENDIX A

PARTICIPANT'S INFORMED CONSENT FORMS

PARTICIPANT'S INFORMED CONSENT FORM FOR THE SCREENING PROCEDURE

Before you are asked to participate as a subject in this research project, we ask that you complete a brief visual screening procedure. The screening procedure consists of two parts, during which your visual acuity will be assessed. These are not professional exams: therefore, the results should not be considered accurate descriptions of your vision. In particular, if you do not pass the screening procedure, it does not mean that you have "bad" vision.

The total screening procedure should take no longer than 20 minutes. We are not able to pay you for this time. However, if you pass the screening procedure you will be asked to be a paid participant in an experiment.

As a subject in this screening procedure you are entitled to certain rights:

1) You may withdraw from participation in this procedure at any time. However, if you do so you will not be asked to participate in the experiment.

2) The principal investigator or his associates will answer any questions you may have concerning this procedure, and you should not sign this consent form until you are satisfied that you understand all the terms involved.

3) The research team members on this project include:
Dr. Robert J. Beaton, Faculty Member;
William F. Reinhart, Graduate Student;
Ulka Gupte, Student;
William Ryan, Student;
Erik Van de Meulebroeke, Student; and
Cindy Wiersch, Student.

4) The data collected during your participation will be treated with confidentiality and used solely for purposes of screening for this research project.

If you have further questions about your rights as a participant, you may contact Dr. E.R. Stout, Chairman of the Institutional Review Board at Virginia Tech, at 301 Burruss Hall.

Your signature below indicates that you have read this document in its entirety, that your questions have been answered, and that you consent to participate in the screening procedure described. The faculty and students involved with this research thank you for your participation.

______________________	______________________
Signature	Telephone Number
______________________	______________________
Printed Name	Social Security number

Displays and Controls Laboratory
Industrial Engineering and Operations Research
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24061
(703) 231-5499

PARTICIPANT'S INFORMED CONSENT FORM FOR THE EXPERIMENT

You are being asked to participate as a subject in a research project. The purpose of this experiment is to examine the perception of depth in a special 3-D television display. The tasks you will be asked to perform as a subject involve identifying relationships between geometric figures displayed on such a display.

The experiment will take place on a single day, and should last no more than three hours. If you decide to participate, you will be paid \$5.00 per hour for your time spent in the laboratory or \$15.00 for the completion of the experiment, whichever is greater. Payment will be made upon completion of your participation.

The expected benefits to you as a participant include monetary payment as well as experience with an interesting new visual display technology. The possible risks to you as a participant include discomfort from sitting in a constrained posture for several hours (although rest breaks will be given) and any visual discomfort or headaches you may experience while viewing the television display. While it is not expected that you will experience undue discomfort, please note that you are free to withdraw from the experiment at any time should you find this to be the case.

As a subject in this experiment you are entitled to certain rights:

1) You may withdraw from participation in this experiment at any time. However, if you do so you will only be paid for your time actually spent participating in the experiment.

2) The principal investigator or his associates will answer any questions you may have concerning this experiment, and you should not sign this consent form until you are satisfied that you understand all the terms involved. However, in cases where experimental details may affect the outcome of the experiment, the researcher may delay a complete disclosure until you have completed participation in the experiment.

3) The research team members on this project include:

Dr. Robert J. Beaton, Faculty Member;
William F. Reinhart, Graduate Student;
Ulka Gupte, Student;
William Ryan, Student;
Erik Van de Meulebroeke, Student; and
Cindy Wiersch, Student.

4) The data collected during your participation will be treated with anonymity. After completion of your participation, your name will be separated from your data. For this reason, if you wish to withdraw your data from our analyses, you must notify the experimenter immediately upon completion of your participation.

If you have further questions about your rights as a participant, you may contact Dr. E.R. Stout, Chairman of the Institutional Review Board at Virginia Tech, at 301 Burruss Hall.

Your signature below indicates that you have read this document in its entirety, that your questions have been answered, and that you consent to participate in the experiment described. The faculty and students involved with this research thank you for your participation.

______________________	______________________
Signature	Telephone Number
______________________	______________________
Printed Name	Social Security number

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APPENDIX B

INSTRUCTIONS TO PARTICIPANTS, EXPERIMENT 1

INSTRUCTIONS TO PARTICIPANTS

Introduction

In this experiment, you will be asked to make judgements about the relationships among simple, geometric figures presented on the screen in front of you. Three figures will be presented together on the screen: a circle, a triangle, and a square. The positions of these figures on the screen will vary from trial to trial. In addition, the *apparent depth* of the figures may also change. By this, we mean that the figures may appear to be closer or further away relative to you and the screen. Your task will be to determine the relative depth of the three figures.

You will first be given an opportunity to practice this task. During these practice trials, please ask the experimenter any questions you may have regarding your task. You will be given a five-minute rest break following completion of the practice trials, a break following completion of one-half the experimental trials, and another break following completion of the experimental trials. After the experimental trials, we would like you to complete a one-page questionnaire and a 10-minute written assessment of your spatial ability.

During the experiment, it will be necessary for you to wear special glasses in order to see the screen images properly. Your experimenter will now demonstrate for you the proper way to wear these glasses. When handling the glasses, please be careful not to smudge the lenses with finger prints.

If you have any questions regarding these instructions, please ask your experimenter at this time

Training: Part A

This is the beginning of your practice time. For this part of the training, you are to simply observe the images presented to you on the screen.

Training Picture 1

The figures you now see on the screen are the same figures that will be used in this experiment. The circle, square, and triangle in this picture are of the same brightness and approximately the same size. In addition, none of these figures overlap each other. Consequently, in this picture there is **no depth information**. In the pictures to follow, the scenes will be changed in such a way as to provide you with depth information. In all cases, each picture is to be compared to this first picture, which has no depth information.

Training Pictures 2-4

In these next pictures, the figures appear to be of different sizes. Since objects appear to us as smaller at greater distances and larger when close to us, the relative sizes of these figures provides depth information. In all cases where the figures appear to be of different sizes, you should assume that this is because they are at different depths. For example, in this first picture, the square appears to be the largest, while the circle appears to be the smallest. If one assumes that the figures are actually the same size but are at different depths, then the square would be said to be closest, while the circle would be said to be farthest away. **Do you understand how relative size may be used to present depth information?**

Relative size is used in this next picture as well. The triangle should appear to be the closest, while the circle should appear to be the farthest away. **Is this what you see?**

Relative size is again used in this picture. The circle should appear to be the closest, while the triangle should appear to be the farthest away. **Is this what you see?**

Training Pictures 5-7

In these next pictures, the figures appear to be of different brightness. Since objects appear to us as less bright at greater distances and brighter when close to us, the relative brightness of these figures provides depth information. In all cases where the figures appear to be of different brightness, you should assume that this is because they are at different depths. For example, in this first picture, the triangle appears to be the brightest, while the square appears to be the least bright. If one assumes that the figures actually have the same brightness but are at different depths, then the triangle would be said to be the closest, while the square would be said to be the farthest away. **Do you understand how relative brightness may be used to present depth information?**

Relative brightness is used in this next picture as well. The circle should appear to be the closest, while the square should appear to be the farthest away. **Is this what you see?**

Relative brightness is again used in this picture. The square should appear to be the closest, while the triangle should appear to be the farthest away. **Is this what you see?**

Training Pictures 8-10

In these next pictures, the figures appear to overlap each other. Since objects may appear to us as hidden behind other objects at greater distances and in front of other objects when close to us, the overlapping of these figures provides depth information. In all cases where the figures appear to overlap each other, you should assume that this is because they are at different depths. For example, in this first picture, the circle is not hidden, while the triangle is overlapped by both the circle and the square. In this figure, the circle would be said to be the closest, while the triangle would be said to be the farthest away. **Do you understand how overlap may be used to present depth information?**

Overlap is used in this next picture as well. The square should appear to be the closest, while the triangle should appear to be the farthest away. **Is this what you see?**

Overlap is again used in this picture. The triangle should appear to be the closest, while the circle should appear to be the farthest away. **Is this what you see?**

Training Pictures 11-13

In these next pictures, the depth cue of stereo is used. This involves presenting different pictures of each figure to each eye, slightly set apart. The usual effect of this separation is a sensation that the figures are in depth. It is sometimes necessary to study the figures for a moment before you can experience this sensation of depth. In this first figure, the square should appear to be the closest figure to you, while the circle should appear to be the farthest figure from you. **Do you understand how stereo may be used to present depth information?**

Stereo is used in this next picture as well. The triangle should appear to be the closest, while the square should appear to be the farthest away. However, this picture should appear to have more depth than the previous picture. **Is this what you see?**

Finally, stereo is again used in this picture. The circle should appear to be the closest, while the triangle should appear to be the farthest away. However, this picture should appear to have more depth than the previous picture. **Is this what you see?** In all cases during the experiment, you are to assume that stereo is an indication that the figures are at different depths.

At this time, do you have any questions about size, brightness, overlap, or stereo depth cues?

Training: Part B

This is the second part of your practice time. For these next practice trials, you are going to see a series of pictures with three figures. In each case, the three figures will be at different depths. You must determine the relative depth order (from closest to farthest) of the figures. You are to respond vocally by saying out loud the relative depth order of the figures, starting from the closest figure to you to the farthest figure from you. For these trials, do not worry about responding rapidly. Rather, respond as accurately as possible. **Do you understand?**

1. Size

The depth information available to you in these next pictures will be **relative size. Do you understand?**

2. Brightness

The depth information available to you in these next pictures will be **relative brightness. Do you understand?**

3. Overlap

The depth information available to you in these next pictures will be **overlap. Do you understand?**

4. Stereo

The depth information available to you in these next pictures will be **stereo. Do you understand?**

Training: Part C

You are now going to see four more series of practice figures. In each case, the three figures will be at different depths. From now on, you will be responding just as if this were the actual experiment. Each trial will begin with one of three possible questions appearing on the screen:

1) Which figure is the farthest from you?;
2) Which figure is the closest to you?; or
3) Which figure is the middle figure?

Your experimenter will now give you a two-button "mouse" device with which you will control the experimental trials. Please hold the mouse in your preferred hand (that is, if you are "right-handed," hold the mouse in your right hand). When you are ready, you should then press **and hold the left button down** to begin the trial. As soon as the figures appear on the screen, determine which of the figures (circle, triangle, or square) occupies the position in question (farthest, closest, or middle). When you can name the figure, release the button. **After** you release button, say the name of the figure out loud to the experimenter ("Circle," "square," or "Triangle"). From now on, your speed of response is important, although accuracy is more important. Therefore, respond as quickly as possible without making an error. **Do you understand?**

Size

The depth information available to you in this first series of pictures will be **relative size**. Respond as quickly as possible without making an error. **Do you understand?**

Brightness

The depth information available to you in this next series of pictures will be **relative brightness**. Respond as quickly as possible without making an error. **Do you understand?**

Overlap

The depth information available to you in this next series of pictures will be **overlap.** Respond as quickly as possible without making an error. **Do you understand?**

Stereo

The depth information available to you in this last series of pictures will be **stereo.** Respond as quickly as possible without making an error. **Do you understand?**

**** REST BREAK ****

Final Instructions

We are now ready to begin the experiment. Remember that each trial will begin with one of three possible questions appearing on the screen:

1) Which figure is the farthest from you?;
2) Which figure is the closest to you?;or
3) Which figure is the middle figure?

When you are ready, you should then press **and hold the button down** to begin the trial. As soon as the figures appear on the screen, determine which of the figures (circle, triangle, or square) occupies the position in question (farthest, closest, or middle). When you can name the figure, release the button. **After** you release button, say the name of the figure out loud to the experimenter ("Circle," "square," or "Triangle"). Your speed of response is important, but accuracy is more important.

There is an important difference between these experimental trials and the training trials which you just completed. While pictures in the training trials always used only one source of depth information at one time, pictures presented during the experiment may use none, one, two, three, or all four sources of depth information. If no depth information is present in the picture, you are to respond, "no depth."

If you have any questions, please ask them now. Your experimenter will be unable to provide you with additional help once the experiment has started. There will be a five-minute break after you have completed these trials.

APPENDIX C

3-D QUESTIONNAIRE

3-D QUESTIONNAIRE

Subject #__________ Gender _______ Date________________

1. To what extent did you experience any of the following during the experiment?:

	Not at all								**Intense**
a. Headache	1	2	3	4	5	6	7	8	9	10
b. Eyestrain	1	2	3	4	5	6	7	8	9	10
c. Nausea	1	2	3	4	5	6	7	8	9	10
d. Blurred vision	1	2	3	4	5	6	7	8	9	10
e. General discomfort	1	2	3	4	5	6	7	8	9	10
f. Other ______________	1	2	3	4	5	6	7	8	9	10

2. Please rate the following for their effectiveness in helping you make relative depth judgements during the experiment:

	Not Helpful							**Very Helpful**		
a. Brightness	1	2	3	4	5	6	7	8	9	10
b. Size	1	2	3	4	5	6	7	8	9	10
c. Overlap	1	2	3	4	5	6	7	8	9	10
d. Stereo	1	2	3	4	5	6	7	8	9	10

3. Were there any **combinations** of brightness, size, overlap, and stereo that were particularly effective (that is, that helped you to see depth)?

4. Were there any **combinations** of brightness, size, overlap, and stereo that were particularly ineffective (that is, that did not help you to see depth or made it more difficult to see depth)?

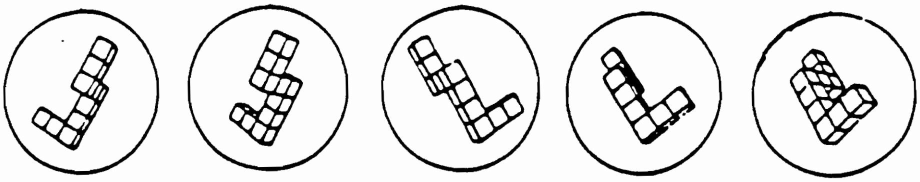
APPENDIX D

MENTAL ROTATIONS TEST

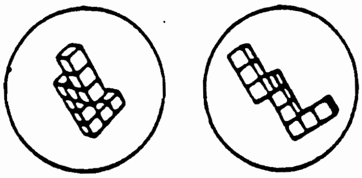
Subject #________ Gender ________

Date __________

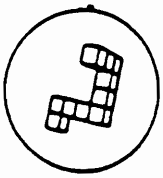
This is a test of your ability to look at a drawing of a given object and find the same object within a set of dissimilar objects. The only difference between the original object and the chosen object will be that they are presented at different angles. An illustration of this principle is given below, where the same single object is given in five different positions. Look at each of them to satisfy yourself that they are only presented at different angles from one another.

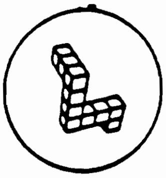


Below are two drawings of new objects. They cannot be made to match the above five drawings.
Satisfy yourself that they are different from the above.



Now let's do some sample problems. For each problem there is a primary object on the far left. You are to determine which two of four objects to the right are the same object given on the far left. In each problem always <u>two</u> of the four drawings are the same object as the one on the left. You are to put Xs in the boxes below the correct ones, and leave the incorrect ones blank. The first sample problem is done for you.





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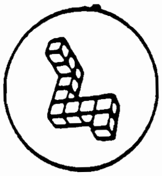

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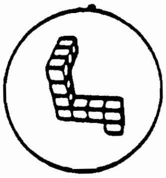

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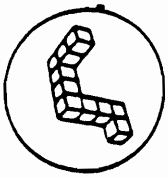

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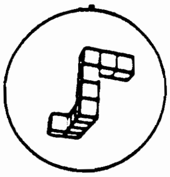
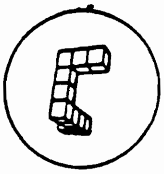
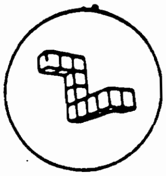
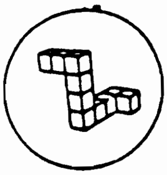
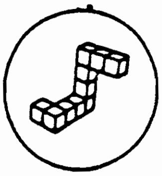
Go to the next page

Do the rest of the sample problems yourself. Which two drawings of the four on the right show the same object as the one on the left? There are always two and only two correct answers for each problem. Put an X under the two correct drawings.

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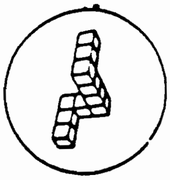
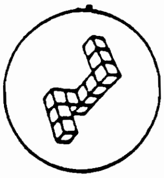
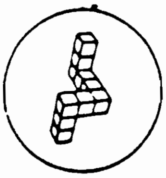
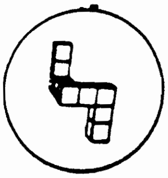
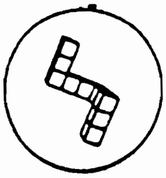

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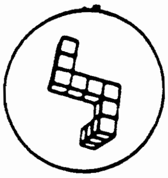
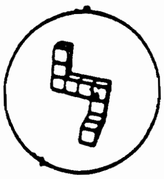
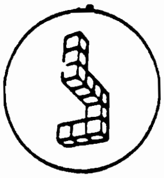
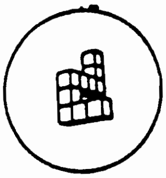
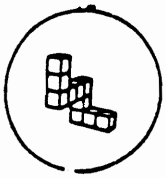

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Answers: (1) first and second drawings are correct
(2) first and third drawings are correct
(3) second and third drawings are correct

This test has two parts. You will have 3 minutes for each of the two parts. Each part has two pages. When you have finished Part I, STOP. Please do not go one to Part 2 until you are asked to do so. Remember: There are always two and only two correct answers for each item.

Work as quickly as you can without sacraficing accuracy. Your score on this test will reflect both the correct and incorrect responses. Therefore, it will not be to your advantage to guess unless you have some idea which choice is correct.

DO NOT TURN THIS PAGE UNTIL ASKED TO DO SO

PART 1

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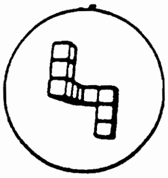

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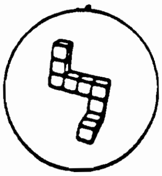

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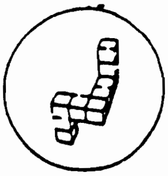

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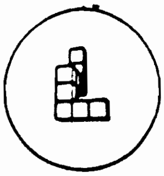

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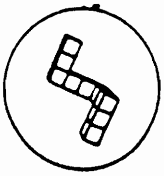

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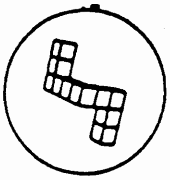

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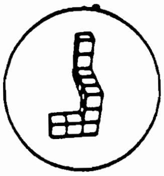

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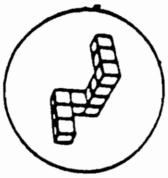

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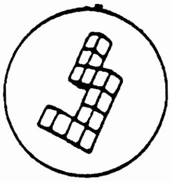

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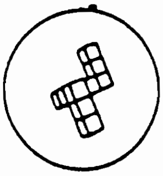

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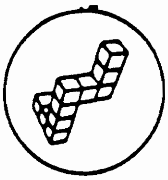

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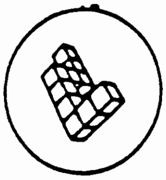

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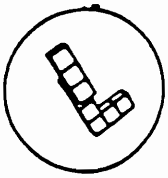

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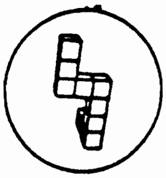

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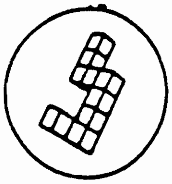

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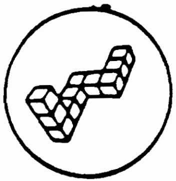

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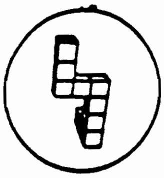

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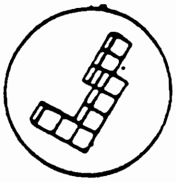

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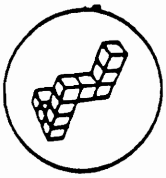

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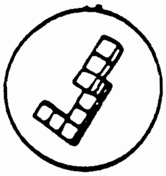

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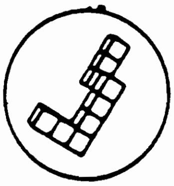

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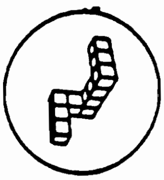

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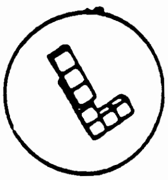

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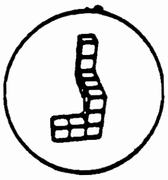

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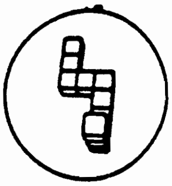

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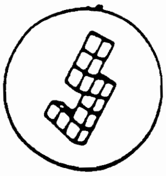
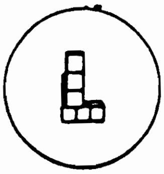
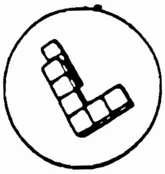
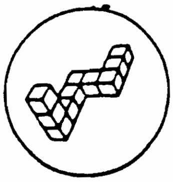
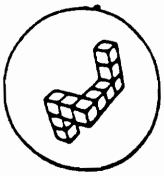
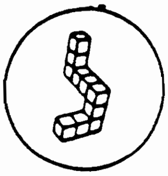
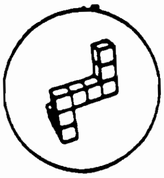
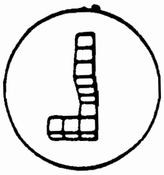
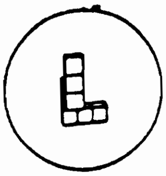
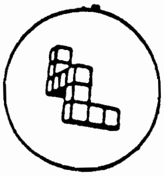
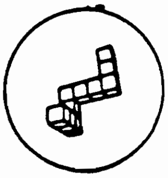
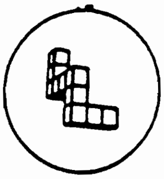
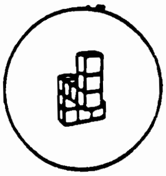
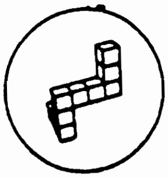
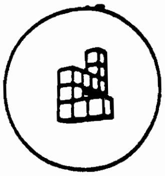
6. 

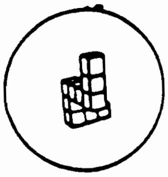
 ☐
 ☐
 ☐
 ☐

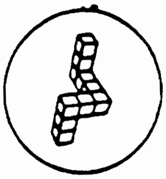
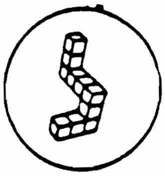
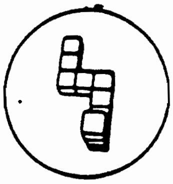
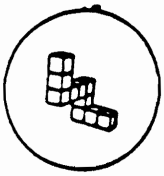
7. 

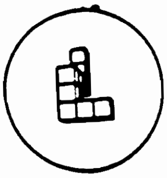
 ☐
 ☐
 ☐
 ☐

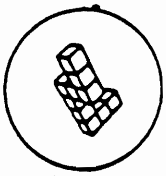
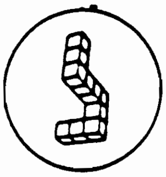
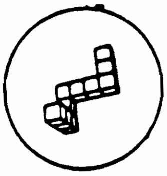
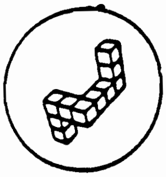
8. 

 ☐
 ☐
 ☐
 ☐

9. 

 ☐
 ☐
 ☐
 ☐

10. 

 ☐
 ☐
 ☐
 ☐

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PART 2

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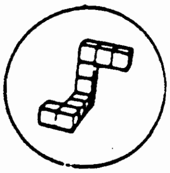

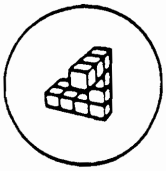

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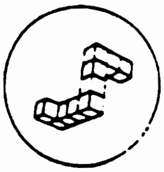

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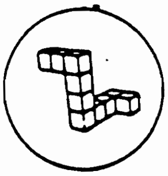

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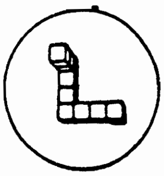

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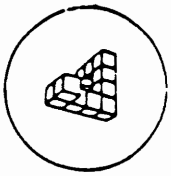

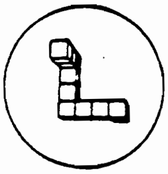

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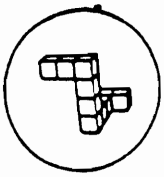

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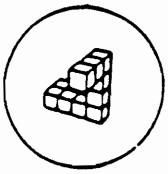

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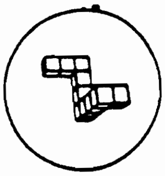

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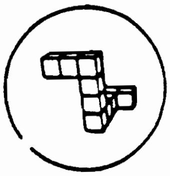

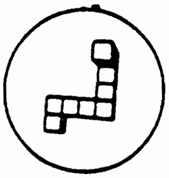

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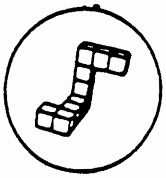

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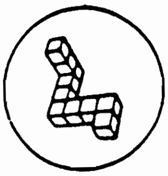

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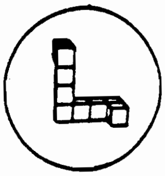

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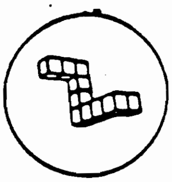

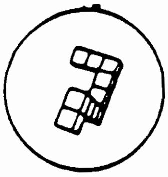

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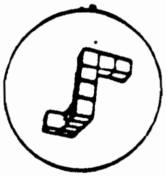

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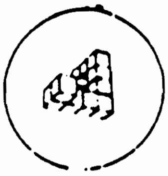

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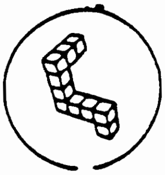

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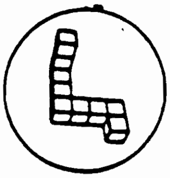

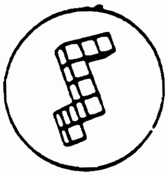

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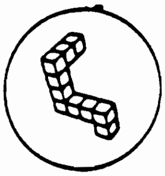

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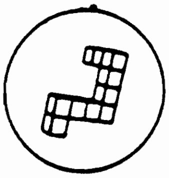

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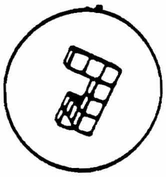

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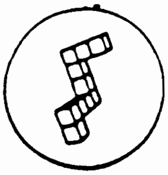

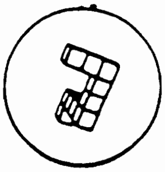
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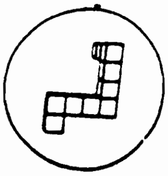
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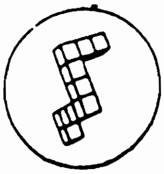
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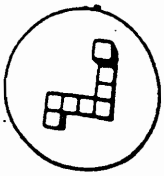
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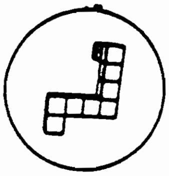

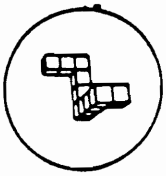
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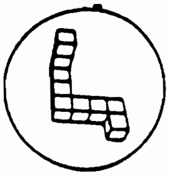
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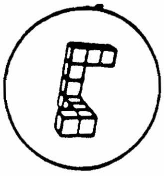
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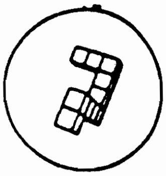
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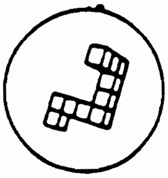

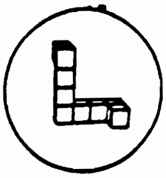
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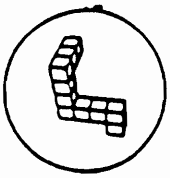
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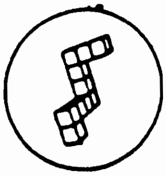
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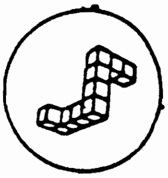
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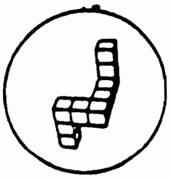

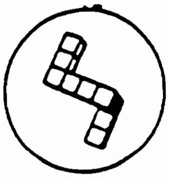
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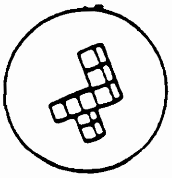
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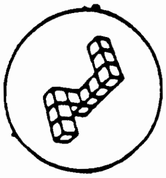
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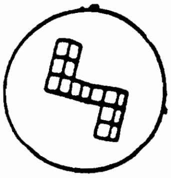
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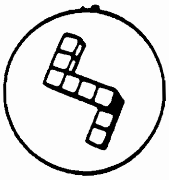

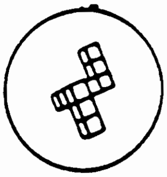
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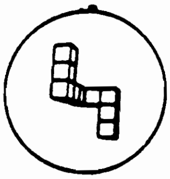
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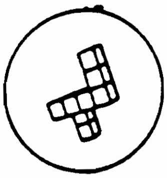
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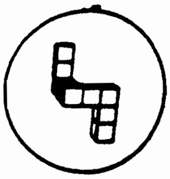
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APPENDIX E

TABLES FROM POST-HOC ANALYSES, EXPERIMENT 1

TABLE E-1

Results of Simple-Effect F-Tests on Size (Sz) for Each Value of Interposition (I) Cue (Response Time (ms))

Source	*df*	*MS*	*F*	*p*
Sz (I Absent)	1	10039149.79	31.55	.0005
Sz (I Present)	1	57705.13	0.18	.6815
I*Sz*S(G)	8	318227.47		

TABLE E-2

Results of Simple-Effect F-Tests on Luminance (L) for Each Value of Interposition (I) Cue (Response Time (ms))

Source	*df*	*MS*	*F*	*p*
L (I Absent)	1	7362658.44	20.35	.0020
L (I Present)	1	83.88	0.00	.9882
L*I*S(G)	8	361858.17		

TABLE E-3

Results of Simple-Effect F-Tests on Luminance (L) for Each Value of Size (Sz) Cue (Response Time (ms))

Source	*df*	*MS*	*F*	*p*
L (Sz Absent)	1	6132042.94	16.12	.0039
L (Sz Present)	1	51969.01	0.14	.7213
L*Sz*S(G)	8	380448.39		

TABLE E-4

Results of Simple-Effect F-Tests on Luminance by Size Interaction (L*Sz) for Each Value of Interposition (I) Cue (Response Time (ms))

Source	*df*	*MS*	*F*	*p*
L*Sz (I Absent)	1	4738389.56	13.73	.0060
L*Sz (I Present)	1	5118.67	0.01	.9061
L*I*Sz*S(G)	8	345006.07		

TABLE E-5

Results of Simple-Effect F-Tests on Luminance (L) for Each Value of Size (Sz) Cue without Interposition (I) Cue (Response Time (ms))

Source	*df*	*MS*	*F*	*p*
L (Sz Absent, I Absent)	1	11957058.00	34.66	.0004
L (Sz Present, I Absent)	1	143990.00	.42	.5363
L*I*Sz*S(G)	8	345006.07		

TABLE E-6

Results of Newman-Keuls Test on Mean Questionnaire Cue Ratings *

Questionnaire Item:	2(a) Luminance	2(d) Disparity	2(b) Size	2(c) Interposition
Mean Value:	6.4	6.6	7.7	9.7

* Means with a common line do not differ significantly at $p \leq .05$

APPENDIX F

SUPPLEMENTAL FIGURES, EXPERIMENT 1

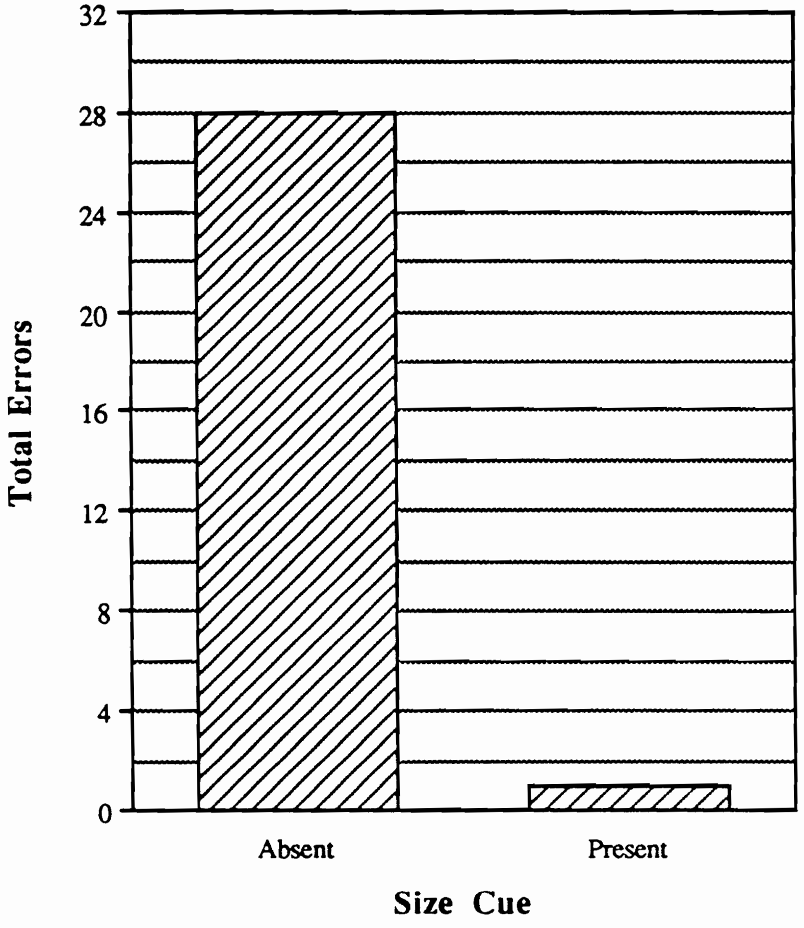


Figure F-1. Total errors as a function of Size cue, Experiment 1.

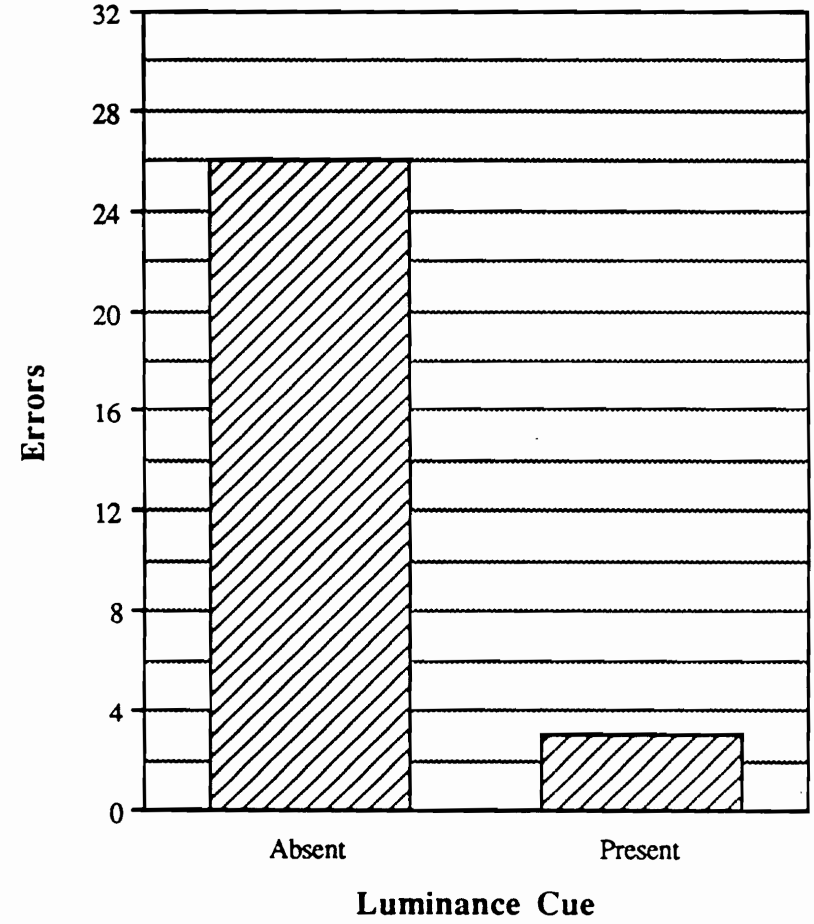


Figure F-2. Total errors as a function of Luminance cue, Experiment 1.

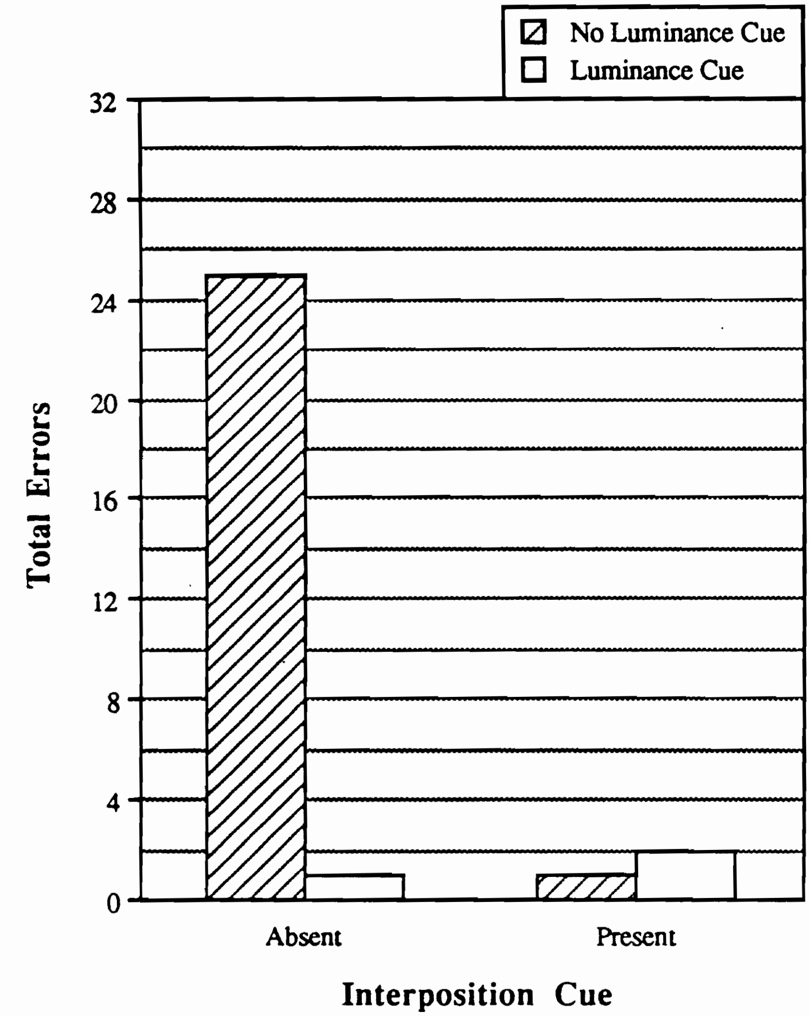


Figure F-3. Total errors as a function of Interposition and Luminance cues, Experiment 1.

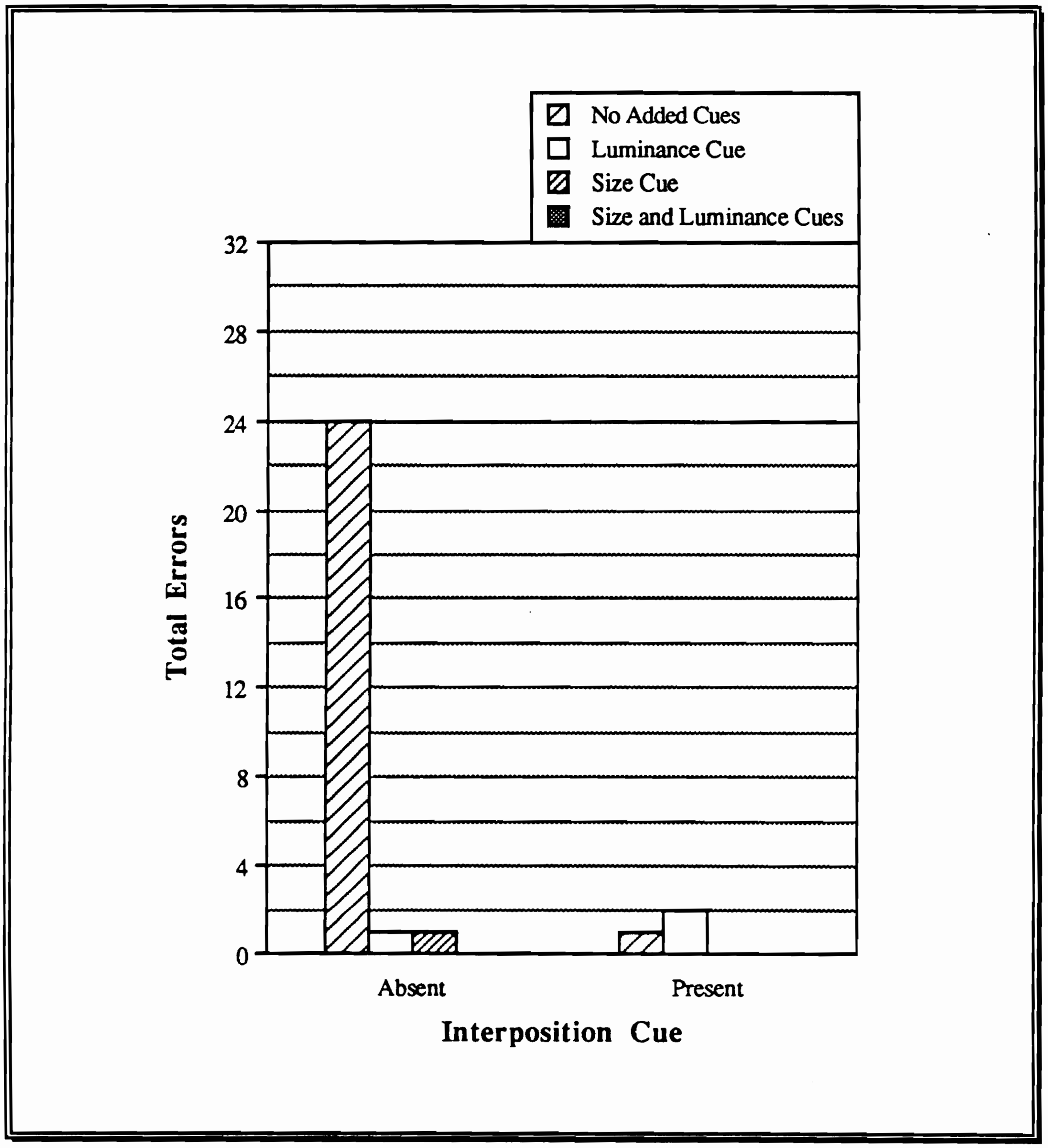


Figure F-4. Total errors as a function of Interposition, Luminance, and Size cues, Experiment 1.

APPENDIX G

IMAGE QUALITY RATING SCALE

DEPTH RATING SCALE

Please use one of the following nine adjectives to describe how convincing the sensation of depth is in each picture:

BEST IMAGINABLE

EXCELLENT

GOOD

OK

PASSABLE

MARGINAL

POOR

AWFUL

WORST IMAGINABLE

APPENDIX H

INSTRUCTIONS TO PARTICIPANTS, EXPERIMENT 2

INSTRUCTIONS TO PARTICIPANTS

Introduction

In this experiment, you will be asked to make judgements about the relationships among simple, geometric figures presented on the screen in front of you. Three figures will be presented together on the screen: a circle, a triangle, and a square. The positions of these figures on the screen will vary from trial to trial. In addition, the *apparent depth* of the figures may also change. By this, we mean that the figures may appear to be closer or further away relative to you and the screen. Your task will be to rate the relative depth of the three figures.

You will first be given an opportunity to practice this task. During these practice trials, please ask the experimenter any questions you may have regarding your task. You will be given a five-minute rest break following completion of the practice trials and a break following completion of one-half the experimental trials. After the experimental trials, we would like you to complete a one-page questionnaire.

During the experiment, it will be necessary for you to wear special glasses in order to see the screen images properly. Your experimenter will now demonstrate for you the proper way to wear these glasses. When handling the glasses, please be careful not to smudge the lenses with finger prints.

If you have any questions regarding these instructions, please ask your experimenter at this time

Training: Part A

This is the beginning of your practice time. During the course of this experiment, you will be using a rating scale to rate the depth that you see in the displays. Your experimenter will now give you a copy of this rating scale. The scale is made up of nine adjectives, from "BEST IMAGINABLE" to "WORST IMAGINABLE." You will use this scale to describe how convincing the sensation of depth is in each display. For this first part of the training, however, you are to simply observe the images presented to you on the screen.

Training Picture 1

The figures you now see on the screen are the same figures that will be used in this experiment. The circle, square, and triangle in this picture are of the same brightness and approximately the same size. In addition, none of these figures overlap each other. Consequently, in this picture there is **no depth information**. When you see a picture with no depth information in the experiment, you should rate that picture as "WORST IMAGINABLE," since there is no sensation of depth in the picture. In the pictures to follow, the scenes will be changed in such a way as to provide you with depth information. In all cases, each picture is to be compared to this first picture, which has no depth information.

Training Pictures 2-4

In these next pictures, the figures appear to be of different sizes. Since objects appear to us as smaller at greater distances and larger when close to us, the relative sizes of these figures provides depth information. In all cases where the figures appear to be of different sizes, you should assume that this is because they are at different depths. For example, in this first picture, the square appears to be the largest, while the circle appears to be the smallest. If one assumes that the figures are actually the same size but are at different depths, then the square would be said to be closest, while the circle would be said to be farthest away. **Do you understand how relative size may be used to present depth information?**

Relative size is used in this next picture as well. The triangle should appear to be the closest, while the circle should appear to be the farthest away. **Is this what you see?**

Relative size is again used in this picture. The circle should appear to be the closest, while the triangle should appear to be the farthest away. **Is this what you see?**

Training Pictures 5-7

In these next pictures, the figures appear to be of different brightness. Since objects appear to us as less bright at greater distances and brighter when close to us, the relative brightness of these figures provides depth information. In all cases where the figures appear to be of different brightness, you should assume that this is because they are at different depths. For example, in this first picture, the triangle appears to be the brightest, while the square appears to be the least bright. If one assumes that the figures actually have the same brightness but are at different depths, then the triangle would be said to be the closest, while the square would be said to be the farthest away. **Do you understand how relative brightness may be used to present depth information?**

Relative brightness is used in this next picture as well. The circle should appear to be the closest, while the square should appear to be the farthest away. **Is this what you see?**

Relative brightness is again used in this picture. The square should appear to be the closest, while the triangle should appear to be the farthest away. **Is this what you see?**

Training Pictures 8-10

In these next pictures, the figures appear to overlap each other. Since objects may appear to us as hidden behind other objects at greater distances and in front of other objects when close to us, the overlapping of these figures provides depth information. In all cases where the figures appear to overlap each other, you should assume that this is because they are at different depths. For example, in this first picture, the circle is not hidden, while the triangle is overlapped by both the circle and the square. In this figure, the circle would be said to be the closest, while the triangle would be said to be the farthest away. **Do you understand how overlap may be used to present depth information?**

Overlap is used in this next picture as well. The square should appear to be the closest, while the triangle should appear to be the farthest away. **Is this what you see?**

Overlap is again used in this picture. The triangle should appear to be the closest, while the circle should appear to be the farthest away. **Is this what you see?**

Training Pictures 11-13

In these next pictures, the depth cue of stereo is used. This involves presenting different pictures of each figure to each eye, slightly set apart. The usual effect of this separation is a sensation that the figures are in depth. It is sometimes necessary to study the figures for a moment before you can experience this sensation of depth. In this first figure, the square should appear to be the closest figure to you, while the circle should appear to be the farthest figure from you. **Do you understand how stereo may be used to present depth information?**

Stereo is used in this next picture as well. The triangle should appear to be the closest, while the square should appear to be the farthest away. However, this picture should appear to have more depth than the previous picture. **Is this what you see?**

Finally, stereo is again used in this picture. The circle should appear to be the closest, while the triangle should appear to be the farthest away. However, this picture should appear to have more depth than the previous picture. **Is this what you see?** In all cases during the experiment, you are to assume that stereo is an indication that the figures are at different depths.

At this time, do you have any questions about size, brightness, overlap, or stereo depth cues?

Training: Part B

This is the second part of your practice time. For these next practice trials, you are going to see a series of pictures with three figures. In each case, the three figures will be at different depths. You must determine the relative depth order (from closest to farthest) of the figures. You are to respond vocally by saying out loud the relative depth order of the figures, starting from the closest figure to you to the farthest figure from you. For these trials, do not worry about responding rapidly. Rather, respond as accurately as possible. **Do you understand?**

1. Size

The depth information available to you in these next pictures will be **relative size. Do you understand?**

2. Brightness

The depth information available to you in these next pictures will be **relative brightness. Do you understand?**

3. Overlap

The depth information available to you in these next pictures will be **overlap. Do you understand?**

4. Stereo

The depth information available to you in these next pictures will be **stereo. Do you understand?**

Training: Part C

You are now going to see one last series of practice figures. In each case, the three figures will be at different depths. From now on, you will be responding just as if this were the actual experiment. Each trial will begin with the following message appearing on the screen:

"Press the button to start the trial"

When you are ready, you should then press **and hold the left mouse button down** to start the trial. When the figures appear on the screen, you are to evaluate the depth that you see in the display. Assign a rating from the list of nine adjectives, based on how convincing the sensation of depth is in that particular picture. When you can make your rating, release the button. After you release the button, say the rating out loud to the experimenter. Your speed of response is not important for this task, although your accuracy is important. Therefore, respond as accurately as possible.

When you make your ratings during these practice trials, there are some important things to keep in mind. First, all ratings should be made in comparison to the pictures which contain no depth information. These pictures are examples of "WORST IMAGINABLE" depth, since there is no depth information in the pictures.

In addition, during these practice trials and in the actual experiment, you will be seeing pictures which contain zero, 1, 2, 3, or 4 sources of depth information. It is possible, but not certain, that you will find combinations of depth cues to provide a different depth sensation than the pictures you have seen which contain only one source of depth information. Try to use the full range of the scale provided, but feel free to give several pictures the same rating if you feel that they create equal sensations of depth. **Do you understand?**

**** Rest Break ****

Final Instructions

We are now ready to begin the experiment. Remember that each trial will begin with the following message appearing on the screen:

"Press the button to start the trial"

When you are ready, you should then press **and hold the left mouse button down** to start the trial. When the figures appear on the screen, you are to evaluate the depth that you see in the display. Assign a rating from the list of nine adjectives, based on how convincing the sensation of depth is in that particular picture. When you can make your rating, release the button. **After** you release the button, say the rating out loud to the experimenter. Since the reading lamp will not be on during the experiment, you will not be able to use the printed list of rating scale adjectives. In order to refresh your memory, the list of adjectives will be displayed on the screen every time you release the button. Your speed of response is not important for this task, although your accuracy is important. Therefore, respond as accurately as possible.

Remember, while pictures in the first two training sessions always used only one source of depth information at one time, pictures presented during the experiment may use zero, 1, 2, 3, or 4 sources of depth information. Try to use the full range of the scale provided, but feel free to give several pictures the same rating if you feel that they create equal sensations of depth. **Do you understand?**

We will begin the experiment by allowing your eyes to adjust to the darkened room for five minutes. If you have any questions, please ask them now. There will be a five-minute break after you have completed one-half of these trials.

APPENDIX I

SUPPLEMENTAL FIGURES, EXPERIMENT 2

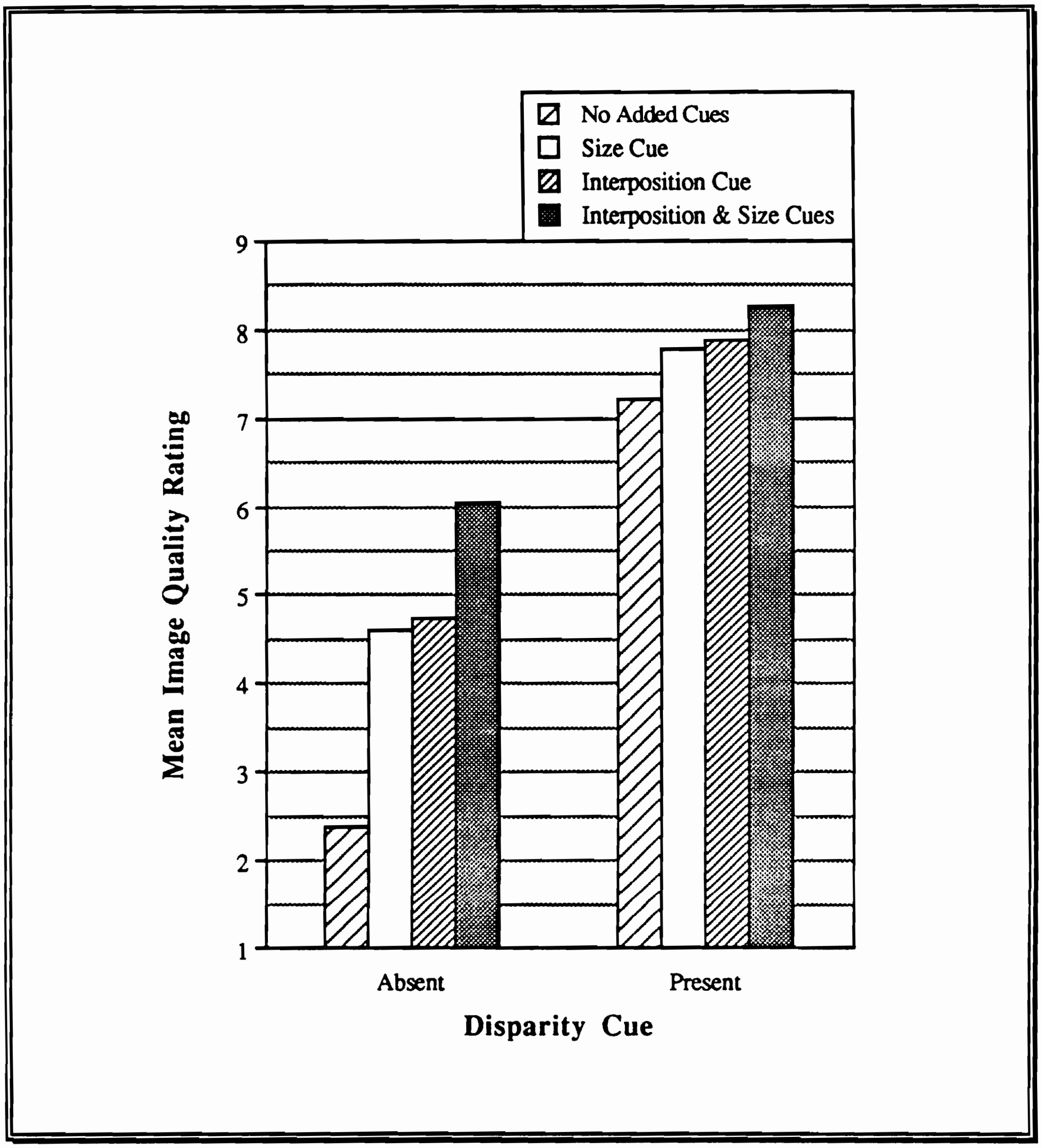


Figure I-1. Total errors as a function of Disparity, Size, and Interposition cues, Experiment 1.

APPENDIX J

TABLES FROM POST-HOC ANALYSES, EXPERIMENT 2

TABLE J-1

Results of Simple-Effect F-Tests on Size (Sz) for Each Value of Interposition (I) Cue (Mean Image Quality Rating)

Source	*df*	*MS*	*F*	*p*
Sz (I Absent)	1	38.7347	88.73	< .0001
Sz (I Present)	1	14.8781	34.08	.0004
I*Sz*S(G)	8	0.4365		

TABLE J-2

Results of Simple-Effect F-Tests on Luminance (L) for Each Value of Interposition (I) Cue (Mean Image Quality Rating)

Source	*df*	*MS*	*F*	*p*
L (I Absent)	1	23.2920	95.50	< .0001
L (I Present)	1	7.7087	31.61	.0005
L*I*S(G)	8	0.2439		

TABLE J-3

Results of Simple-Effect F-Tests on Luminance (L) for Each Value of Size (Sz)Cue

(Mean Image Quality Rating)

Source	*df*	*MS*	*F*	*p*
L (Sz Absent)	1	26.0681	272.94	< .0001
L (Sz Present)	1	6.2347	65.28	< .0001
L*Sz*S(G)	8	0.0955		

TABLE J-4

Results of Simple-Effect F-Tests on Size (Sz) for Each Value of Disparity (D) Cue (Mean Image Quality Rating)

Source	*df*	*MS*	*F*	*p*
Sz (D Absent)	1	62.7170	219.12	< .0001
Sz (D Present)	1	4.6722	16.32	.0037
Sz*D*S(G)	8	0.2862		

TABLE J-5

Results of Simple-Effect F-Tests on Luminance (L) for Each Value of Disparity (D) Cue (Mean Image Quality Rating)

Source	*df*	*MS*	*F*	*p*
L (D Absent)	1	25.5003	161.74	< .0001
L (D Present)	1	6.5170	41.34	.0002
L*D*S(G)	8	0.1577		

TABLE J-6

Results of Simple-Effect F-Tests on Interposition (I) for Each Value of Disparity (D) Cue (Mean Image Quality Rating)

Source	*df*	*MS*	*F*	*p*
I (D Absent)	1	72.5170	63.34	< .0001
I (D Present)	1	6.8056	5.94	.0407
I*D*S(G)	8	1.1449		

TABLE J-7

Results of Simple-Effect F-Tests on Luminance by Size Interaction (L*Sz) for Each Value of Interposition (I) Cue (Mean Image Quality Rating)

Source	*df*	*MS*	*F*	*p*
L*Sz (I Absent)	1	5.3389	26.24	.0009
L*Sz (I Present)	1	0.0889	0.44	.5272
L*I*Sz*S(G)	8	0.2035		

TABLE J-8

Results of Simple-Effect F-Tests on Luminance (L) for Each Value of Size (Sz) Cue with No Interposition (I) Cue (Mean Image Quality Rating)

Source	*df*	*MS*	*F*	*p*
L (Sz Absent, I Absent)	1	25.4669	125.17	< .0001
L (Sz Present, I Absent)	1	3.1640	15.55	.0043
L*I*Sz*S(G)	8	0.2035		

TABLE J-9

Results of Simple-Effect F-Tests on Luminance by Interposition Interaction (L*I) for Each Value of Disparity (D) Cue (Mean Image Quality Rating)

Source	*df*	*MS*	*F*	*p*
L*I (D Absent)	1	3.9014	17.99	.0028
L*I (D Present)	1	0.0056	0.03	.8768
L*I*D*S(G)	8	0.2168		

TABLE J-10

Results of Simple-Effect F-Tests on Luminance (L) for Each Value of Interposition (I) Cue with No Disparity (D) Cue (Mean Image Quality Rating)

Source	*df*	*MS*	*F*	*p*
L (I Absent, D Absent)	1	24.6752	113.81	< .0001
L (I Present, D Absent)	1	4.7266	21.80	.0016
L*I*D*S(G)	8	0.2168		

TABLE J-11

Results of Simple-Effect F-Tests on Luminance by Size Interaction (L*Sz) for Each Value of Disparity (D) Cue (Mean Image Quality Rating)

Source	*df*	*MS*	*F*	*p*
L*Sz (D Absent)	1	6.8056	66.03	< .0001
L*Sz (D Present)	1	0.0000	0.00	> .9999
L*Sz*D*S(G)	8	0.1031		

TABLE J-12

Results of Simple-Effect F-Tests on Luminance (L) for Each Value of Size (Sz) Cue with No Disparity (D) Cue (Mean Image Quality Rating)

Source	*df*	*MS*	*F*	*p*
L (Sz Absent, D Absent)	1	29.3266	284.56	< .0001
L (Sz Present, D Absent)	1	2.9793	28.91	.0007
L*Sz*D*S(G)	8	0.1031		

TABLE J-13

Results of Simple-Effect F-Tests on Interposition by Luminance by Size Interaction (I*L*Sz) for Each Value of Disparity (D) Cue (Mean Image Quality Rating)

Source	*df*	*MS*	*F*	*p*
I*L*Sz (D Absent)	1	2.6281	37.16	.0003
I*L*Sz (D Present)	1	0.1531	2.17	.1794
L*I*Sz*D*S(G)	8	0.0707		

TABLE J-14

Results of Simple-Effect F-Tests on Luminance by Size Interaction (L*Sz) for Each Value of Interposition (I) Cue with No Disparity (D) Cue (Mean Image Quality Rating)

Source	*df*	*MS*	*F*	*p*
L*Sz (I Absent, D Absent)	1	8.9460	126.49	< .0001
L*Sz (I Present, D Absent)	1	0.4877	6.90	.0304
L*I*Sz*D*S(G)	8	0.0707		

TABLE J-15

Results of Simple-Effect F-Tests on Luminance (L) for Each Value of Size (Sz) Cue with No Disparity (D) Cue and No Interposition (I) Cue (Mean Image Quality Rating)

Source	*df*	*MS*	*F*	*p*
L(Sz Absent, D Absent, I Absent)	1	31.6681	447.76	< .0001
L(Sz Present, D Absent, I Absent)	1	1.9531	27.62	.0008
L*I*Sz*D*S(G)	8	0.0707		

TABLE J-16

Results of Simple-Effect F-Tests on Luminance (L) for Each Value of Size (Sz) Cue with No Disparity (D) Cue and with Interposition (I) Cue (Mean Image Quality Rating)

Source	*df*	*MS*	*F*	*p*
L(Sz Absent, D Absent, I Present)	1	4.1253	58.33	< .0001
L(Sz Present, D Absent, I Present)	1	1.0889	15.40	.0044
L*I*Sz*D*S(G)	8	0.0707		

TABLE J-17

Results of Newman-Keuls Test on Mean Questionnaire Cue Ratings *

Questionnaire Item:	2(a) Luminance	2(b) Size	2(c) Interposition	2(d) Disparity
Mean Value:	6.4	7.0	7.9	9.4
	———	———	———	
			———	———

* Means with a common line do not differ significantly at $p \leq .05$

APPENDIX K

INSTRUCTIONS TO PARTICIPANTS, EXPERIMENT 3

INSTRUCTIONS TO PARTICIPANTS, DAY 0

Introduction

In this experiment, you will be asked to make judgements about the relationships among symbols presented on the screen in front of you. The horizontal and vertical positions of these symbols will vary from trial to trial. In addition, the apparent depth of the symbols may also change. By this, we mean that the symbols may appear to be closer to you or farther away from you.

Your experimental task will be to identify symbols located at specific depths.

Today you will be given an opportunity to practice this task. The purpose of this practice is to acquaint you with: 1) the type of scenes you will view; 2) the trackball controller you will use; and 3) the overall structure of the experiment. During these practice trials, please ask the experimenter any questions you may have regarding your task.

During the experiment, it will be necessary for you to wear special glasses in order to see the screen images properly. When handling the glasses, please be careful to avoid smudging the lenses with fingerprints.

Training: Stage A

This is the first stage of your practice session. During this stage, you are to simply observe the images presented to you on the screen, adjust the trackball as described below, and ask the experimenter any questions that may occur to you.

Scene 1 - Demo

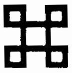
This scene will introduce the symbology which is used in the experiment. You should see several symbols placed within a grid. Note that all the symbols are of the same brightness and the same size. The symbols and the grid should all appear to be at the same depth. The position of the grid will remain constant throughout the experiment (horizontally, vertically, and in depth). However, in the scenes to follow, the symbols will be changed in such a way as to portray them in depth.

Note that there are three types of symbols. The first type, called a foreground symbol, appears like this:

Foreground Symbol

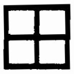
The second type of symbol is called a background symbol and appears like this:

Background Symbol



The third type of symbol is your cursor. This is the symbol which you will control with the trackball. The cursor appears like this:

Cursor



Using the trackball, practice moving the cursor about the screen both vertically and horizontally. When you are finished, press and release the center button. When using the trackball, please use your preferred hand to operate the trackball and your nonpreferred hand to operate the thumbwheel and the buttons.

Scene 2 - Size

In this scene, the symbols appear to be of different sizes. In all cases where the symbols appear to be of different sizes, you should assume that this is because they are at different depths. For example, in this scene, the foreground symbol on the right side of the screen appears to be larger than the foreground symbol on the left side of the screen. If one assumes that the two symbols are actually the same size but are at different depths, then the foreground symbol on the right would be said to be nearest, while the foreground symbol on the left would be said to be farthest away.

Please note that the **background** symbols will always be the located at the farthest position in depth possible. Therefore, none of the symbols on the screen will ever be smaller (or farther away) than background symbols. Is this clear?

At this time, practice moving your cursor in depth using the trackwheel. Rotate the trackwheel slowly forward to move the cursor farther away from you, and rotate the trackwheel slowly backward to move the cursor nearer to you. Note how the size of the cursor changes as you adjust the trackwheel. Also, practice moving the cursor vertically and horizontally as you did previously. When you are finished, press and release the center button.

Scene 3 - Brightness

In this scene, the symbols appear to be of different brightness levels. Since objects appear less bright when far away and brighter when near to us, the relative brightness of these symbols provides depth information. In all cases where the symbols appear to be of different brightness, you should assume that this is because they are at different depths. For example, in this scene, the foreground symbol on the right appears to be brighter than the foreground symbol on the left. If one assumes that the symbols actually have the same brightness but are at different depths, then the foreground symbol on the right would be said to be the nearest, while the foreground symbol on the left would be said to be the farthest away.

Please note that the **background** symbols will always be the located at the farthest position in depth possible. Therefore, none of the symbols on the screen will ever be less bright (or farther away) than background symbols. Is this clear?

At this time, practice moving your cursor in depth using the trackwheel. Rotate the trackwheel slowly forward to move the cursor farther away from you, and rotate the trackwheel slowly backward to move the cursor nearer to you. Note how the brightness of the cursor changes as you adjust the trackwheel. Also, practice moving the cursor vertically and horizontally as you did previously. When you are finished, press and release the center button.

Scene 4 - Stereo

In this scene, the depth cue of stereo is used. This involves presenting a different picture to each eye, the two pictures being slightly set apart. The usual effect of this separation is a sensation of depth. It may be necessary to view the symbols for a moment before you can experience this sensation of depth. In all cases during the experiment, you are to assume that stereo is an indication that the symbols are at different depths. In this scene, the foreground symbol on the right should appear to be the nearest, while the foreground symbol on the left should appear to be the farthest away.

Please note that the **background** symbols will always be the located at the farthest position in depth possible. Therefore, none of the symbols on the screen will ever have more stereo depth (or be farther away) than background symbols. Is this clear?

At this time, practice moving your cursor in depth using the trackwheel. Rotate the trackwheel slowly forward to move the cursor farther away from you, and rotate the trackwheel slowly backward to move the cursor nearer to you. Note how the apparent depth of the cursor changes as you adjust the trackwheel. Also, practice moving the cursor vertically and horizontally as you did previously. When you are finished, press and release the center button.

At this time, do you have any questions about size, brightness, or stereo depth cues? Do you have any questions about how to control the trackball or trackwheel?

Training: Stage B

This is the final stage of training. You will progress through a number of simulated trials. These trials are identical to the actual experiment. Therefore, you should respond as if this were the actual experiment. Please make sure you understand fully before continuing.

Before you begin this stage, please read all instructions below.

When you are ready to begin the trial, you should press and release the center button. As soon as the symbols appear on the screen, identify the one foreground symbol which is located at a depth different from the other foreground symbols. This particular foreground symbol is referred to as the target symbol. Please remember that only foreground symbols are eligible to be targets. Background symbols will never be targets. Do not move the cursor until you have identified the target symbol. For some of the trials, the depth separation between the target and the other foreground symbols will be very small. Consequently, it may be very difficult for you to find the target. If you cannot identify the target symbol after considerable effort, you should make your best guess.

Once you have identified the target symbol, you are to move the cursor to the position of the target symbol by using the trackball and trackwheel. You should move the cursor to the same depth (size and/or brightness and/or stereo) and the same vertical and horizontal position as the target. The cursor frame should match the edges of the target symbol. Once you are satisfied that the cursor is located at the same position as the target symbol in all three dimensions, you are to press and release the center button to end the trial.

At this time, you will be presented with a subjective rating scale. Using the trackball, you should highlight your choice of the ratings presented. Your rating should represent the overall quality of depth; that is, how well you feel depth information was presented in the preceding trial. Please try to use the full range of the rating scale. Once your choice is highlighted, press and release the center button to indicate your final decision.

From now on, your speed of response is important, although accuracy is more important. Therefore, respond as quickly as possible without making an error.

NOTE: It is very important that you do not initiate cursor movement until you have located the target symbol. Also, it is important that you press and release the center button as soon as you are satisfied that the cursor is correctly positioned over the target symbol.

INSTRUCTIONS TO PARTICIPANTS, DAYS 1,2, AND 3

Before you begin, please review all instructions below.

When you are ready to begin the first trial, you should press and release the center button. As soon as the symbols appear on the screen, identify the one foreground symbol which is located at a depth different from the other foreground symbols. This particular foreground symbol is referred to as the target symbol. Please remember that only foreground symbols are eligible to be targets. Background symbols will never be targets. Do not move the cursor until you have identified the target symbol. For some of the trials, the depth separation between the target and the other foreground symbols will be very small. Consequently, it may be very difficult for you to find the target. If you cannot identify the target symbol after considerable effort, you should make your best guess.

Once you have identified the target symbol, you are to move the cursor to the position of the target symbol by using the trackball and trackwheel. You should move the cursor to the same depth (size and/or brightness and/or stereo) and the same vertical and horizontal position as the target. The cursor frame should match the edges of the target symbol. Once you are satisfied that the cursor is located at the same position as the target symbol in all three dimensions, you are to press and release the center button to end the trial.

Following each trial, use the trackball to highlight your choice of ratings in the subjective rating scale. Your rating should represent the overall quality of depth; that is, how well you feel depth information was presented in the preceding trial. Please try to use the full range of the rating scale. Once your choice is highlighted, press and release the center button to indicate your final decision.

Remember, your speed of response is important, although accuracy is more important. Therefore, respond as quickly as possible without making an error.

NOTE: It is very important that you do not initiate cursor movement until you have located the target position. Also, it is important that you press and release the center button as soon as you are satisfied that the cursor is correctly positioned over the target symbol.

If you have any questions, please ask them now. Your experimenter will be unable to provide you with additional help once the experiment has started. The experiment should last between one and one and a half hours. There will be one five-minute break halfway through the experiment. The experiment will be preceded by a five-minute adaptation period so that your eyes may become accustomed to the dark.

APPENDIX L

SUPPLEMENTAL TABLES OF MEANS, EXPERIMENT 3

TABLE L-1

Mean Search Time (s) as a Function of Separation (Sp), Complexity (C), Disparity (D), Size (Sz), and Luminance (L), Experiment 3

				Sp (depth planes)			
C (symbols)	*D**	*S**	*L**	*1*	*2*	*3*	*4*
2	0	0	0	12.680	12.683	12.019	13.555
2	0	0	1	8.424	4.746	4.097	2.368
2	0	1	0	7.055	3.408	2.551	2.211
2	0	1	1	6.099	2.392	1.865	1.664
2	1	0	0	6.784	4.335	2.716	2.399
2	1	0	1	7.009	3.352	2.085	1.854
2	1	1	0	5.445	2.608	2.011	1.701
2	1	1	1	4.107	2.231	1.746	1.586
4	0	0	0	18.378	16.109	17.103	18.426
4	0	0	1	14.049	6.434	3.766	2.801
4	0	1	0	12.417	5.991	3.008	2.515
4	0	1	1	8.576	3.153	2.142	2.252
4	1	0	0	10.574	4.889	3.517	2.773
4	1	0	1	8.842	4.030	2.271	2.002
4	1	1	0	6.406	2.925	2.231	2.057
4	1	1	1	5.676	2.543	1.764	1.789
6	0	0	0	21.489	20.723	20.742	21.999
6	0	0	1	19.139	10.104	5.328	3.377
6	0	1	0	13.315	6.399	3.889	3.037
6	0	1	1	10.185	3.608	2.729	2.119
6	1	0	0	9.327	5.821	4.032	2.862
6	1	0	1	8.624	4.177	2.643	2.170
6	1	1	0	8.258	3.802	2.608	2.000
6	1	1	1	5.620	3.134	2.654	2.145

* Cue absent = 0, cue present = 1

TABLE L-2

Total Search Errors as a Function of Separation (Sp), Complexity (C), Disparity (D), Size (Sz), and Luminance (L), Experiment 3

				Sp (depth planes)			
C (symbols)	*D**	*S**	*L**	*1*	*2*	*3*	*4*
2	0	0	0	47	40	36	34
2	0	0	1	20	5	2	1
2	0	1	0	12	4	1	0
2	0	1	1	7	0	0	0
2	1	0	0	20	7	2	2
2	1	0	1	14	1	0	0
2	1	1	0	3	1	3	0
2	1	1	1	5	1	0	0
4	0	0	0	51	45	50	45
4	0	0	1	30	3	3	1
4	0	1	0	6	1	2	0
4	0	1	1	7	1	1	0
4	1	0	0	13	2	1	0
4	1	0	1	7	0	0	0
4	1	1	0	2	1	0	0
4	1	1	1	3	1	0	0
6	0	0	0	54	51	55	51
6	0	0	1	30	10	1	2
6	0	1	0	16	2	0	1
6	0	1	1	7	0	2	0
6	1	0	0	6	2	2	0
6	1	0	1	9	0	0	1
6	1	1	0	3	1	1	1
6	1	1	1	2	1	2	0

* Cue absent = 0, cue present = 1

TABLE L-3

Mean X-Y Positioning Error (pixels) as a Function of Separation (Sp), Complexity (C), Disparity (D), Size (Sz), and Luminance (L), Experiment 3 **

				Sp (depth planes)			
C (symbols)	*D**	*S**	*L**	*1*	2	*3*	*4*
2	0	0	0	.077	.170	.208	.224
2	0	0	1	.235	.416	.277	.340
2	0	1	0	.288	.294	.214	.244
2	0	1	1	.231	.371	.298	.324
2	1	0	0	.493	.333	.321	.366
2	1	0	1	.300	.348	.314	.332
2	1	1	0	.338	.289	.339	.284
2	1	1	1	.324	.675	.317	.277
4	0	0	0	.268	.333	.100	.067
4	0	0	1	.327	.242	.306	.224
4	0	1	0	.182	.289	.263	.267
4	0	1	1	.344	.217	.289	.356
4	1	0	0	.386	.382	.337	.429
4	1	0	1	.326	.334	.255	.324
4	1	1	0	.340	.324	.439	.321
4	1	1	1	.461	.183	.441	.337
6	0	0	0	.637	.222	.764	.111
6	0	0	1	.227	.265	.289	.256
6	0	1	0	.242	.301	.315	.238
6	0	1	1	.265	.244	.297	.348
6	1	0	0	.316	.357	.340	.268
6	1	0	1	.232	.302	.315	.368
6	1	1	0	.365	.435	.322	.374
6	1	1	1	1.113	.333	.354	.428

* Cue absent = 0, cue present = 1

** Trials associated with search errors were excluded

TABLE L-4

Mean Z Positioning Error (depth planes) as a Function of Separation (Sp), Complexity (C), Disparity (D), Size (Sz), and Luminance (L), Experiment 3 **

				Sp (depth planes)			
C (symbols)	*D**	*S**	*L**	*1*	*2*	*3*	*4*
2	0	0	0	2.462	2.700	1.708	3.462
2	0	0	1	0.300	0.255	0.241	0.373
2	0	1	0	0.292	0.268	0.186	0.267
2	0	1	1	0.170	0.083	0.183	0.100
2	1	0	0	0.125	0.057	0.138	0.086
2	1	0	1	0.065	0.034	0.033	0.033
2	1	1	0	0.053	0.000	0.000	0.033
2	1	1	1	0.000	0.017	0.000	0.000
4	0	0	0	2.667	2.600	2.200	2.200
4	0	0	1	0.467	0.351	0.421	0.356
4	0	1	0	0.148	0.390	0.379	0.233
4	0	1	1	0.094	0.153	0.034	0.117
4	1	0	0	0.085	0.276	0.136	0.133
4	1	0	1	0.019	0.033	0.067	0.033
4	1	1	0	0.034	0.051	0.033	0.050
4	1	1	1	0.053	0.051	0.050	0.017
6	0	0	0	1.500	2.111	4.600	1.667
6	0	0	1	0.267	0.380	0.322	0.224
6	0	1	0	0.205	0.276	0.400	0.186
6	0	1	1	0.132	0.083	0.103	0.183
6	1	0	0	0.111	0.138	0.121	0.083
6	1	0	1	0.098	0.033	0.083	0.068
6	1	1	0	0.000	0.017	0.000	0.034
6	1	1	1	0.034	0.017	0.000	0.000

* Cue absent = 0, cue present = 1

** Trials associated with search errors were excluded

TABLE L-5

Mean Positioning Time (s) as a Function of Separation (Sp), Complexity (C), Disparity (D), Size (Sz), and Luminance (L), Experiment 3 **

				Sp (depth planes)			
C (symbols)	*D**	*S**	*L**	*1*	*2*	*3*	*4*
2	0	0	0	7.998	8.384	8.488	10.952
2	0	0	1	11.561	10.718	9.698	9.754
2	0	1	0	10.321	10.583	9.715	10.223
2	0	1	1	10.739	10.114	9.654	9.633
2	1	0	0	9.178	9.665	9.414	9.242
2	1	0	1	10.552	8.925	8.191	8.510
2	1	1	0	9.937	9.704	8.325	9.489
2	1	1	1	9.060	9.266	8.915	9.185
4	0	0	0	9.595	7.336	11.036	11.181
4	0	0	1	12.996	10.468	9.468	9.136
4	0	1	0	10.454	11.045	9.741	10.497
4	0	1	1	10.050	9.352	10.216	9.431
4	1	0	0	9.503	10.386	10.153	9.173
4	1	0	1	10.433	8.805	8.534	9.199
4	1	1	0	9.438	8.735	9.636	8.957
4	1	1	1	9.508	9.461	8.486	8.237
6	0	0	0	9.917	9.565	6.380	8.274
6	0	0	1	11.006	10.515	10.467	9.969
6	0	1	0	10.323	9.979	10.229	8.879
6	0	1	1	10.465	10.135	9.637	9.970
6	1	0	0	10.753	9.550	8.448	9.308
6	1	0	1	9.682	9.403	7.570	9.186
6	1	1	0	10.987	9.403	9.199	8.497
6	1	1	1	9.446	9.492	9.009	8.790

* Cue absent = 0, cue present = 1

** Trials associated with search errors were excluded

TABLE L-6

Mean Image Quality Rating as a Function of Separation (Sp), Complexity (C), Disparity (D), Size (Sz), and Luminance (L), Experiment 3

				Sp (depth planes)			
C (symbols)	*D**	*S**	*L**	*1*	*2*	*3*	*4*
2	0	0	0	2.217	2.117	2.117	2.350
2	0	0	1	3.233	4.500	5.233	5.833
2	0	1	0	4.050	5.517	6.167	6.600
2	0	1	1	4.333	6.283	6.733	7.200
2	1	0	0	5.217	5.933	6.683	7.233
2	1	0	1	5.200	6.650	7.250	7.700
2	1	1	0	5.400	6.883	7.317	7.600
2	1	1	1	6.300	7.317	7.850	8.067
4	0	0	0	1.767	2.000	1.817	1.983
4	0	0	1	2.783	4.017	4.967	5.633
4	0	1	0	3.450	4.817	5.700	6.350
4	0	1	1	4.283	5.983	6.533	6.933
4	1	0	0	4.750	6.183	6.800	7.183
4	1	0	1	4.817	6.517	7.333	7.617
4	1	1	0	5.933	7.067	7.483	7.767
4	1	1	1	5.900	7.250	7.867	8.050
6	0	0	0	1.567	1.767	1.683	1.767
6	0	0	1	1.967	3.850	4.900	5.750
6	0	1	0	3.100	4.983	5.883	6.150
6	0	1	1	3.850	5.600	6.283	7.083
6	1	0	0	5.233	6.417	6.567	7.333
6	1	0	1	5.200	6.683	7.483	7.567
6	1	1	0	5.683	6.950	7.450	7.783
6	1	1	1	6.067	7.100	7.517	8.117

* Cue absent = 0, cue present = 1

APPENDIX M

SUPPLEMENTAL FIGURES, EXPERIMENT 3

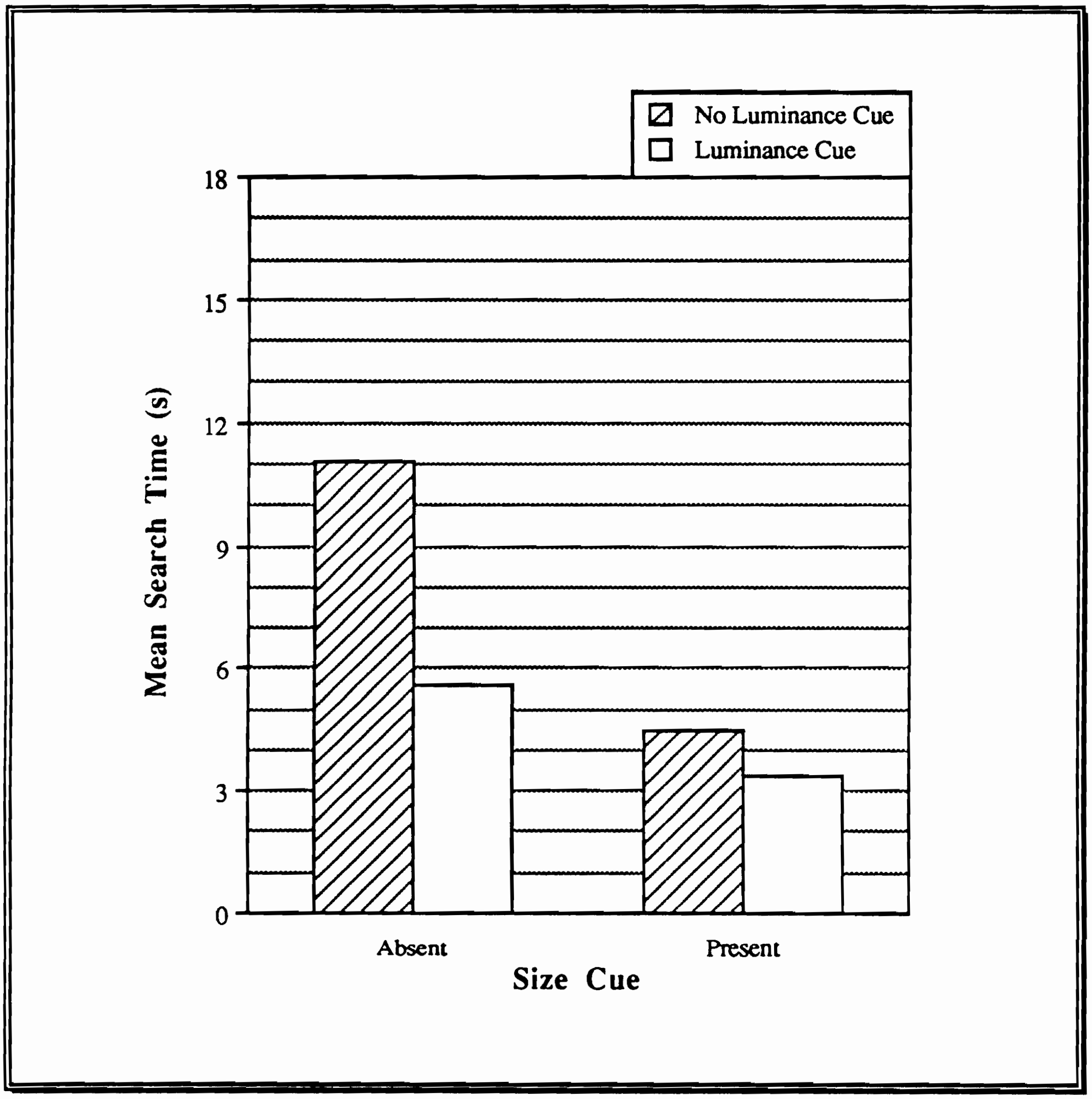


Figure M-1. Mean search time (s) as a function of Size and Luminance cues, Experiment 3.

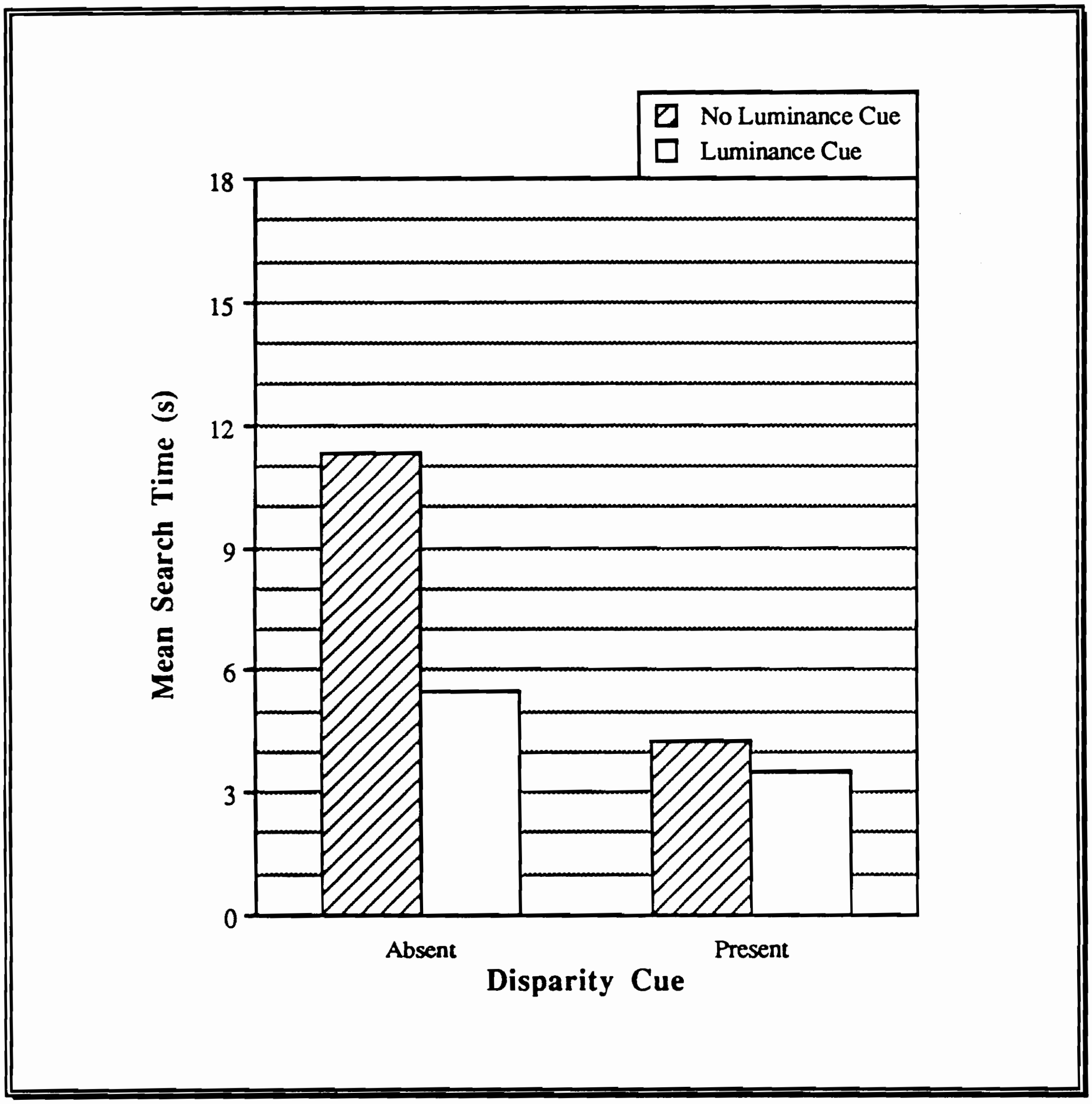


Figure M-2. Mean search time (s) as a function of Disparity and Luminance cues, Experiment 3.

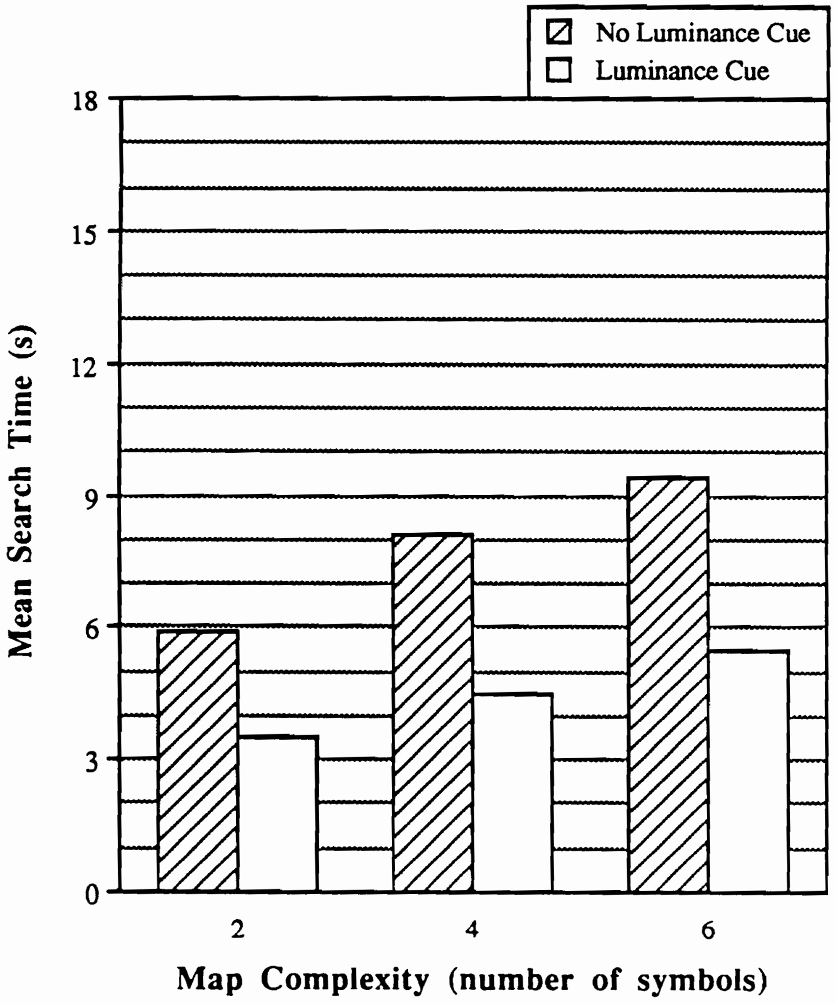


Figure M-3. Mean search time (s) as a function of Complexity and Luminance cue, Experiment 3.

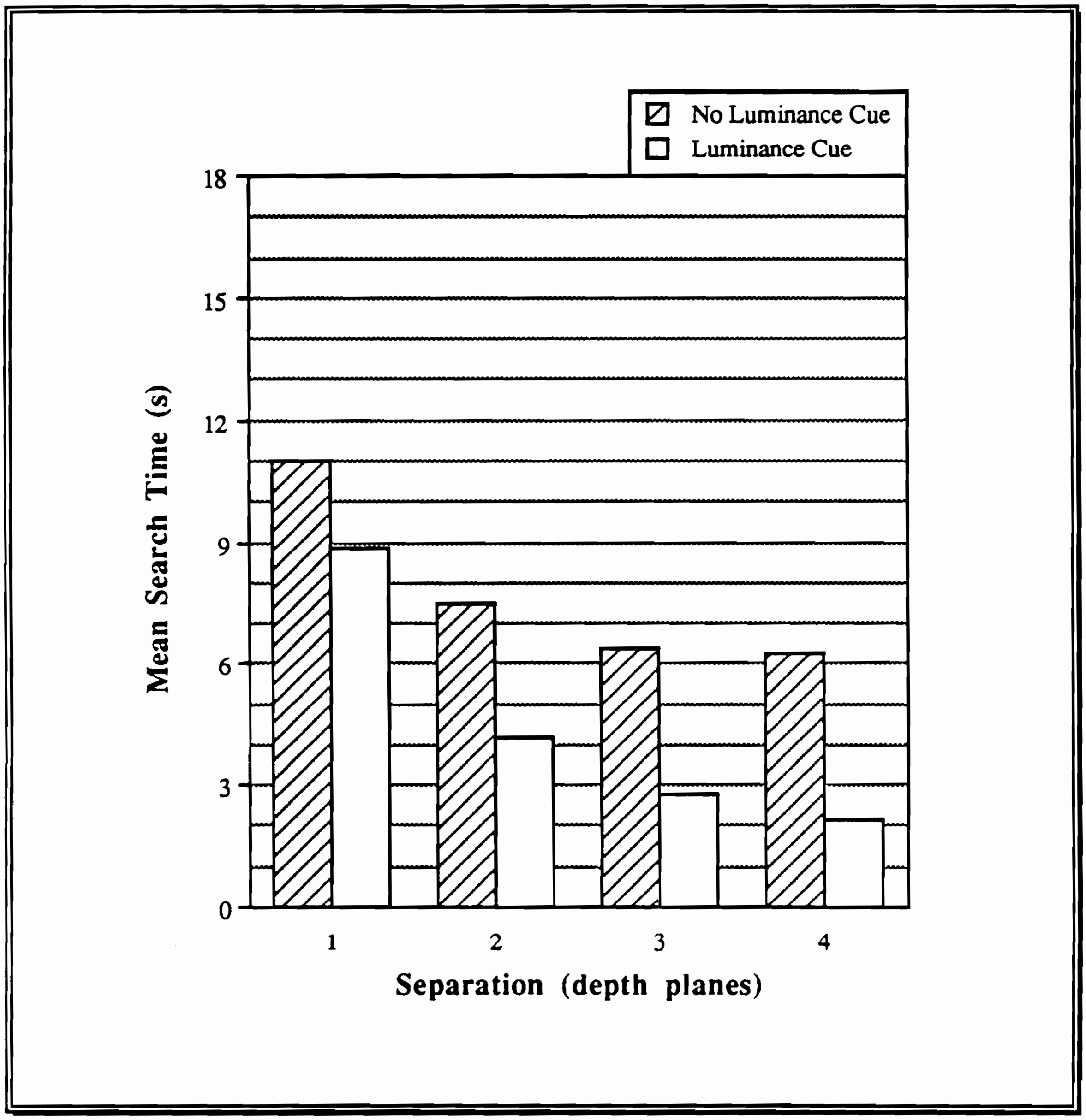


Figure M-4. Mean search time (s) as a function of Separation and Luminance cue, Experiment 3.

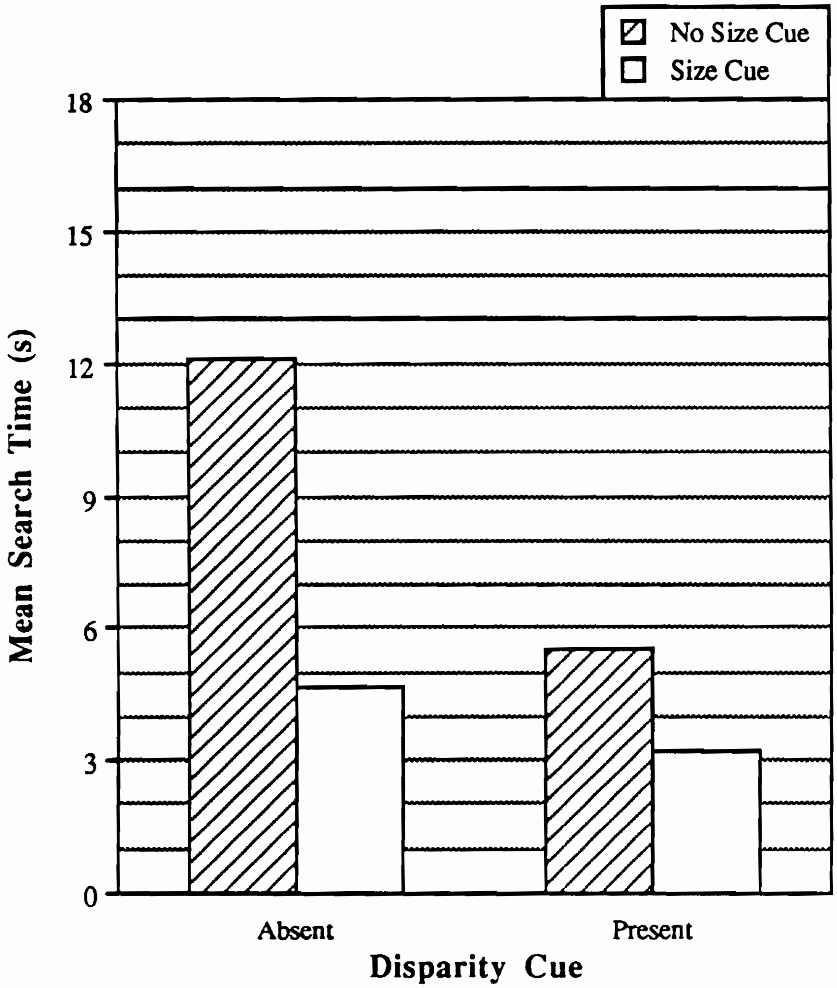


Figure M-5. Mean search time (s) as a function of Disparity and Size cues, Experiment 3.

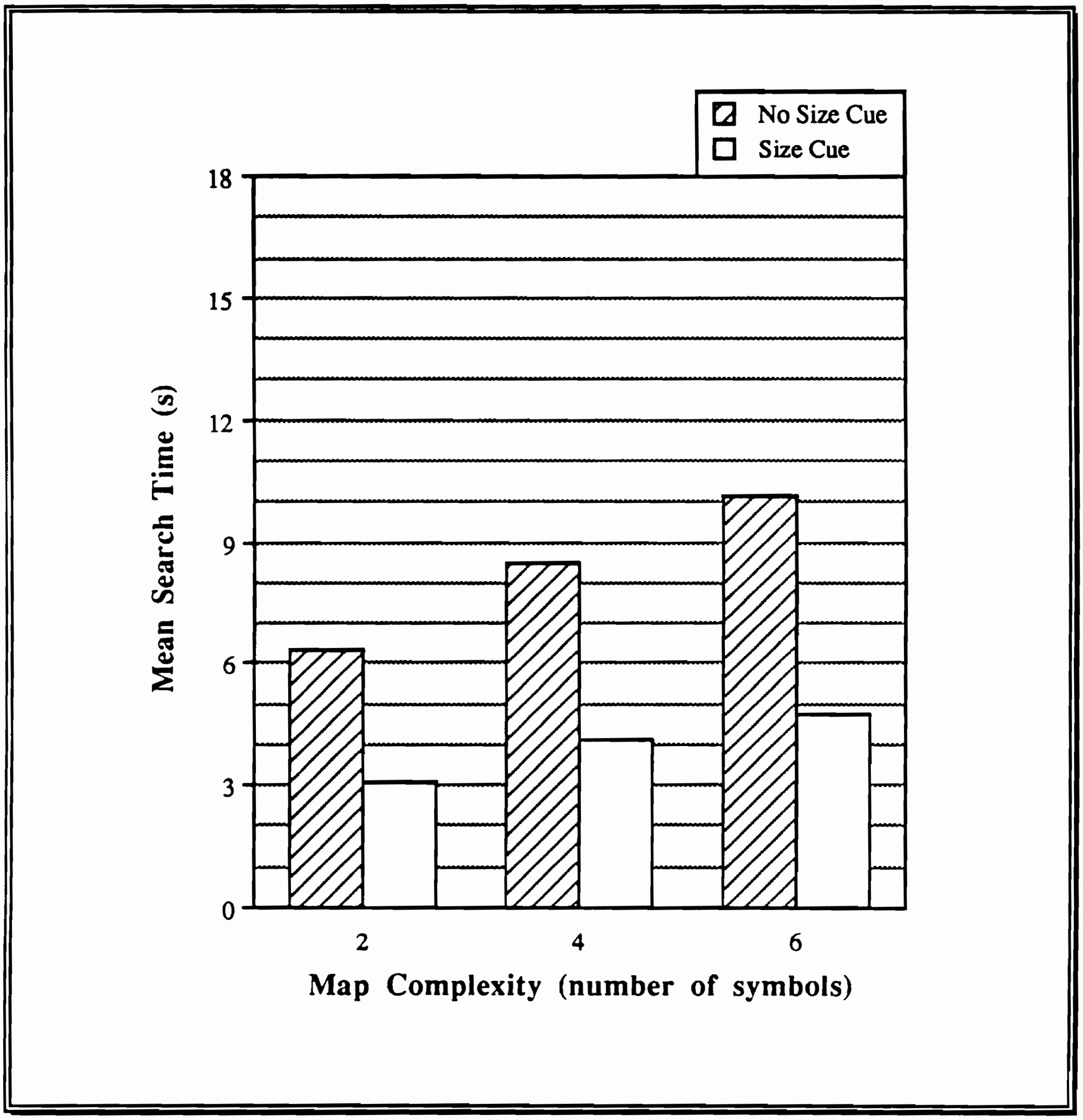


Figure M-6. Mean search time (s) as a function of Complexity and Size cue, Experiment 3.

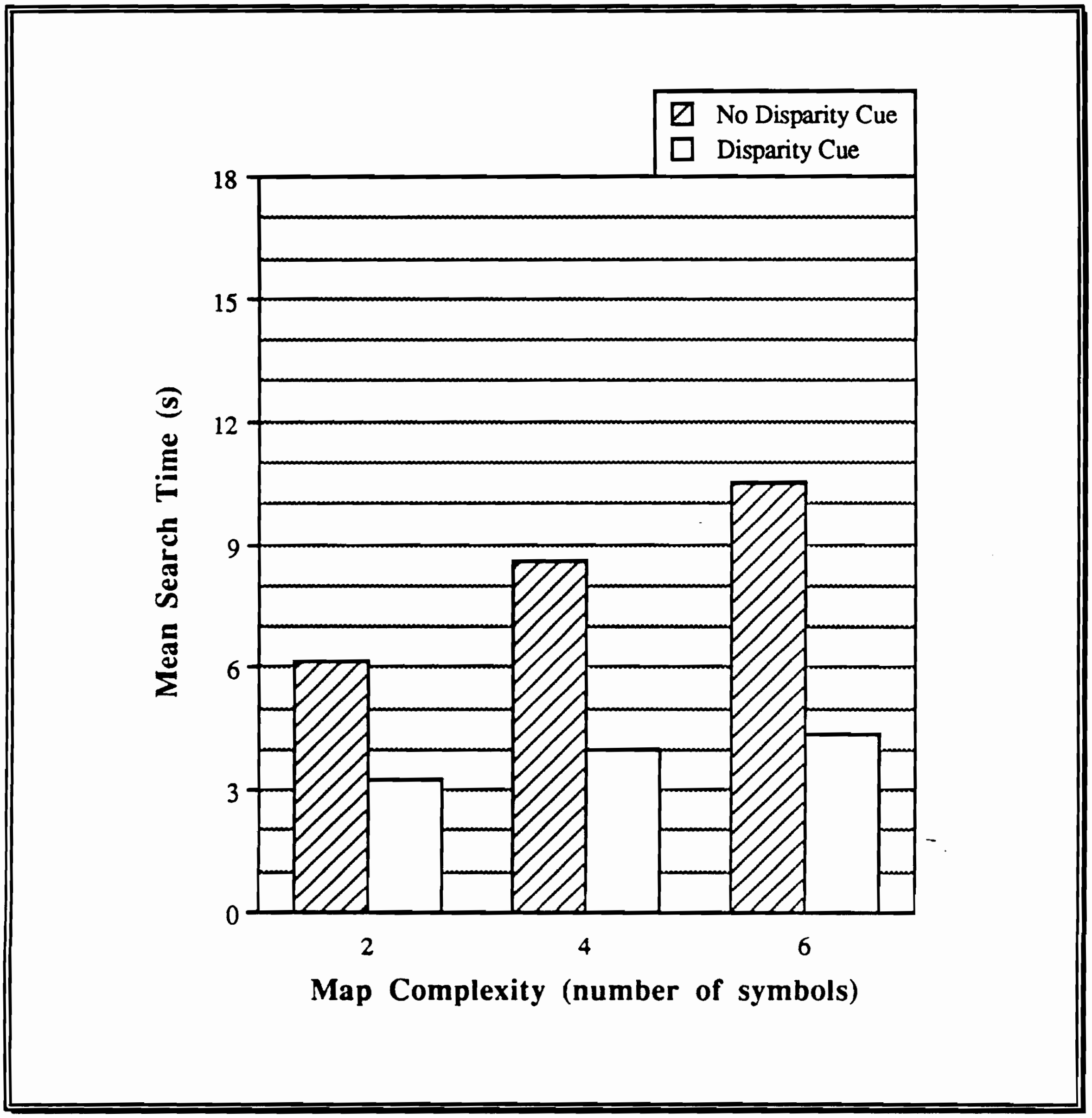


Figure M-7. Mean search time (s) as a function of Complexity and Disparity cue, Experiment 3.

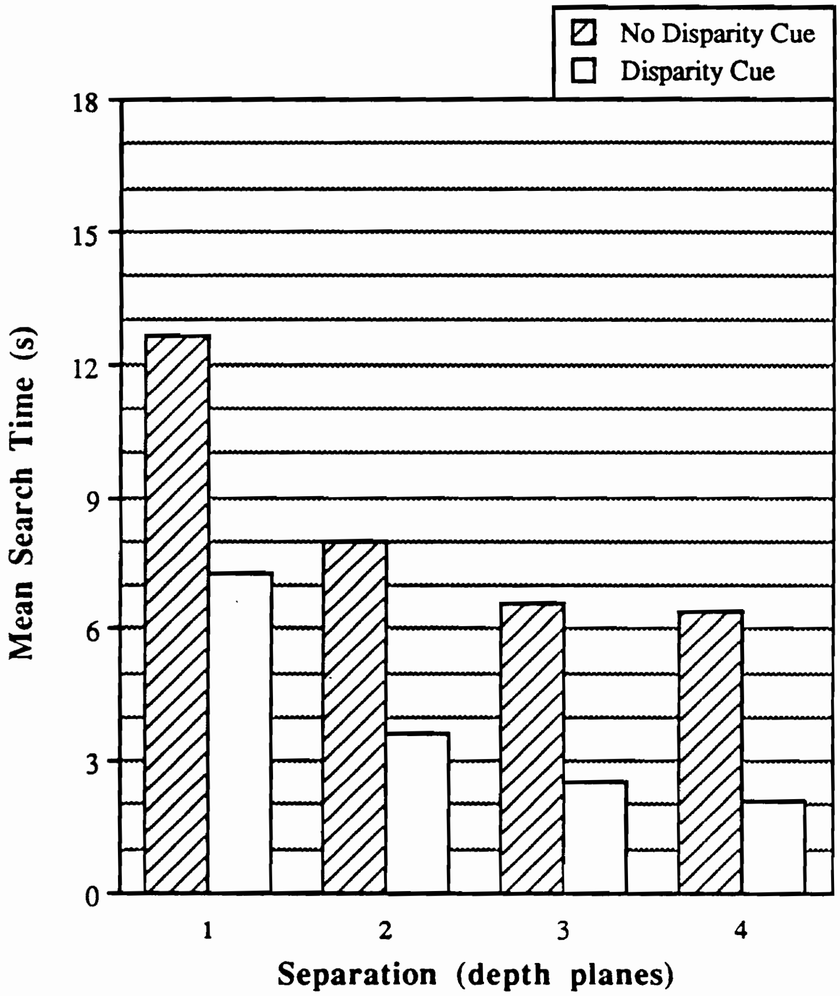


Figure M-8. Mean search time (s) as a function of Separation and Disparity cue, Experiment 3.

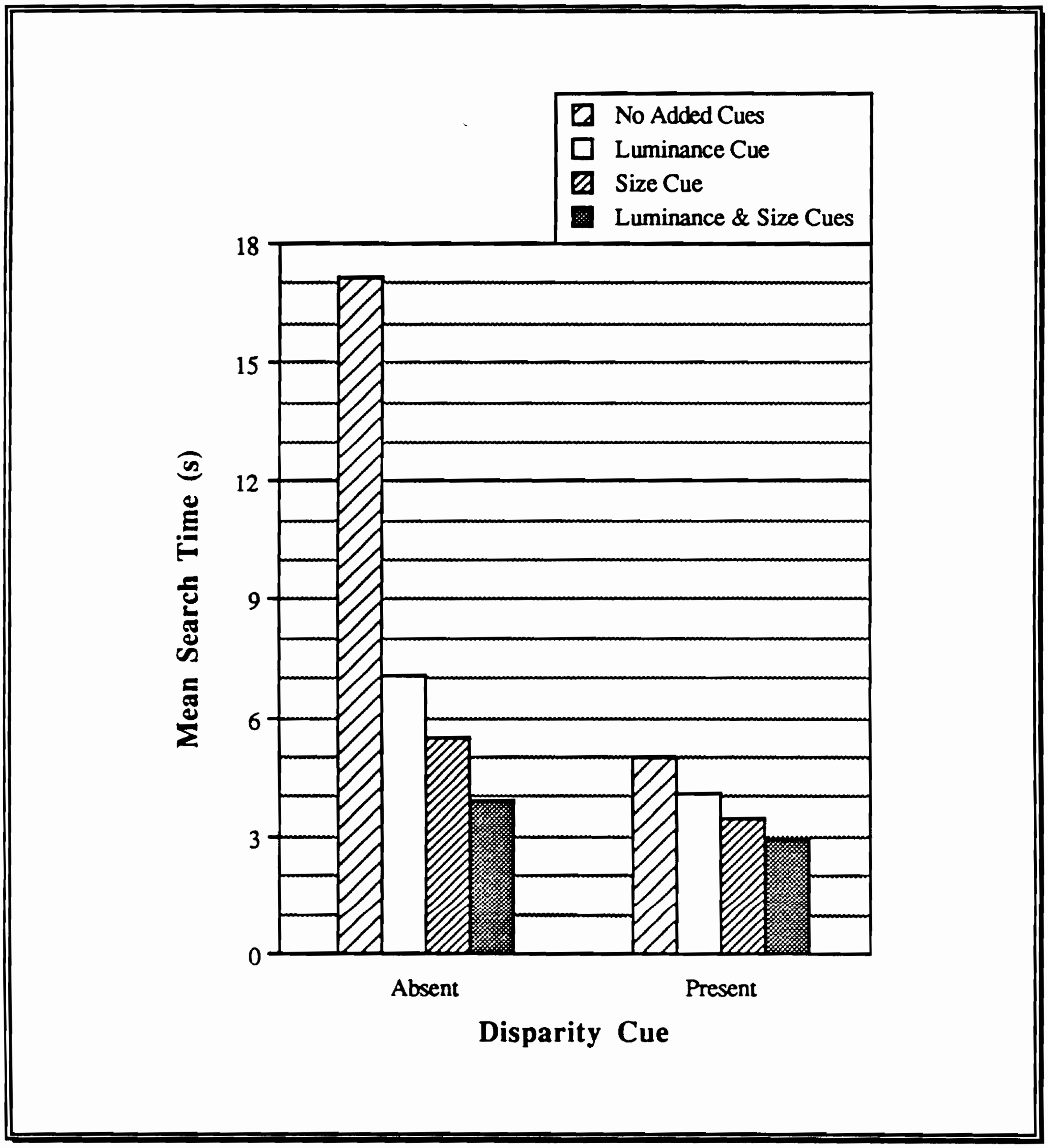


Figure M-9. Mean search time (s) as a function of Disparity, Luminance, and Size cues, Experiment 3.

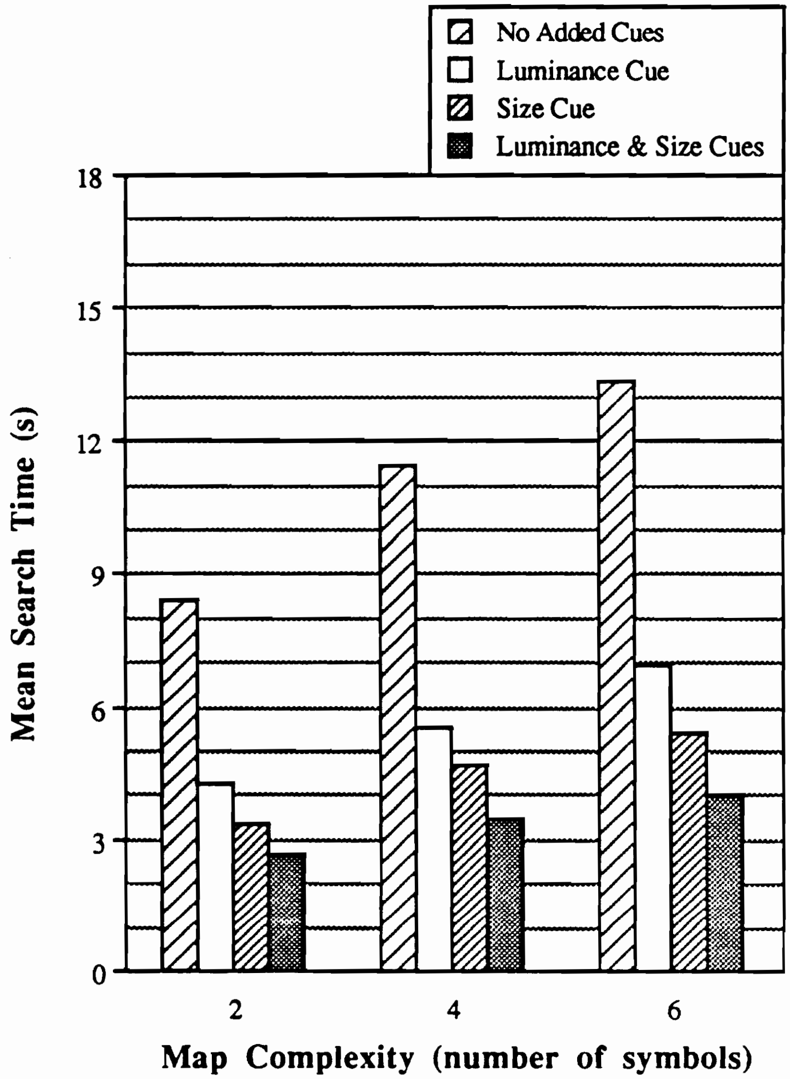


Figure M-10. Mean search time (s) as a function of Complexity and Luminance and Size cues, Experiment 3.

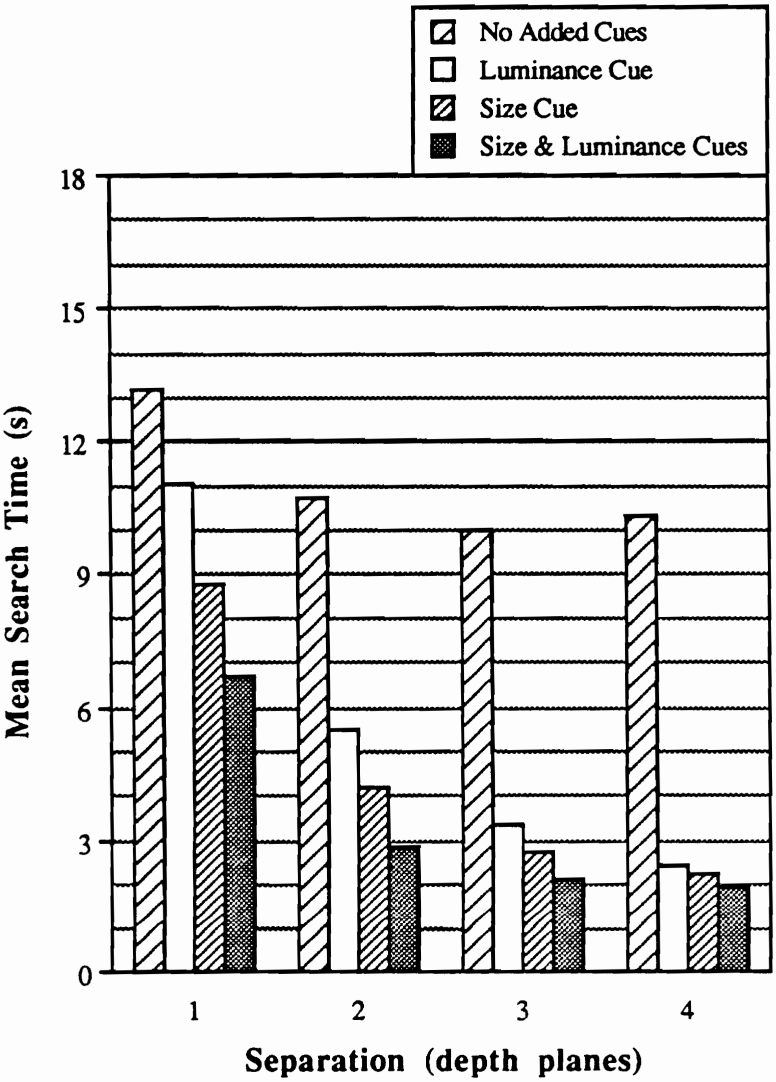


Figure M-11. Mean search time (s) as a function of Separation and Luminance and Size cues, Experiment 3.

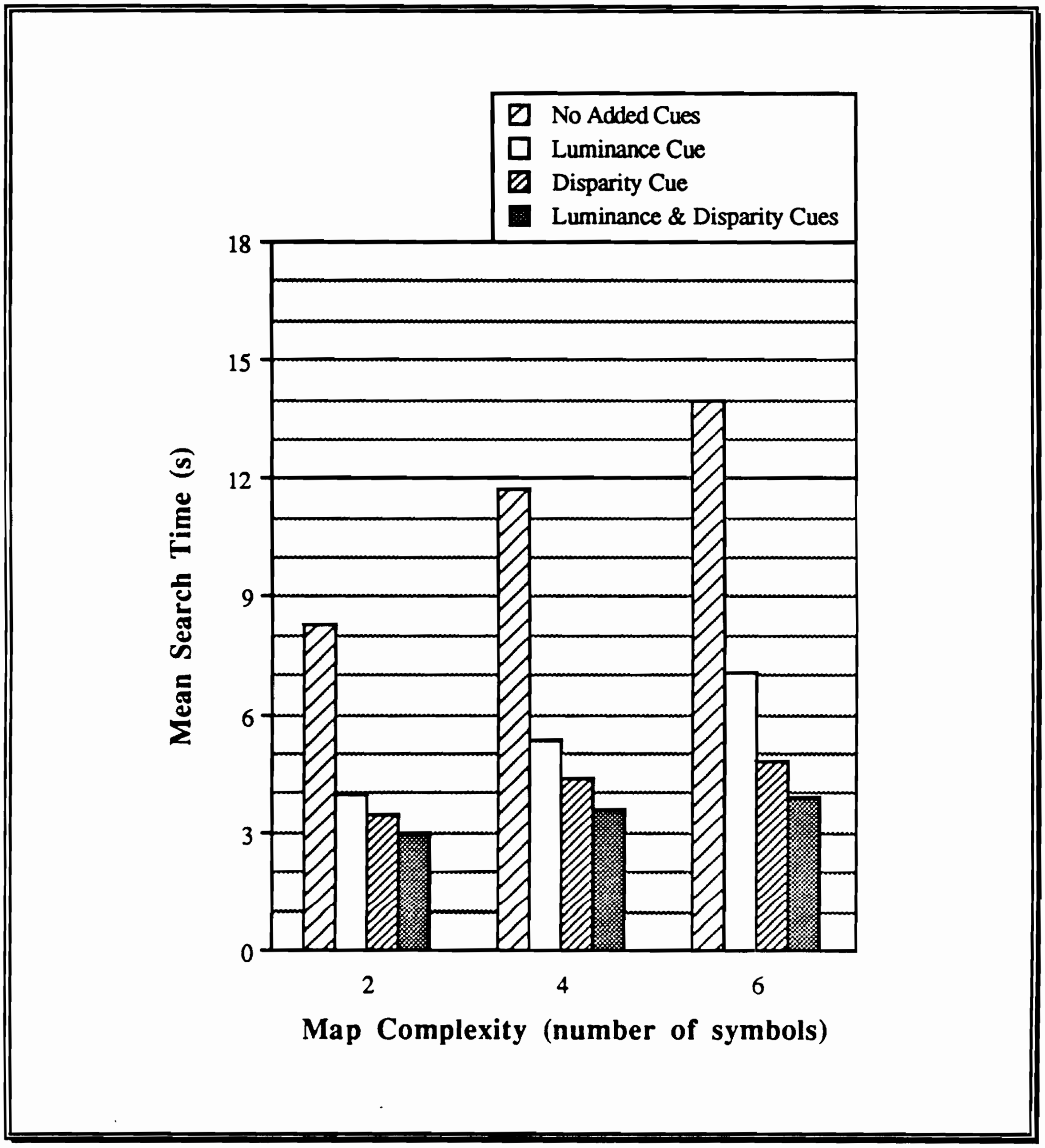


Figure M-12. Mean search time (s) as a function of Complexity and Luminance and Disparity cues, Experiment 3.

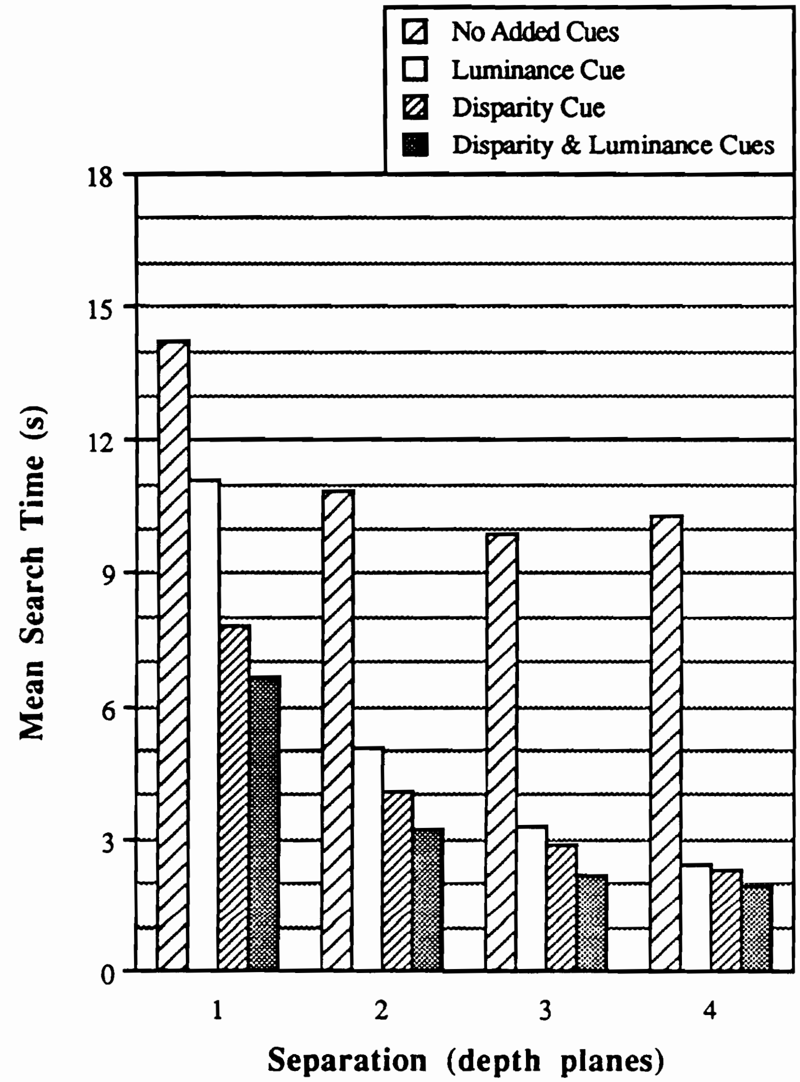


Figure M-13. Mean search time (s) as a function of Separation and Luminance and Disparity cues, Experiment 3.

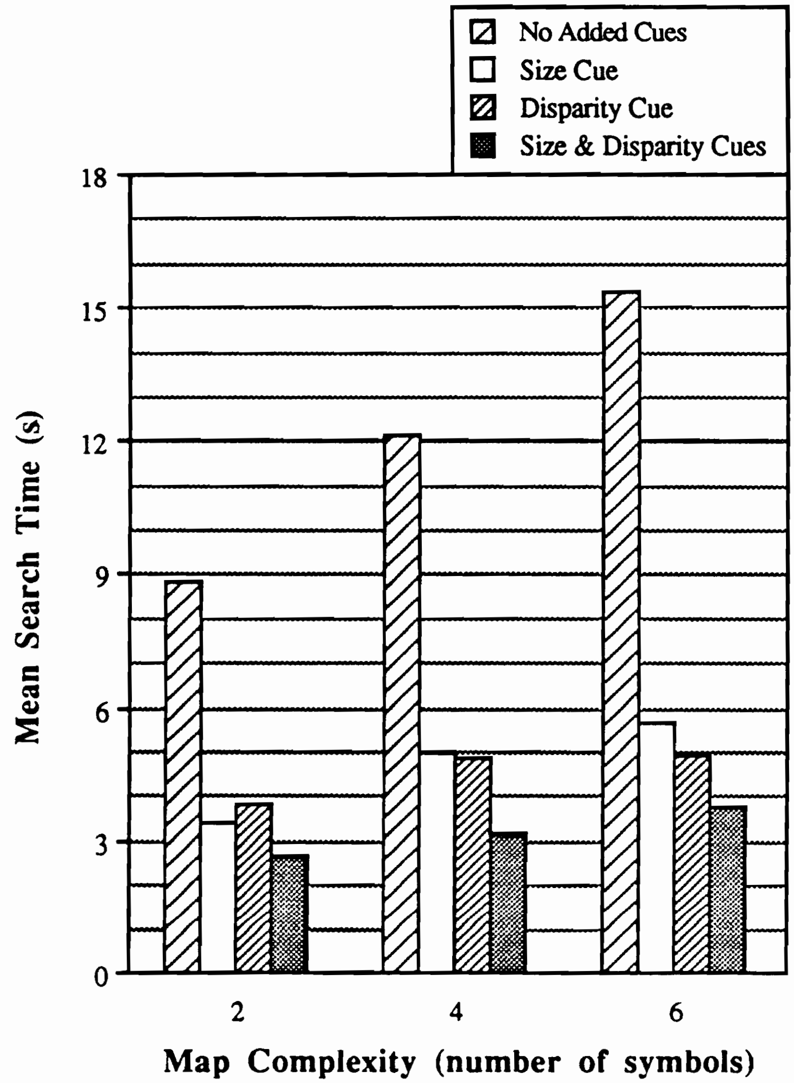


Figure M-14. Mean search time (s) as a function of Complexity and Size and Disparity cues, Experiment 3.

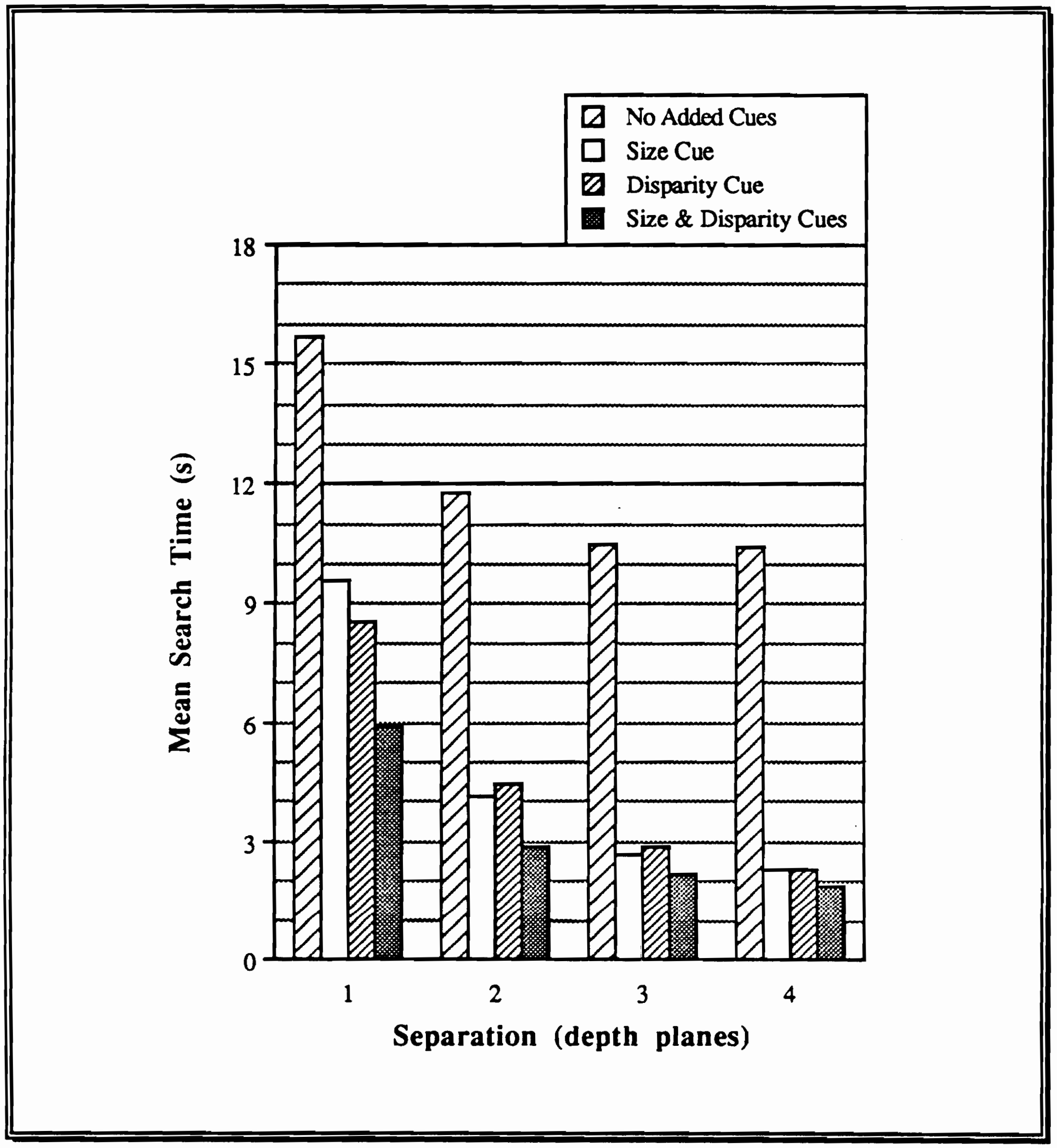


Figure M-15. Mean search time (s) as a function of Separation and Size and Disparity cues, Experiment 3.

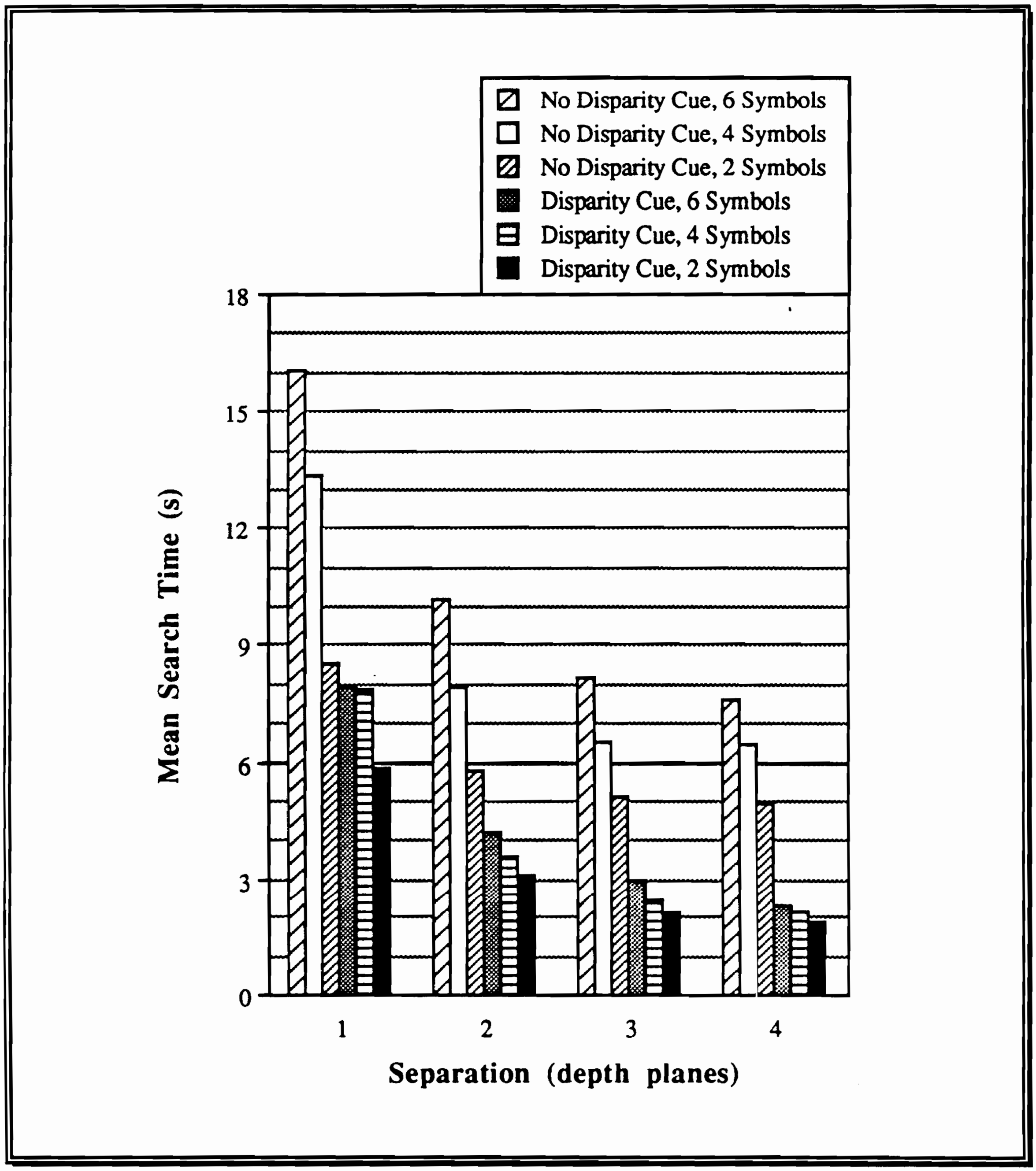


Figure M-16. Mean search time (s) as a function of Separation, Disparity Cue, and Complexity, Experiment 3.

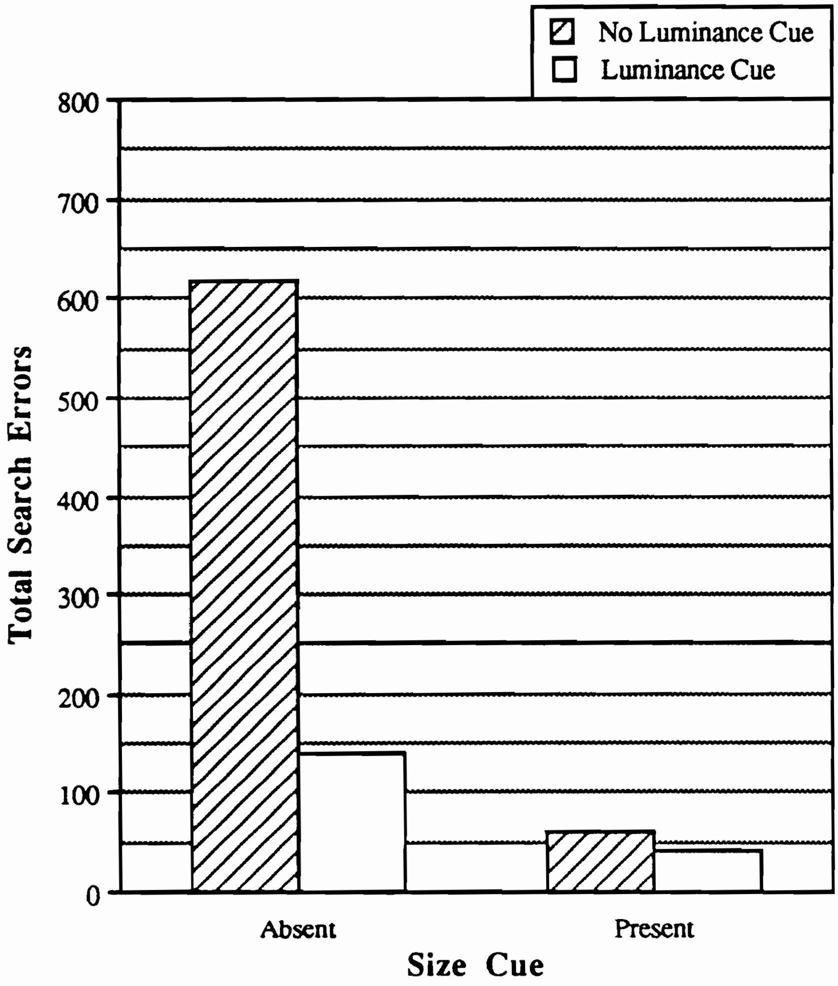


Figure M-17. Total search errors as a function of Size and Luminance cues, Experiment 3.

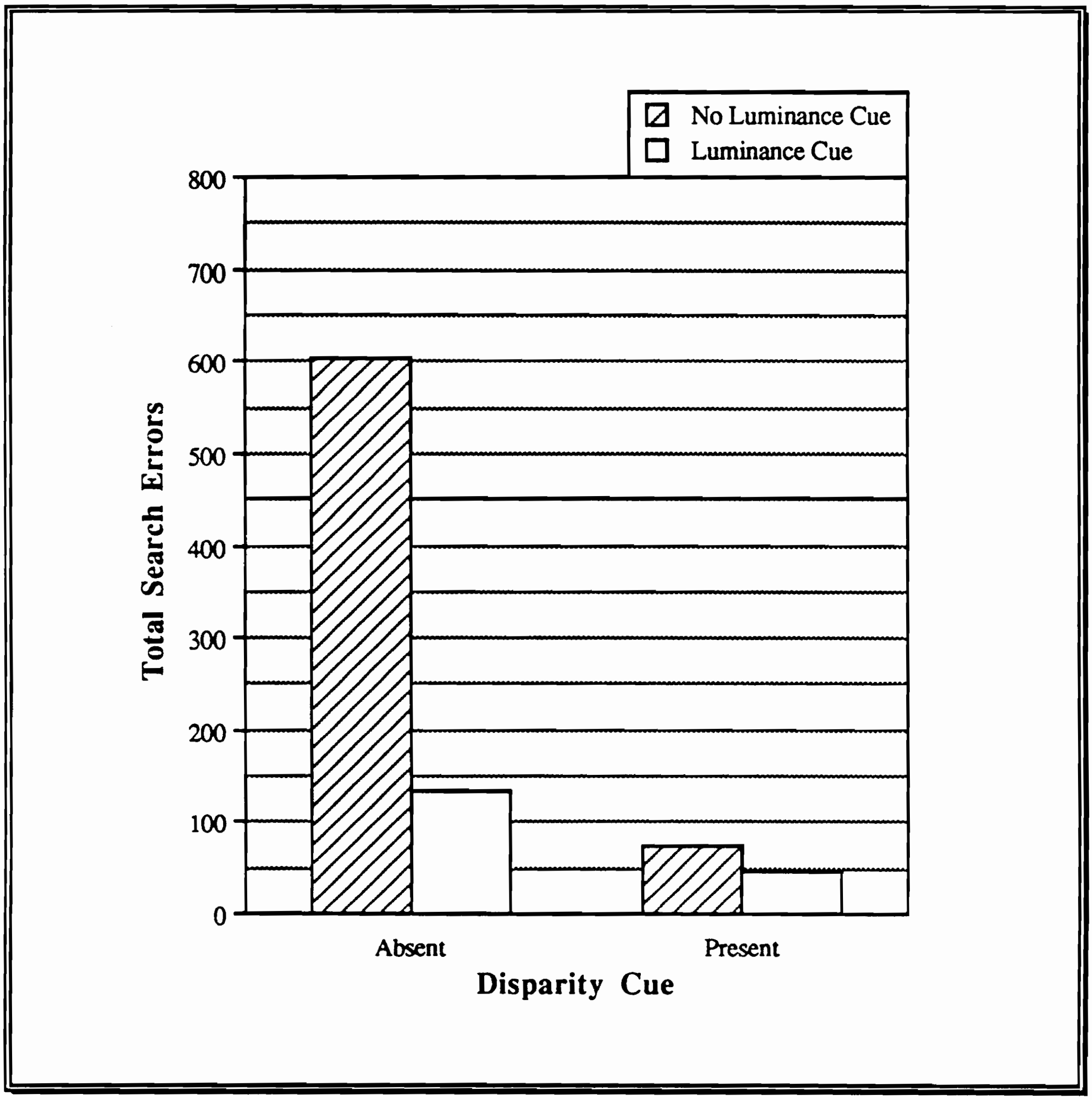


Figure M-18. Total search errors as a function of Disparity and Luminance cues, Experiment 3.

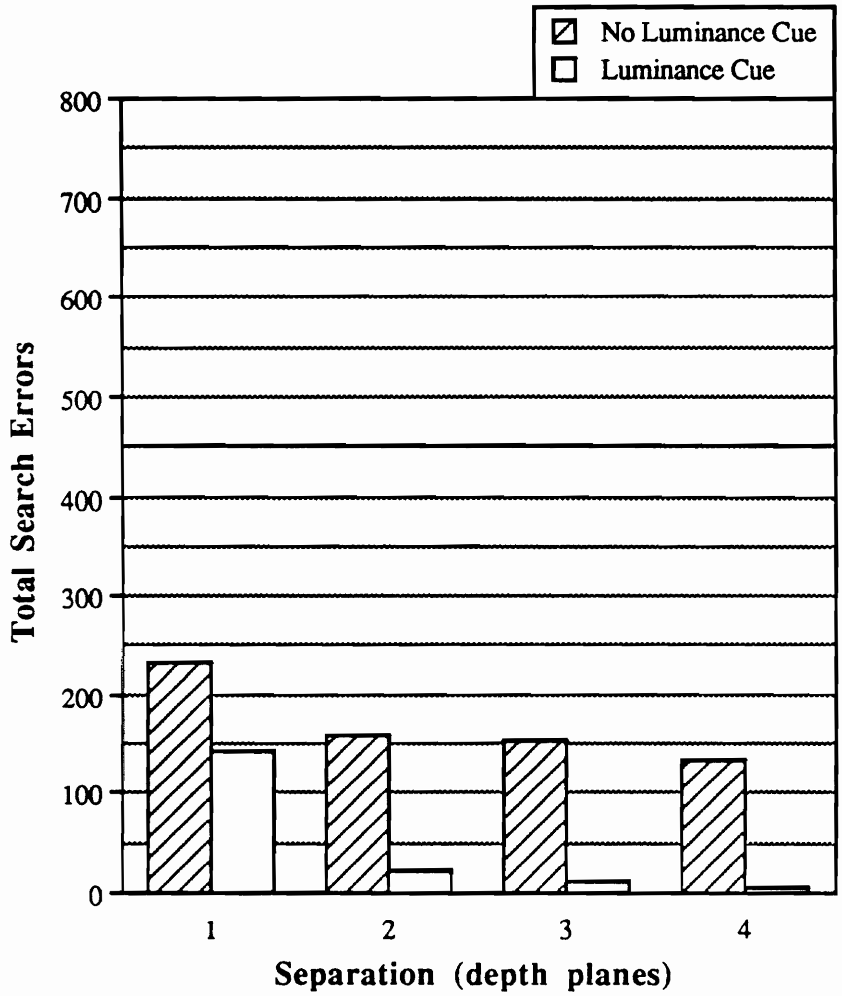


Figure M-19. Total search errors as a function of Separation and Luminance cue, Experiment 3.

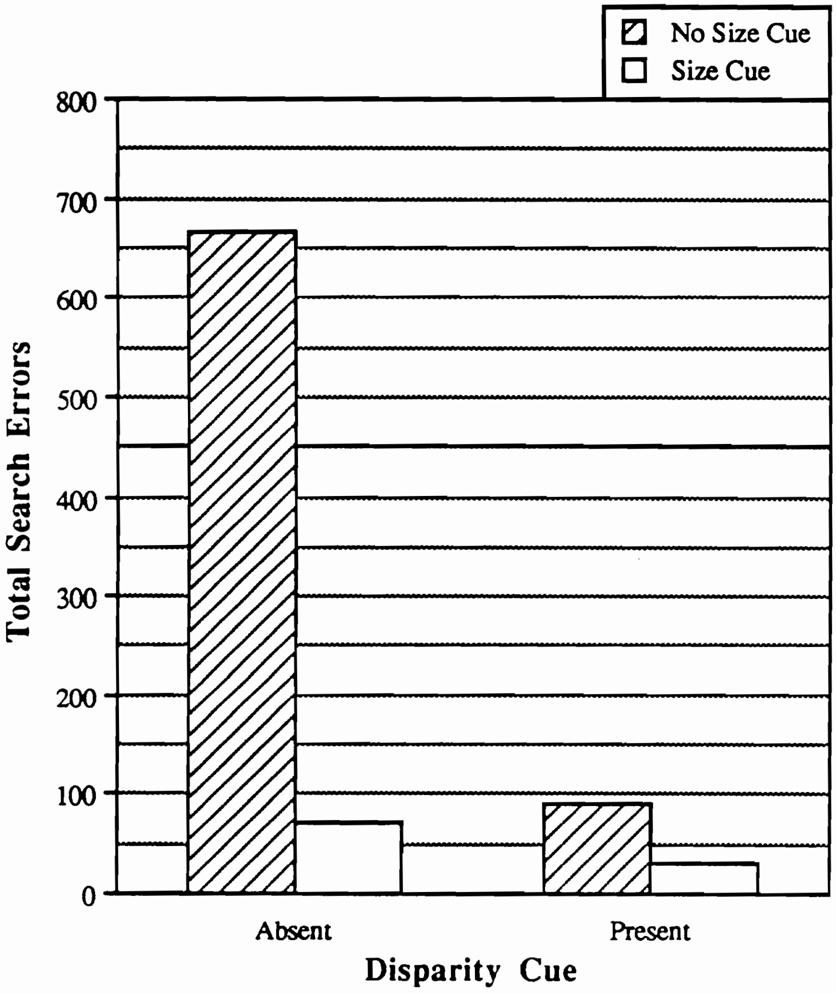


Figure M-20. Total search errors as a function of Disparity and Size cues, Experiment 3.

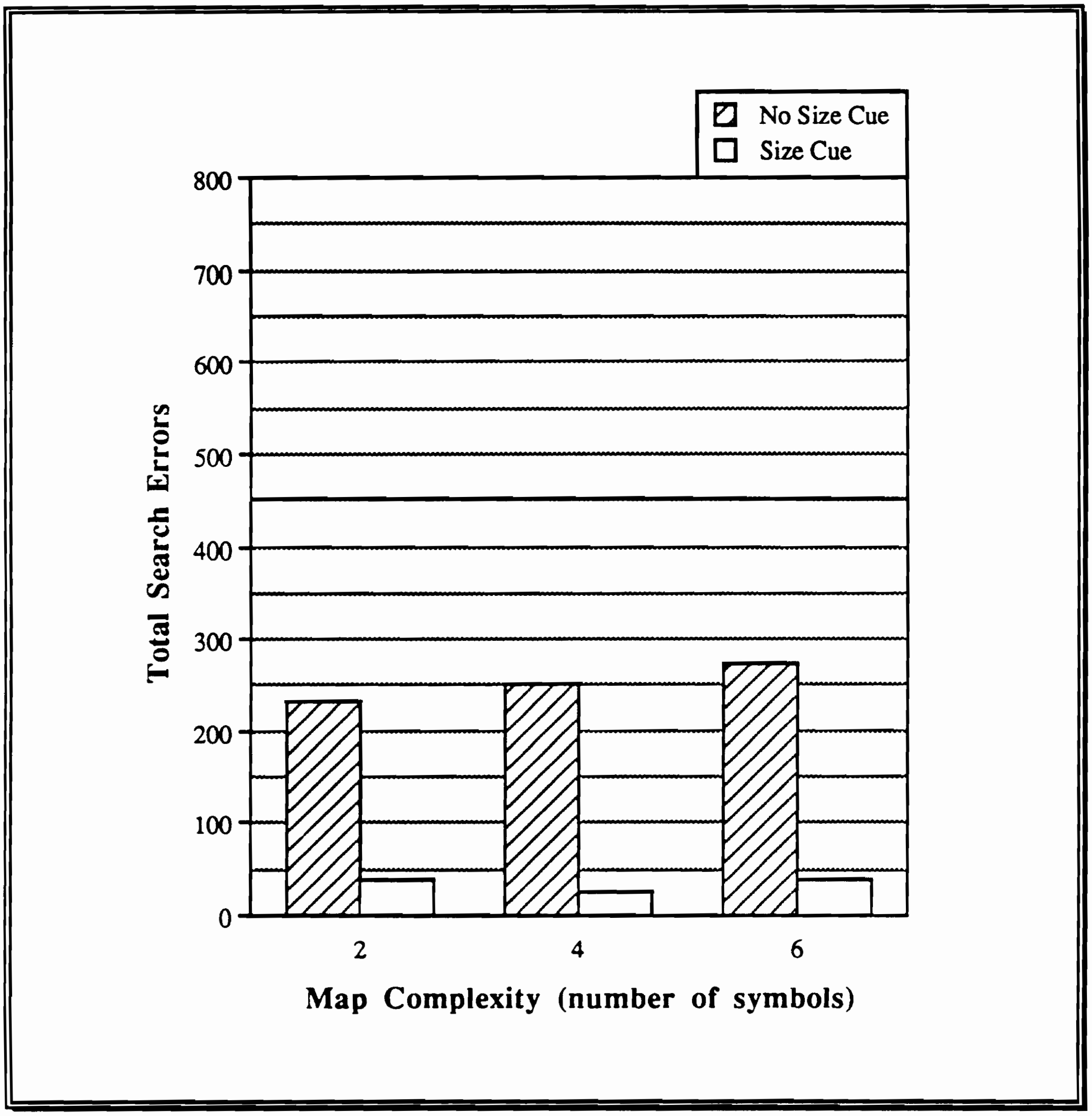


Figure M-21. Total search errors as a function of Complexity and Size cue, Experiment 3.

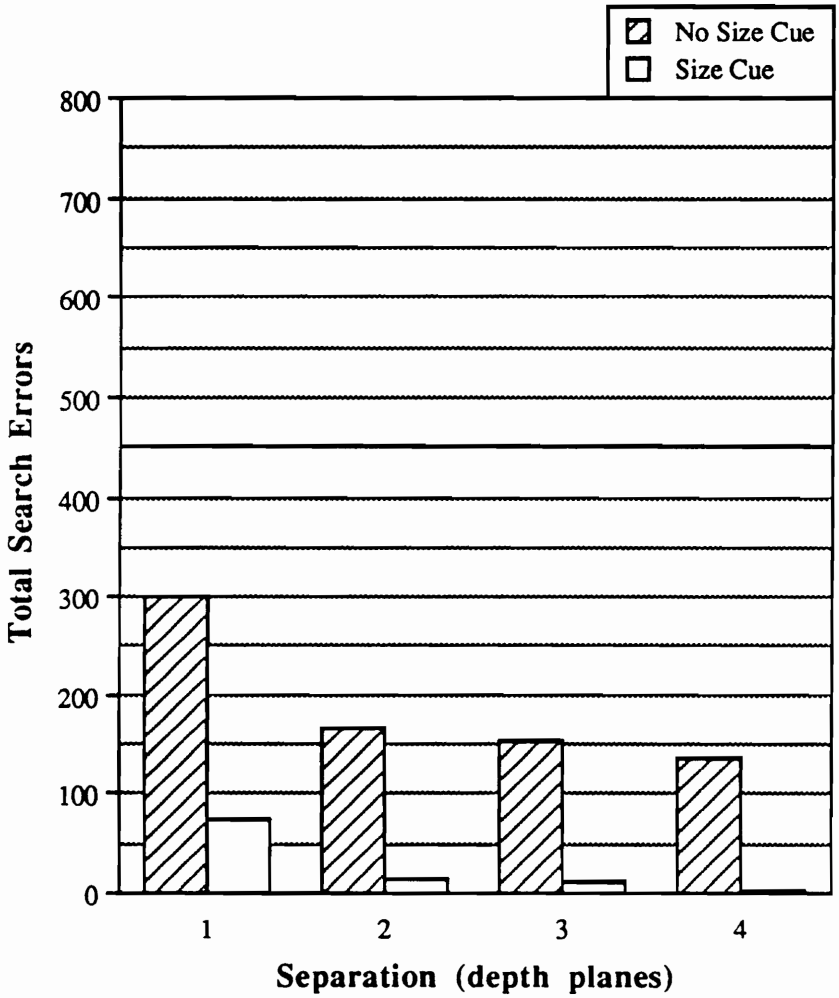


Figure M-22. Total search errors as a function of Separation and Size cue, Experiment 3.

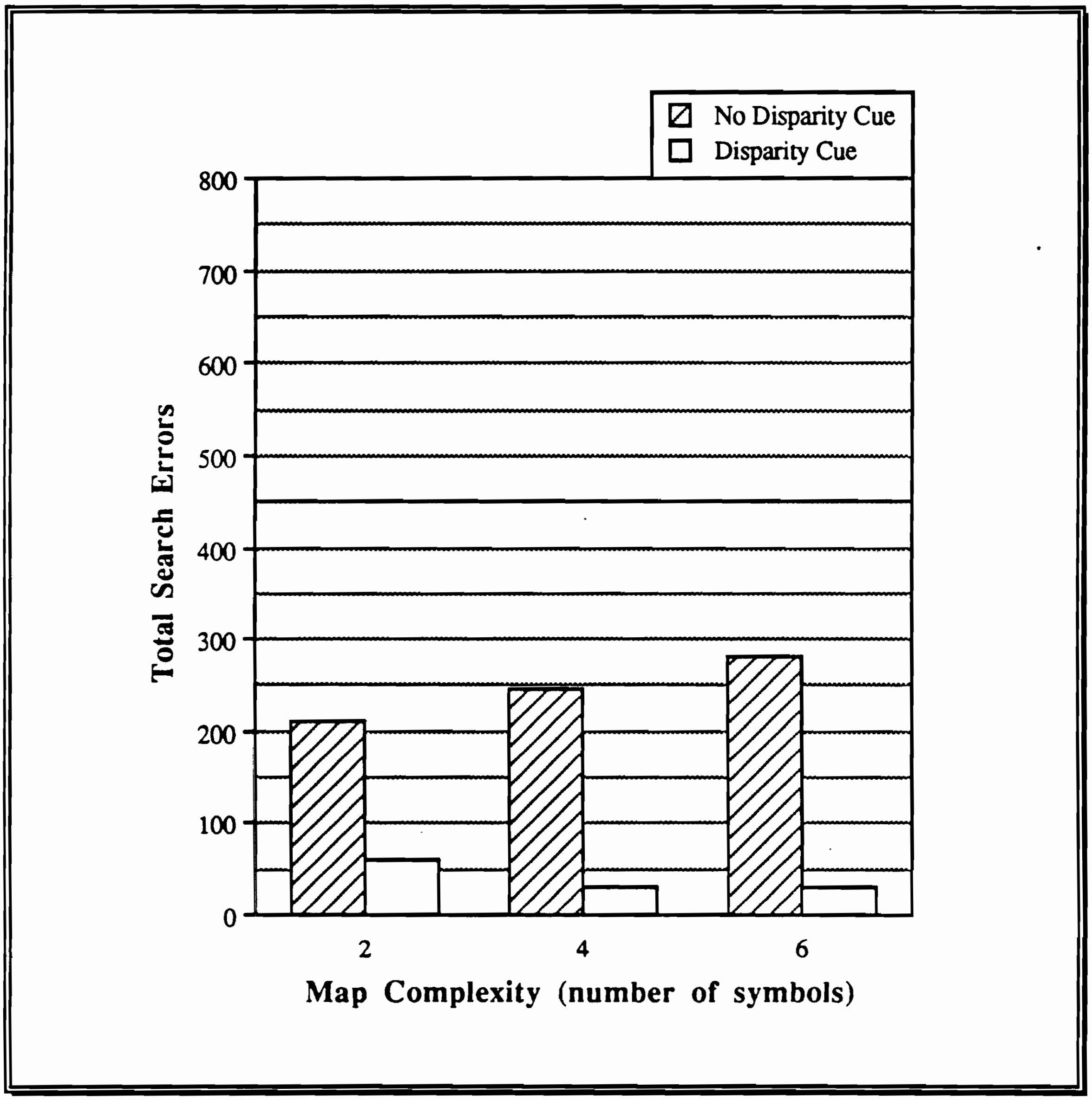


Figure M-23. Total search errors as a function of Complexity and Disparity cue, Experiment 3.

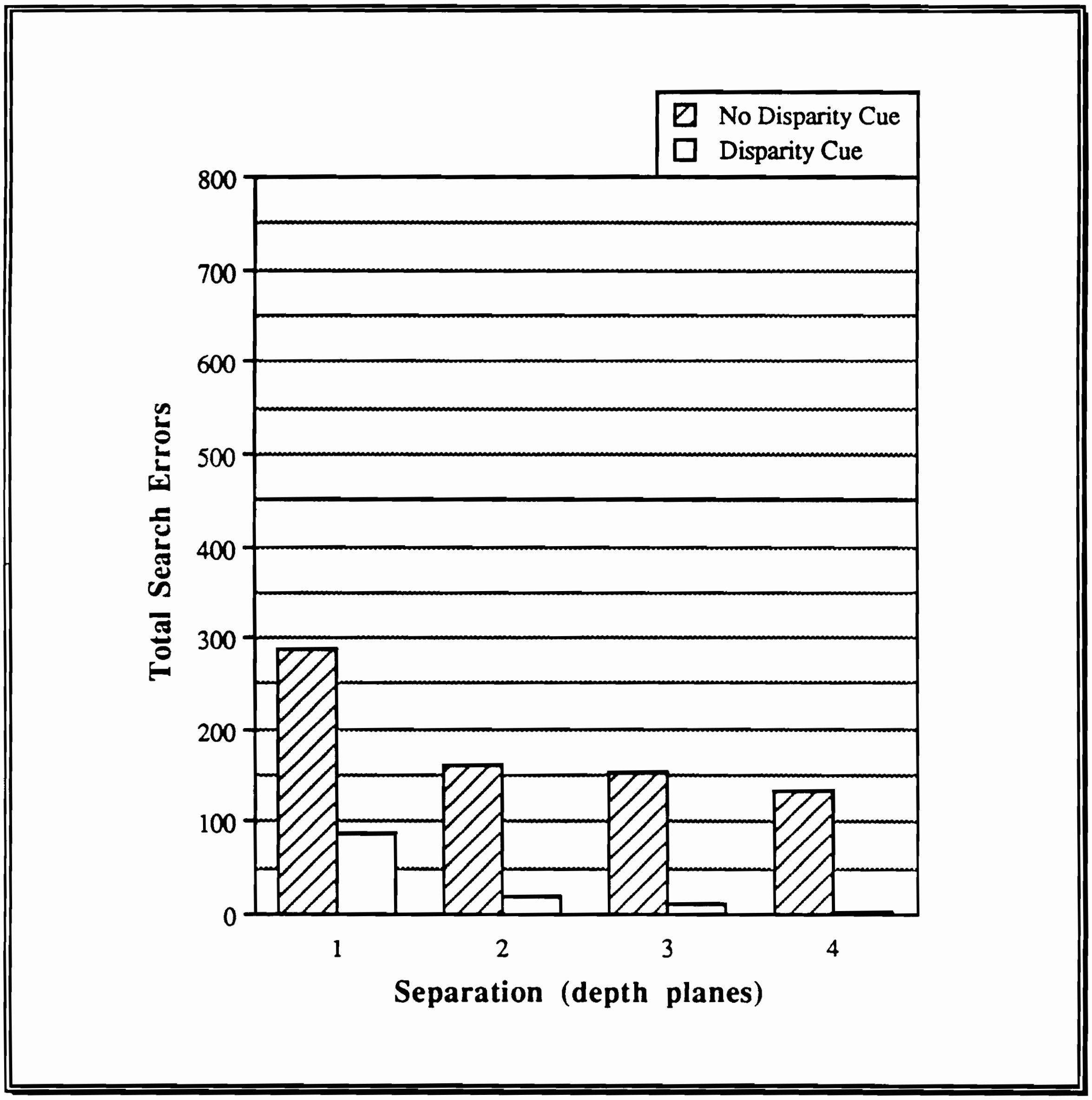


Figure M-24. Total search errors as a function of Separation and Disparity cue, Experiment 3.

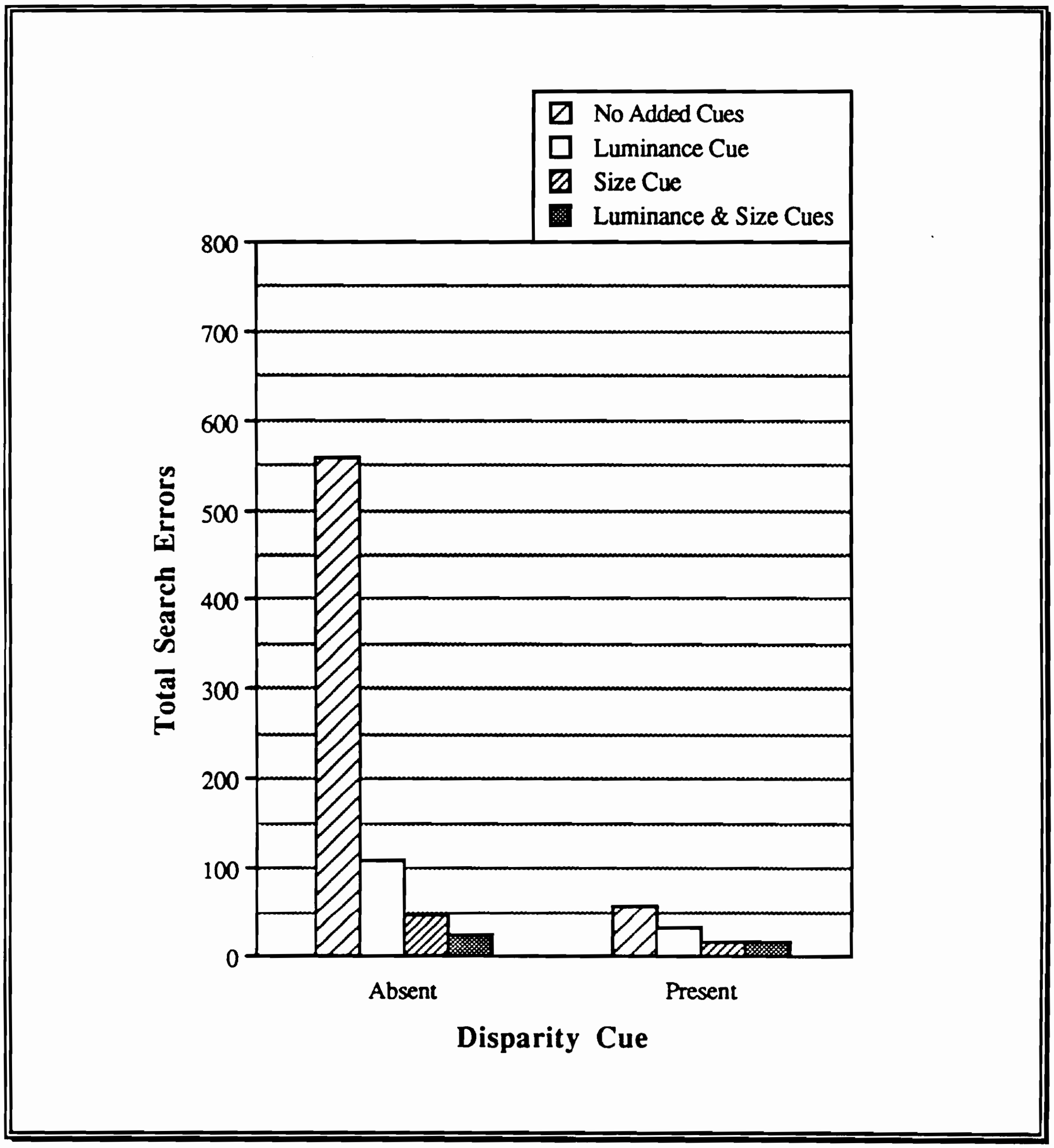


Figure M-25. Total search errors as a function of Disparity,Luminance, and Size cues, Experiment 3.

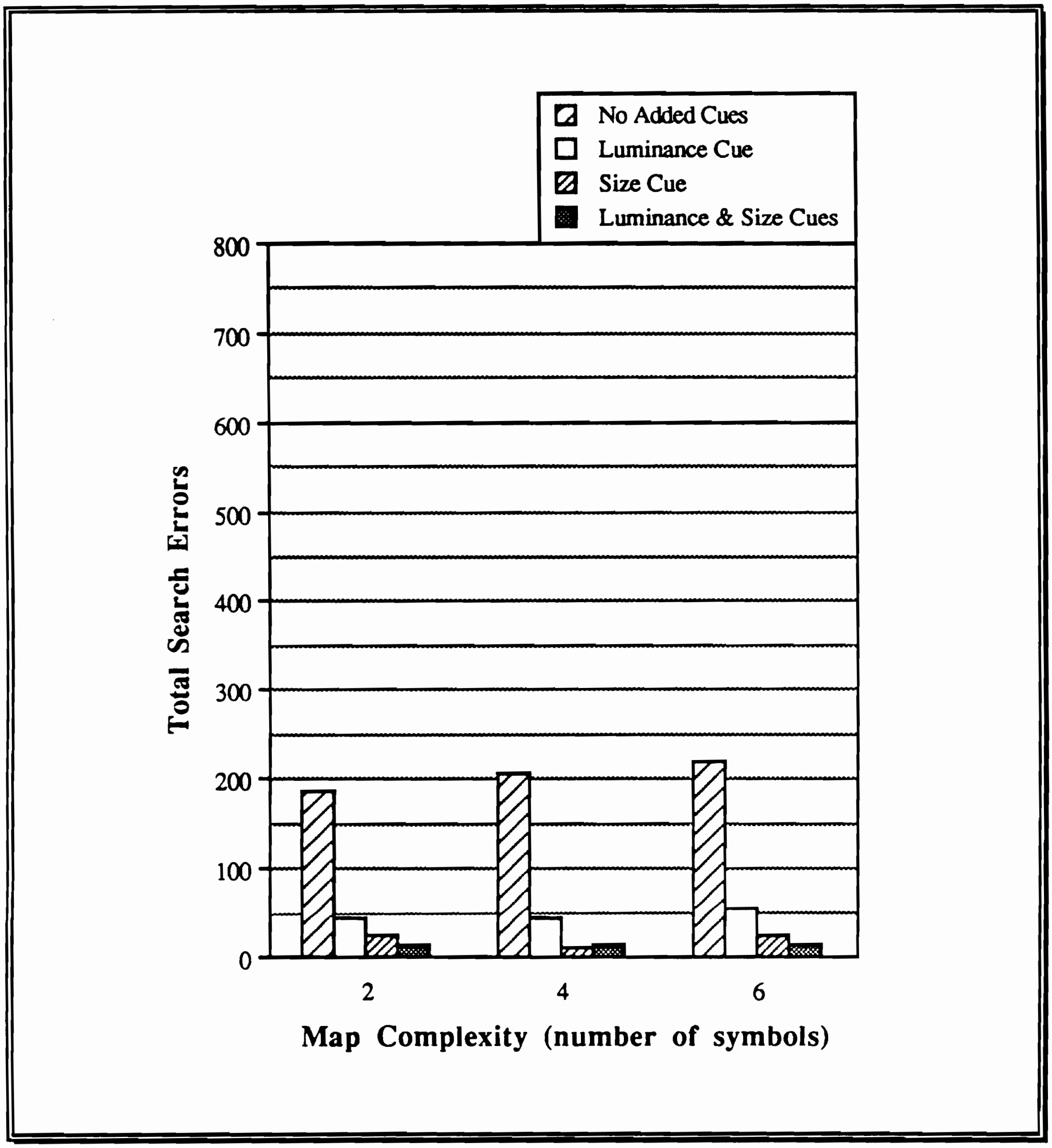


Figure M-26. Total search errors as a function of Complexity and Luminance and Size cues, Experiment 3.

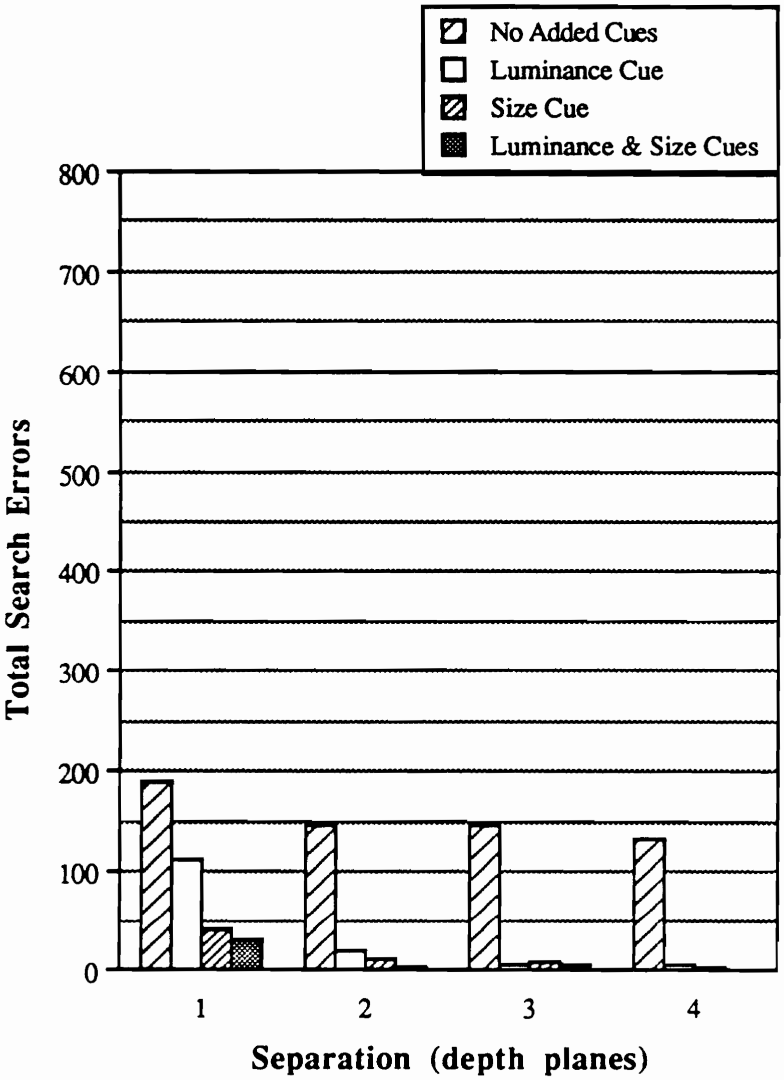


Figure M-27. Total search errors as a function of Separation and Luminance and Size cues, Experiment 3.

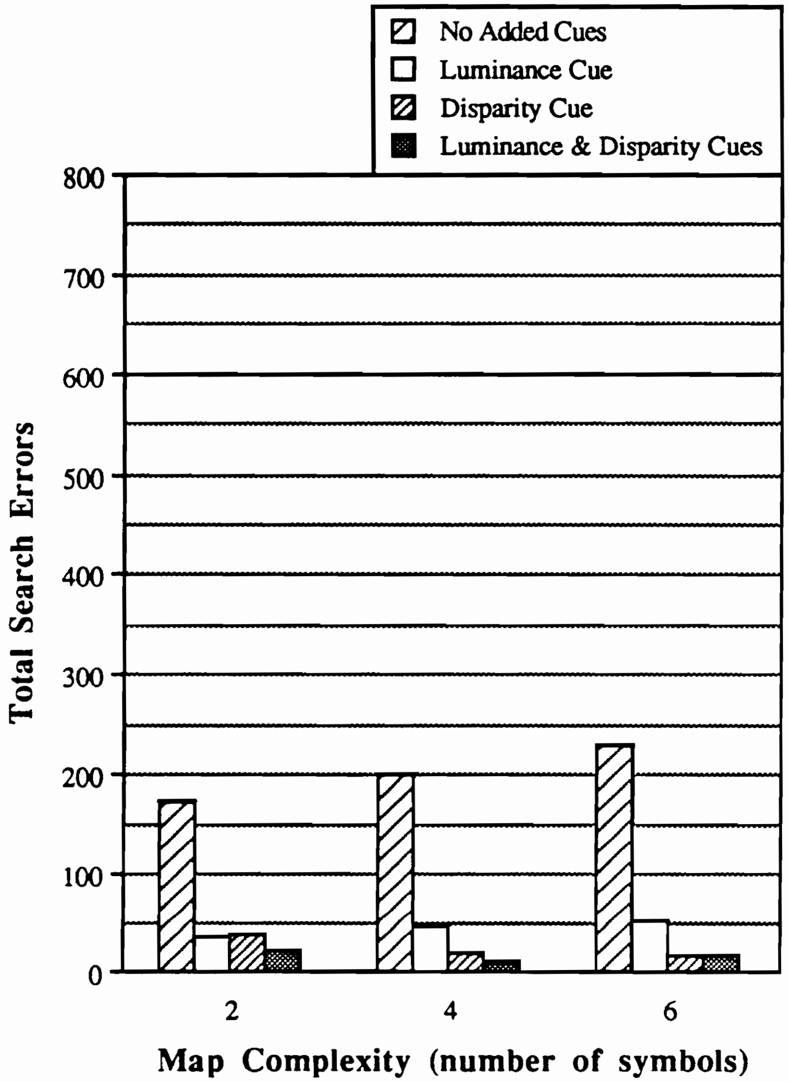


Figure M-28. Total search errors as a function of Complexity and Luminance and Disparity cues, Experiment 3.

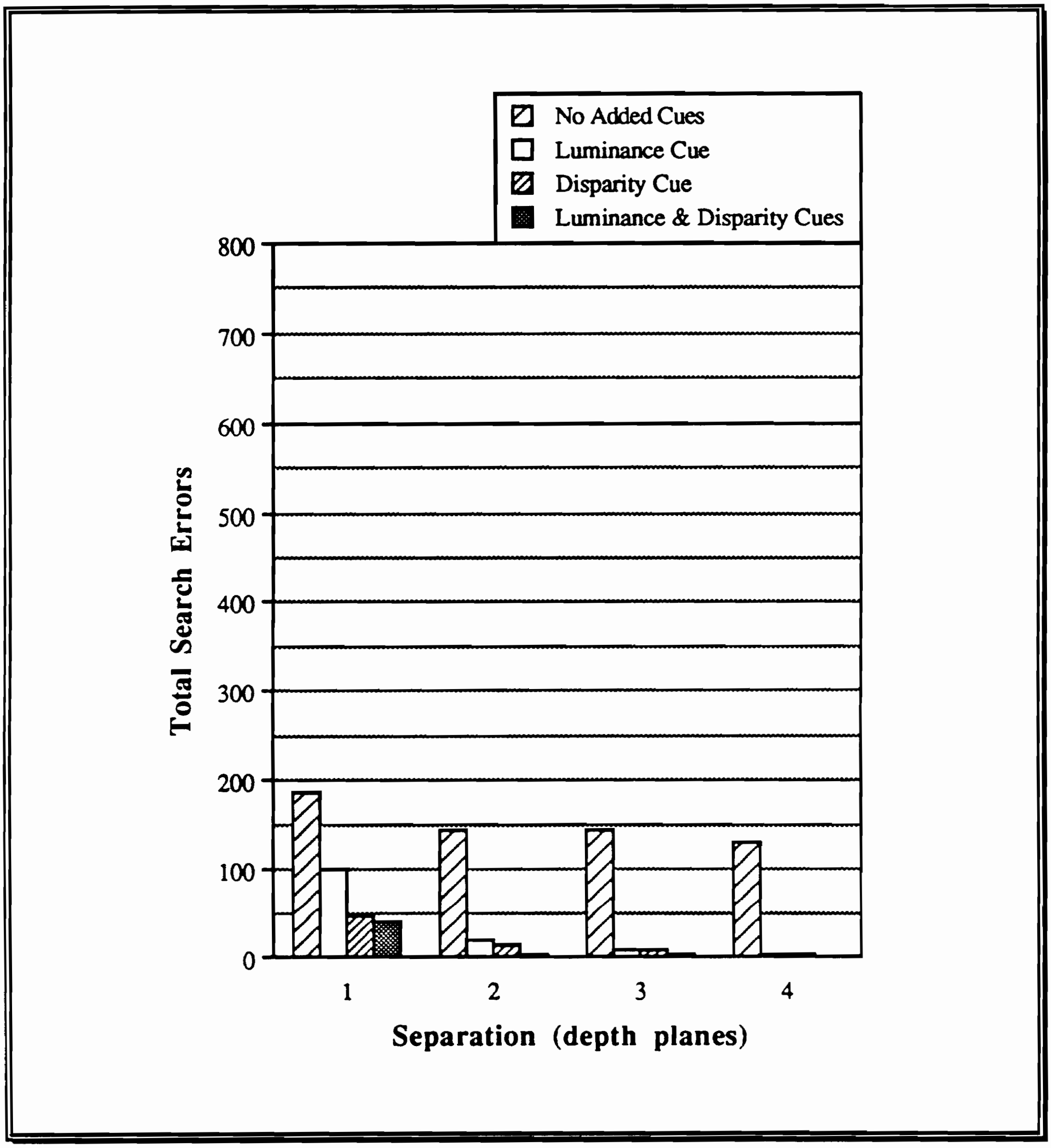


Figure M-29. Total search errors as a function of Separation and Luminance and Disparity cues, Experiment 3.

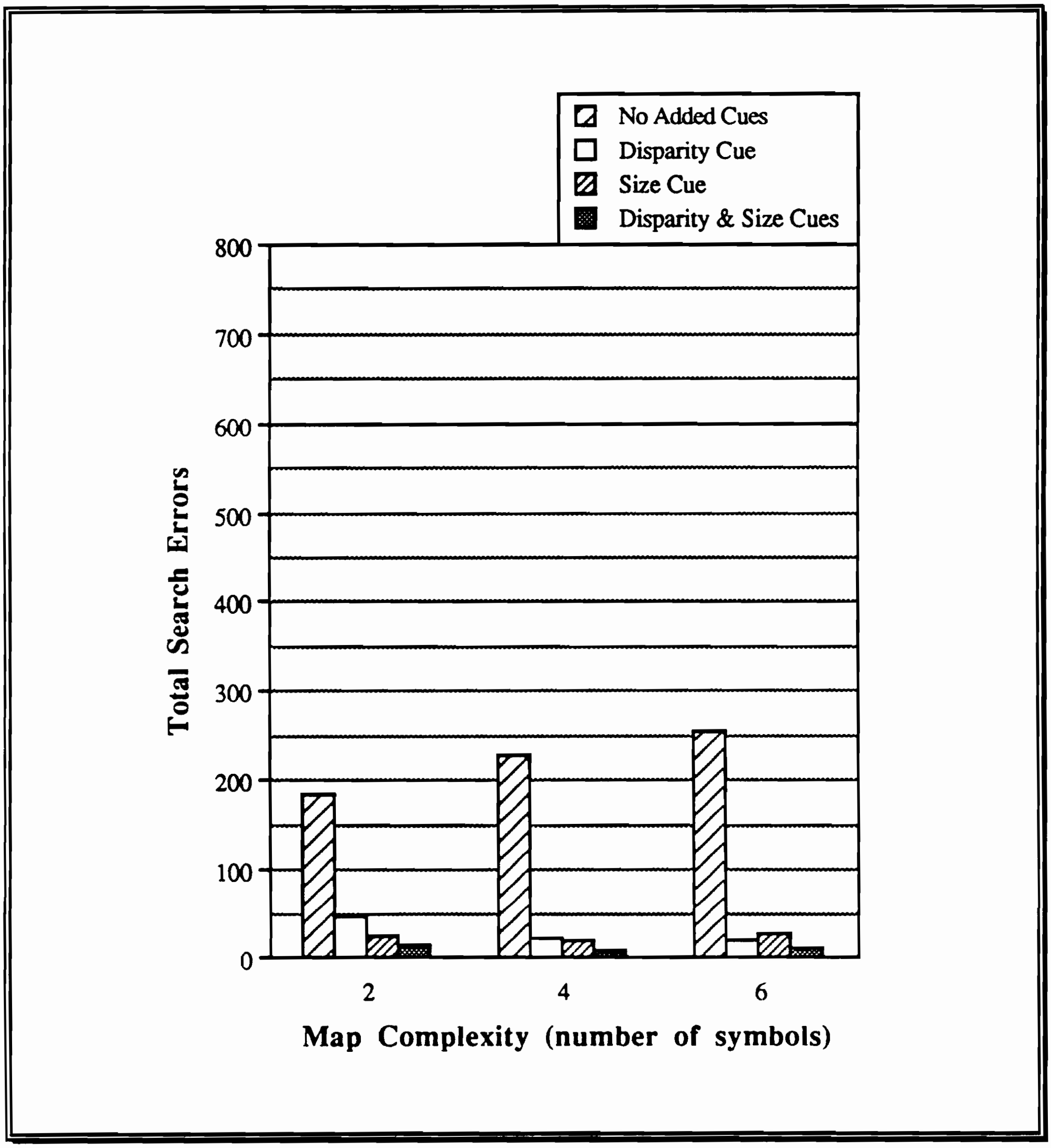


Figure M-30. Total search errors as a function of Complexity and Disparity and Size cues, Experiment 3.

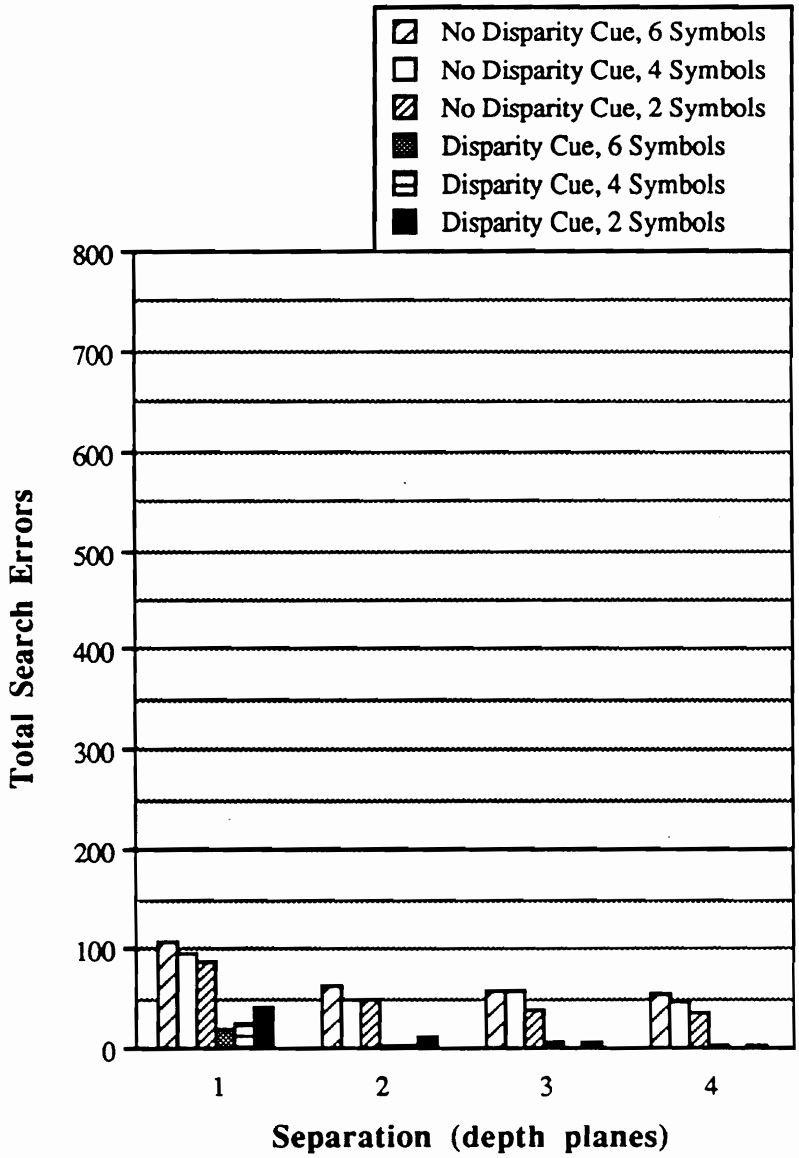


Figure M-31. Total search errors as a function of Separation, Disparity cue, and Complexity, Experiment 3.

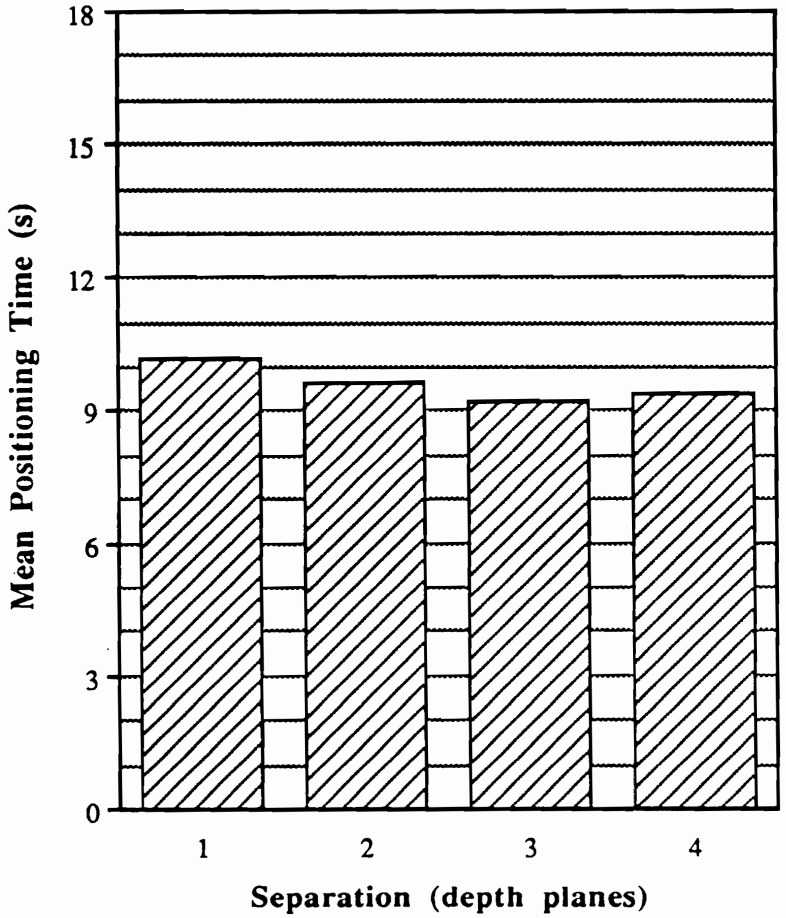


Figure M-32. Mean positioning time (s) as a function of Separation, Experiment 3.

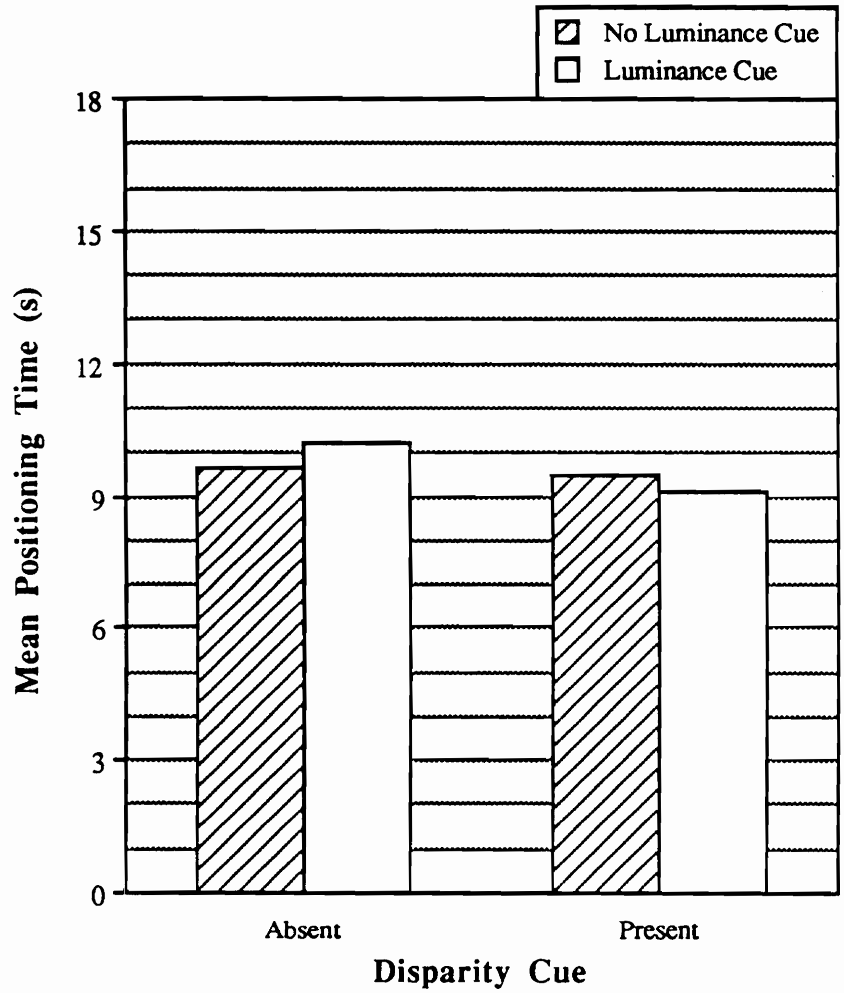


Figure M-33. Mean positioning time (s) as a function of Disparity and Luminance cues, Experiment 3.

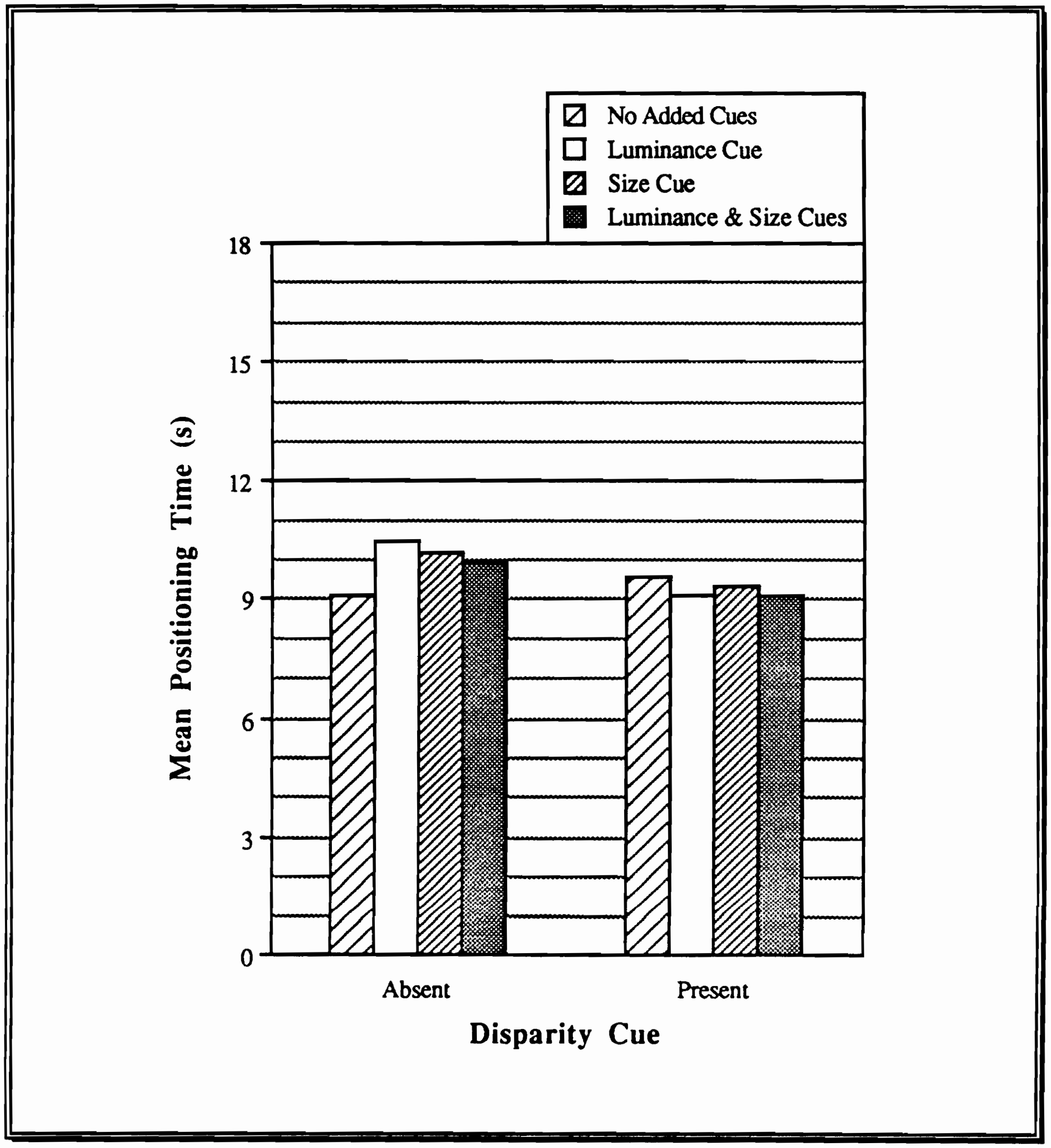


Figure M-34. Mean positioning time (s) as a function of Disparity, Luminance, and Size cues, Experiment 3.

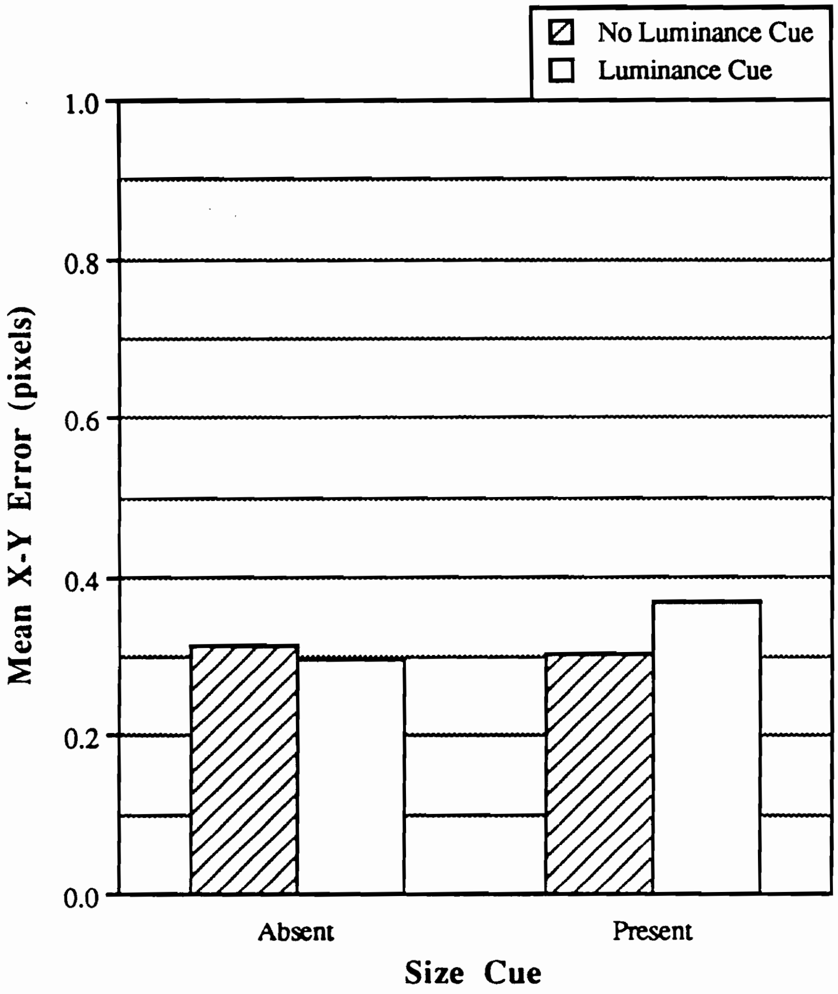


Figure M-35. Mean positioning error (X-Y) as a function of Size and Luminance cues, Experiment 3.

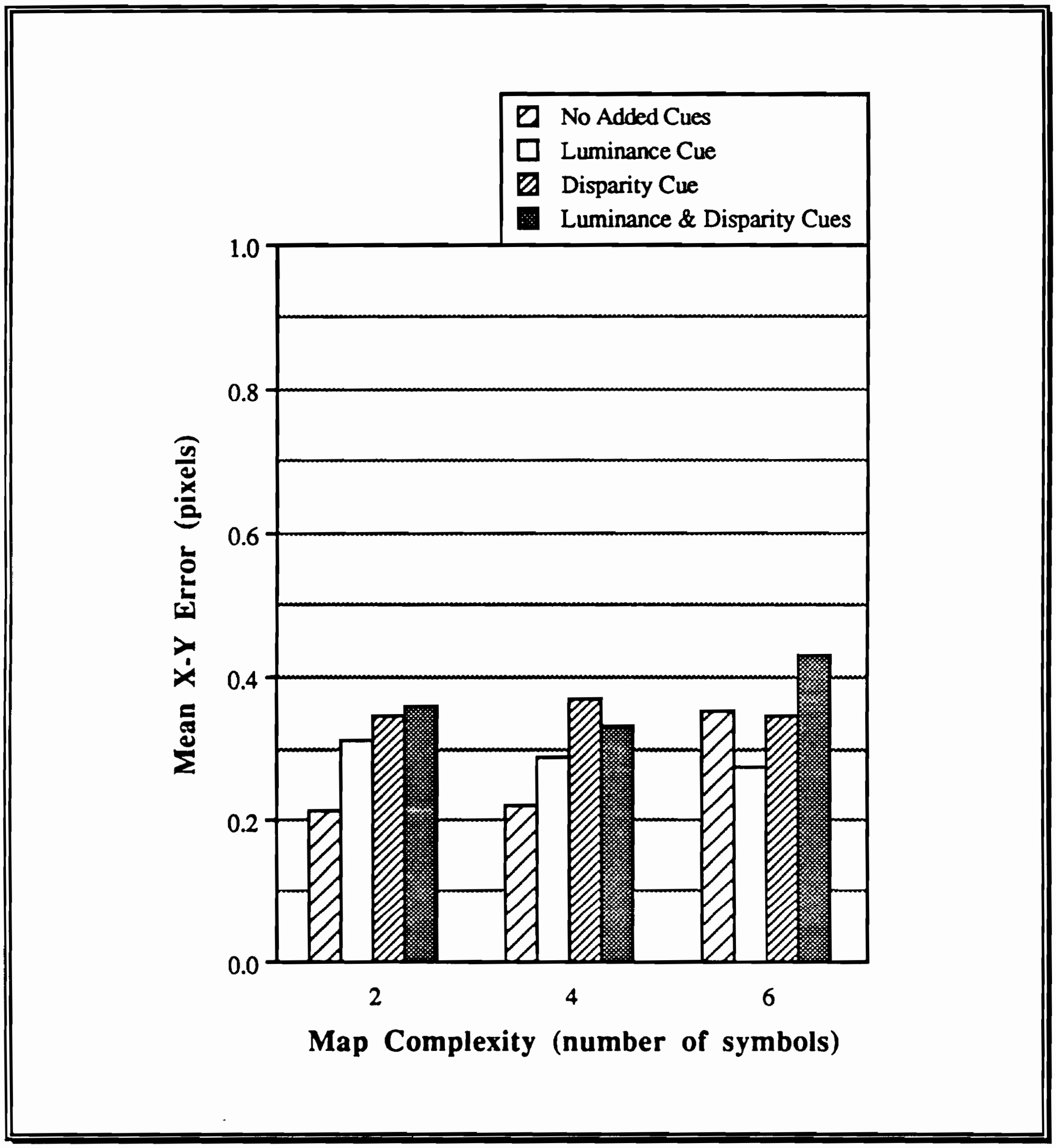


Figure M-36. Mean positioning error (X-Y) as a function of Complexity and Luminance and Disparity cues, Experiment 3.

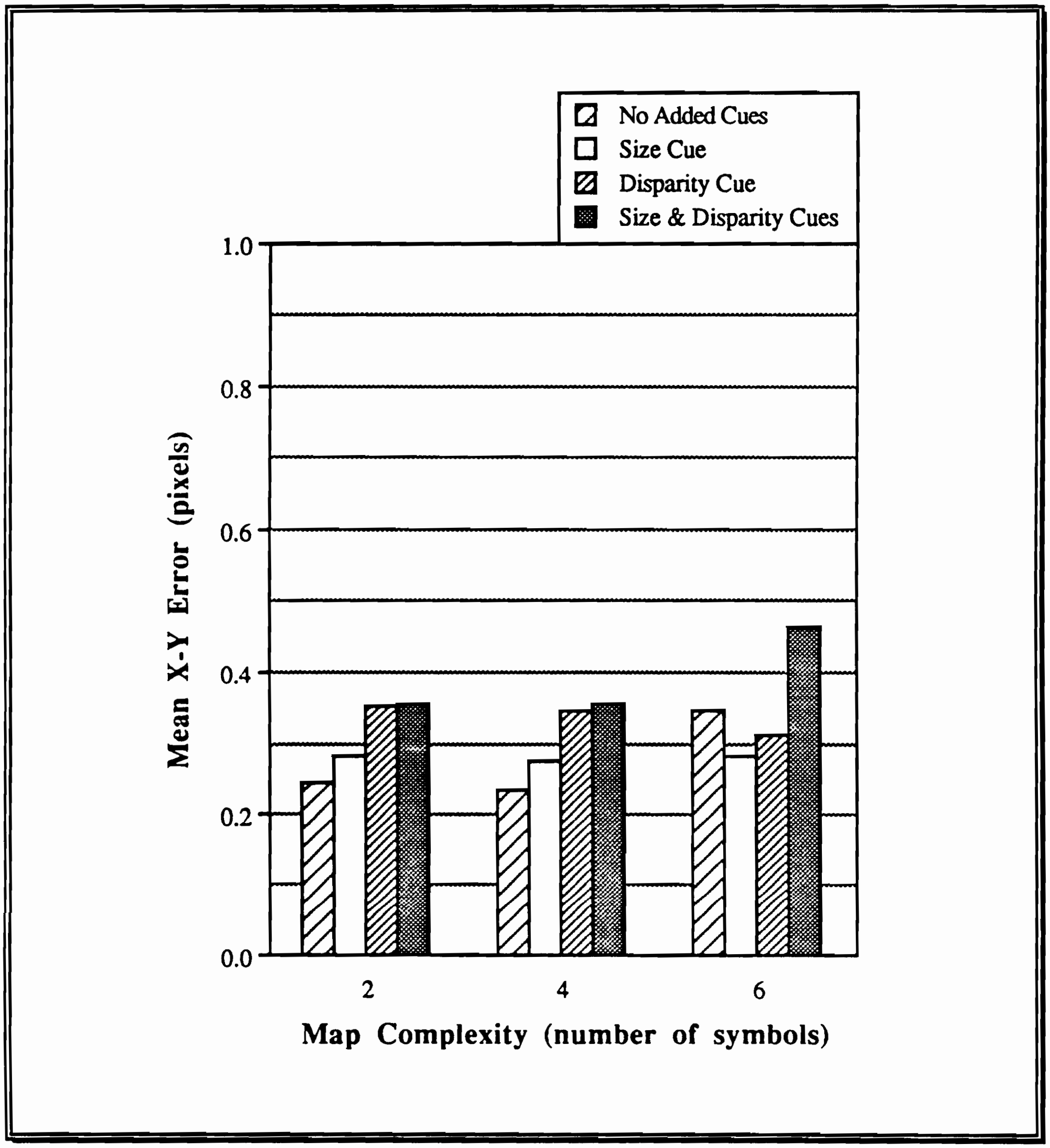


Figure M-37. Mean positioning error (X-Y) as a function of Complexity and Size and Disparity cues, Experiment 3.

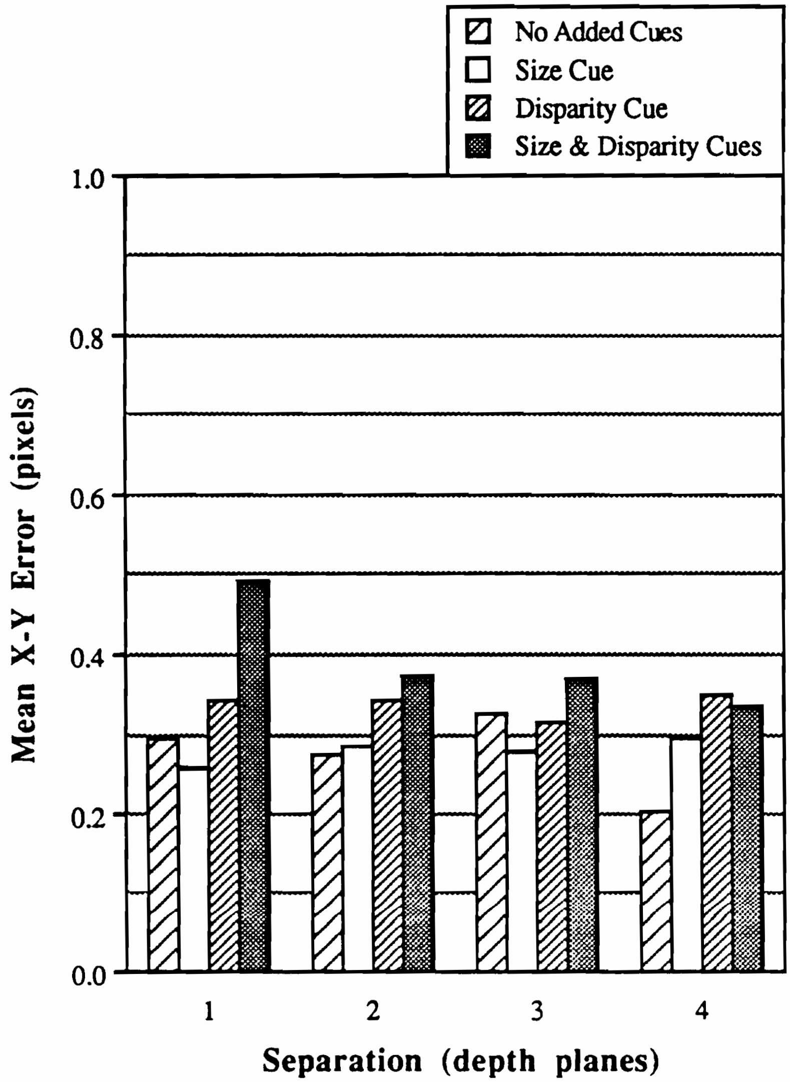


Figure M-38. Mean positioning error (X-Y) as a function of Separation and Size and Disparity cues, Experiment 3.

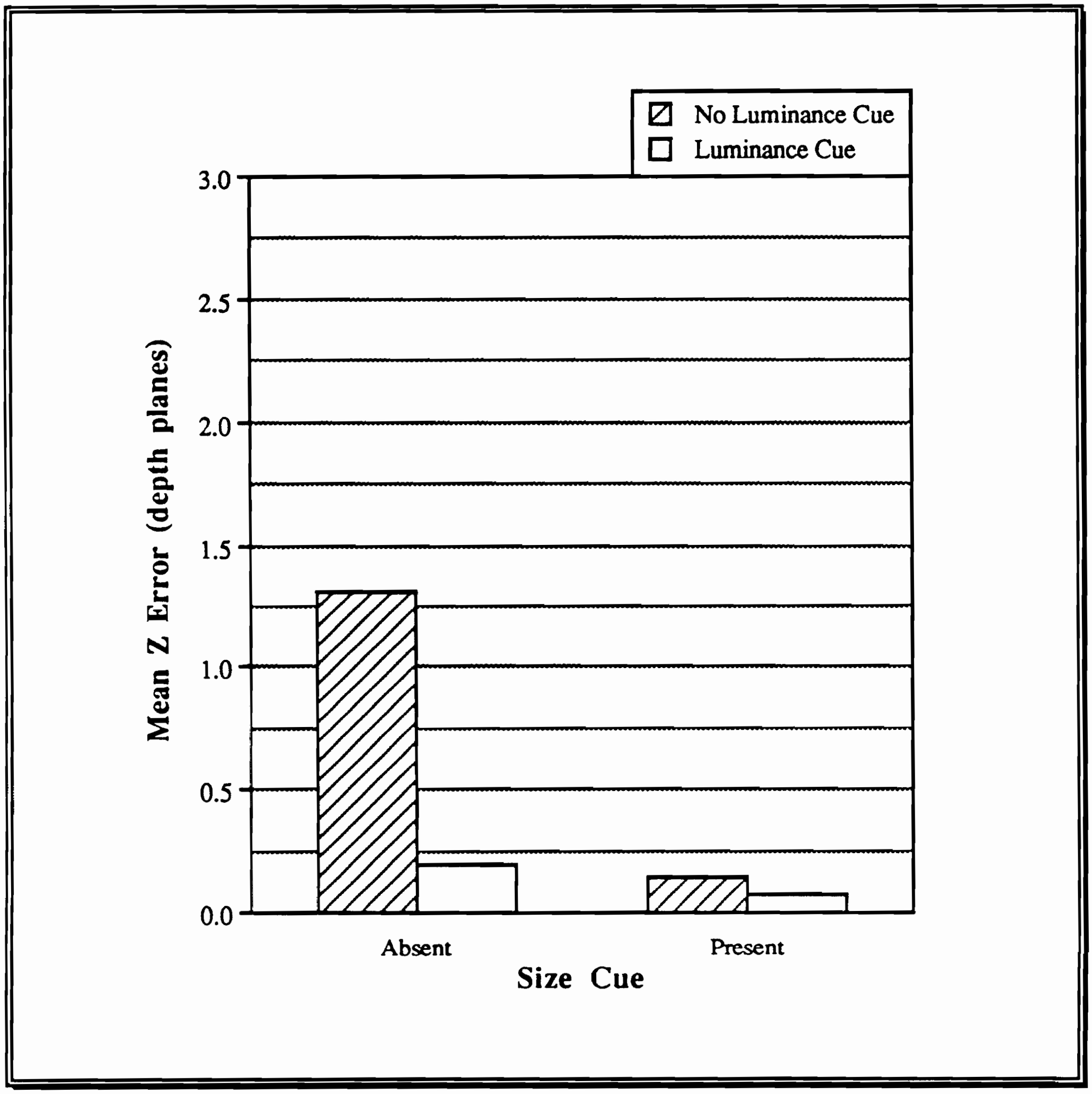


Figure M-39. Mean positioning error (Z) as a function of Size and Luminance cues, Experiment 3.

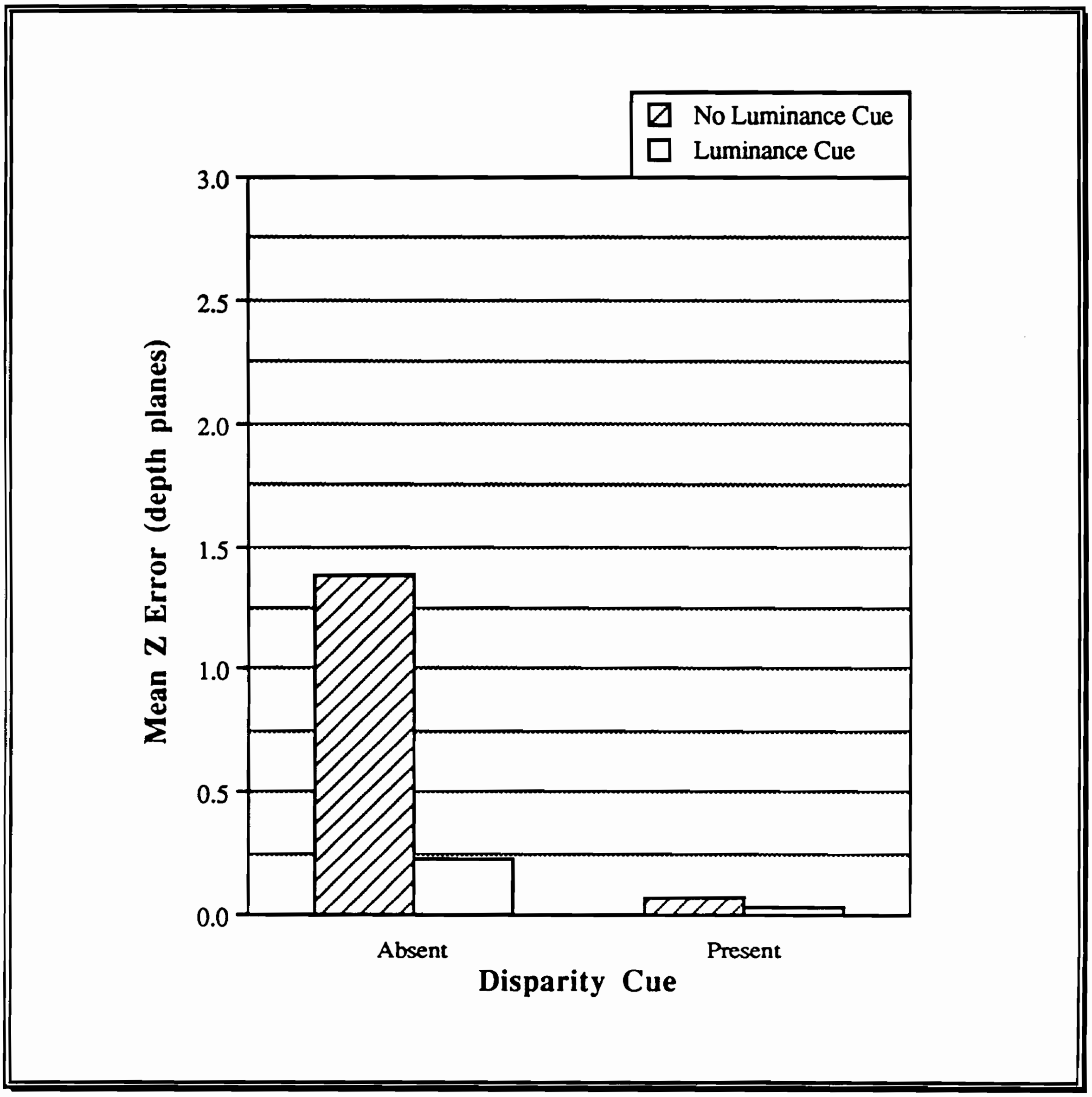


Figure M-40. Mean positioning error (Z) as a function of Disparity and Luminance cues, Experiment 3.

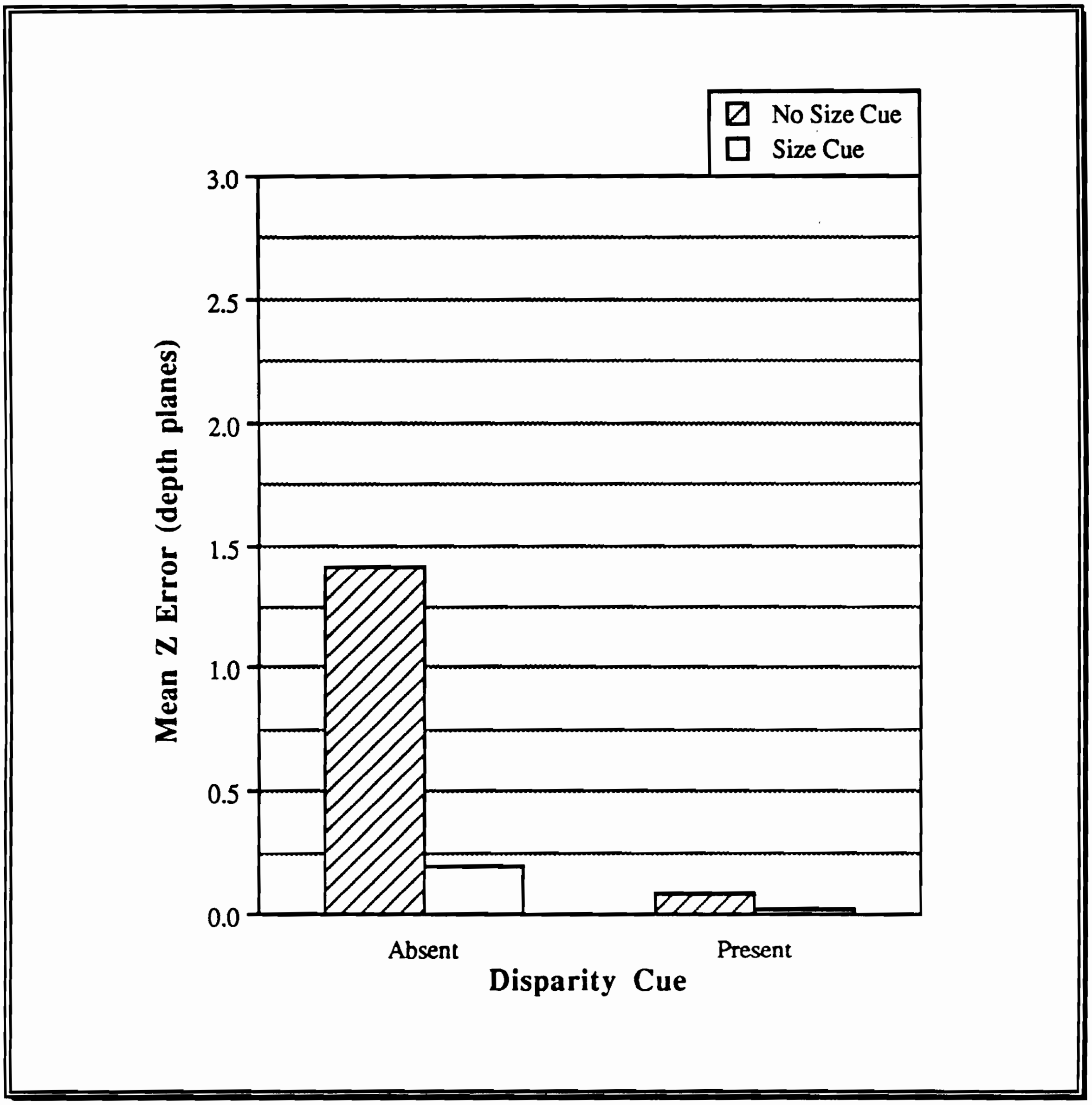


Figure M-41. Mean positioning error (Z) as a function of Disparity and Size cues, Experiment 3.

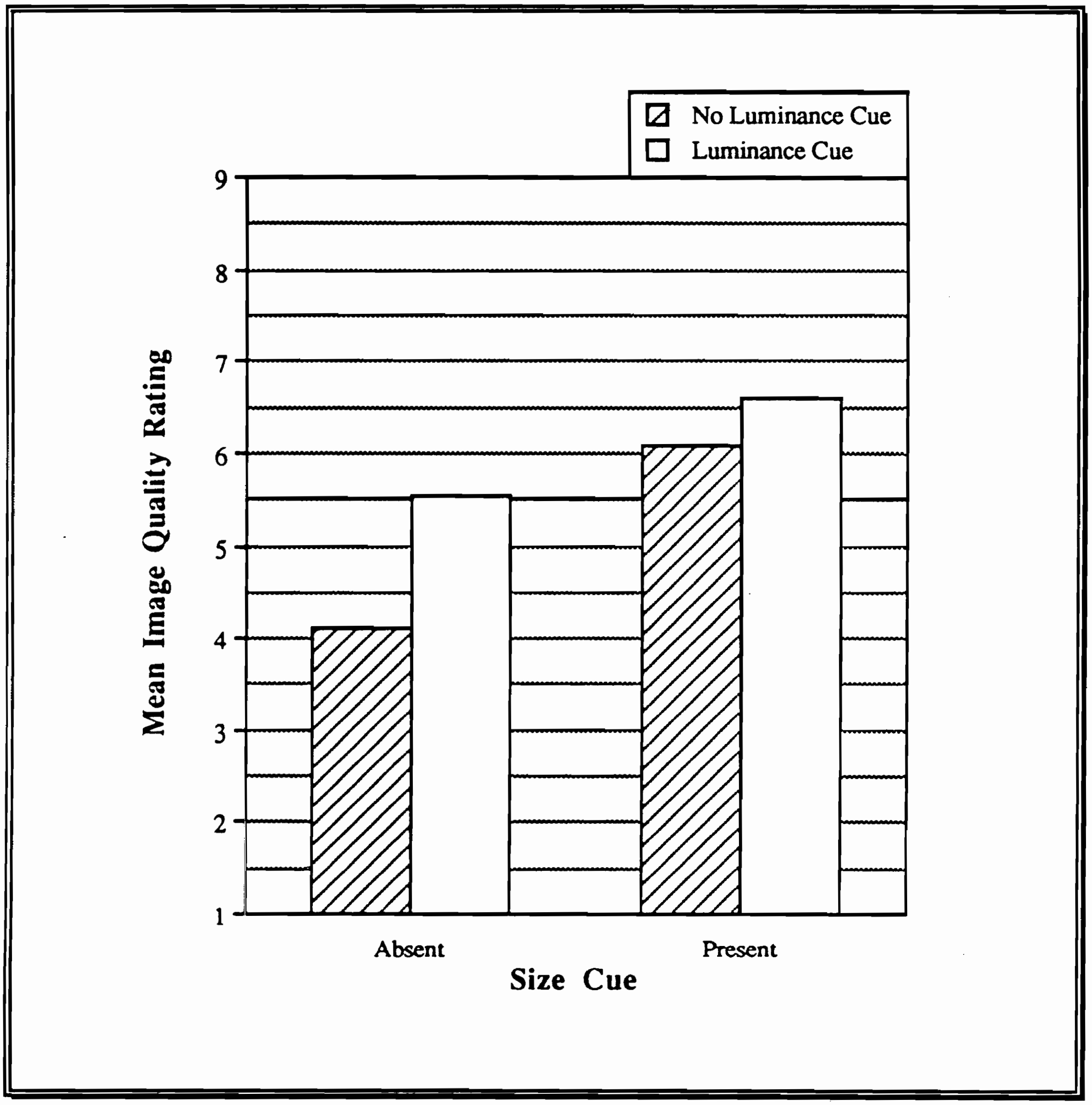


Figure M-42. Mean image quality rating as a function of Size and Luminance cues, Experiment 3.

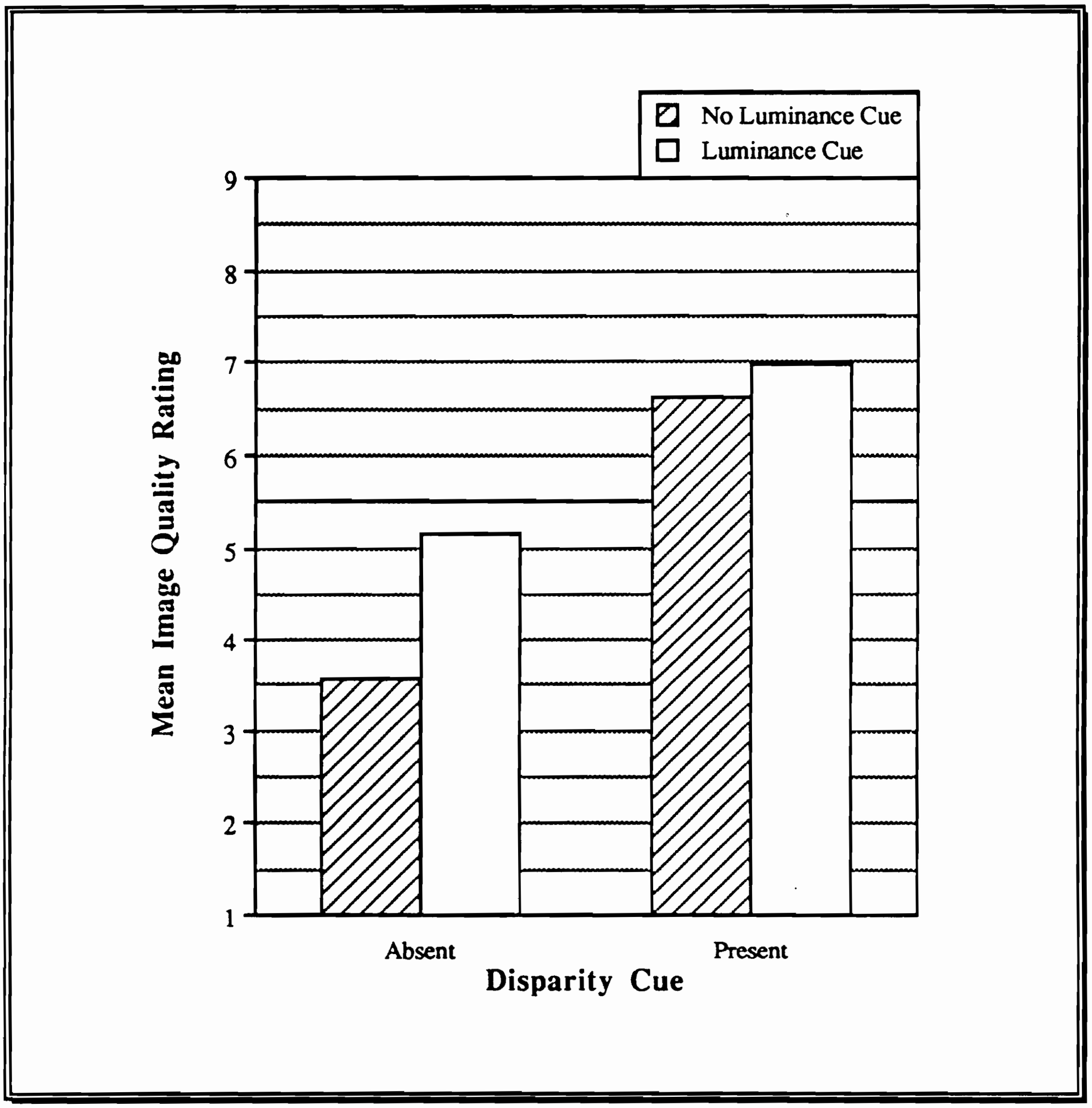


Figure M-43. Mean image quality rating as a function of Disparity and Luminance cues, Experiment 3.

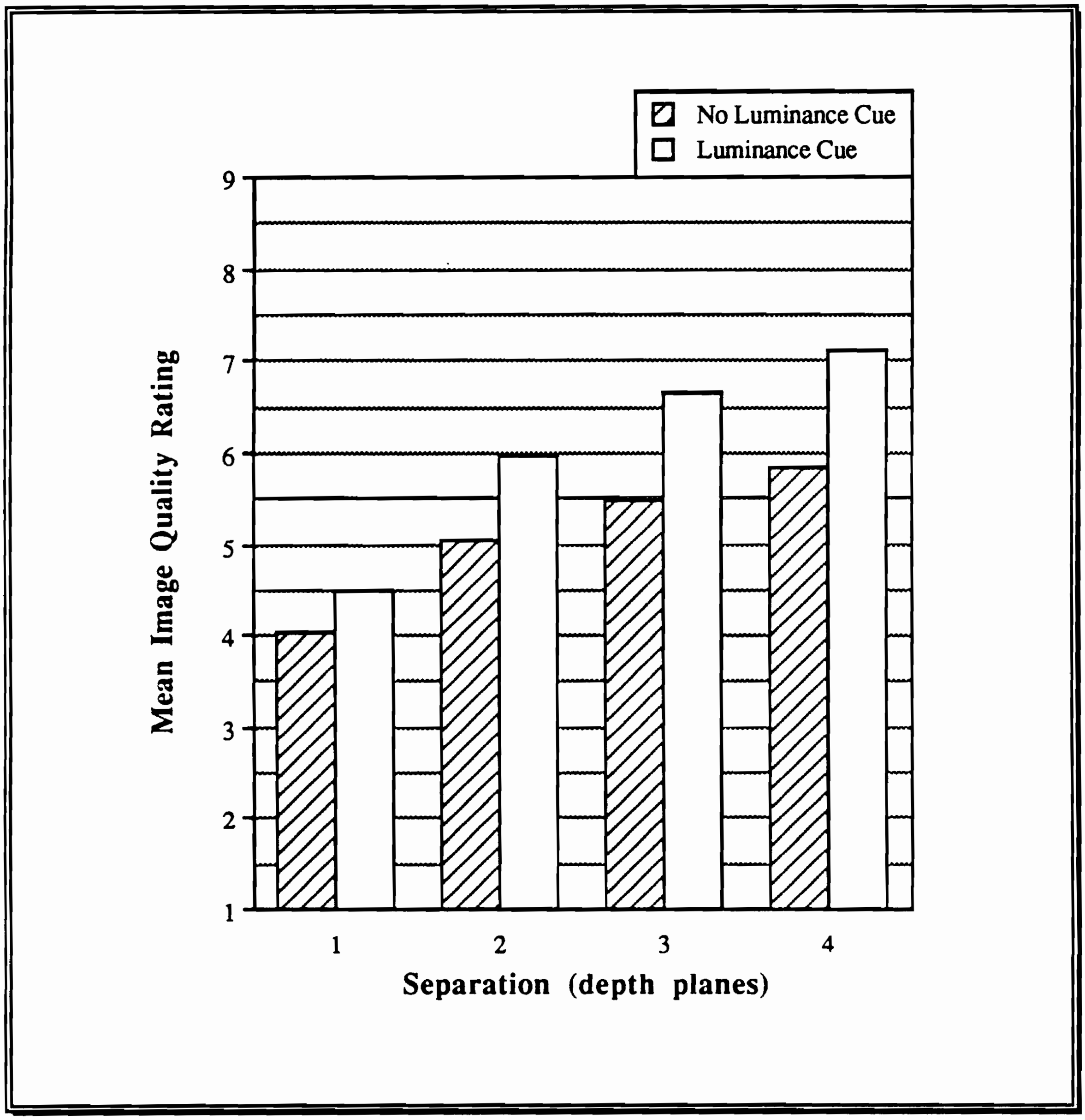


Figure M-44. Mean image quality rating as a function of Separation and Luminance cue, Experiment 3.

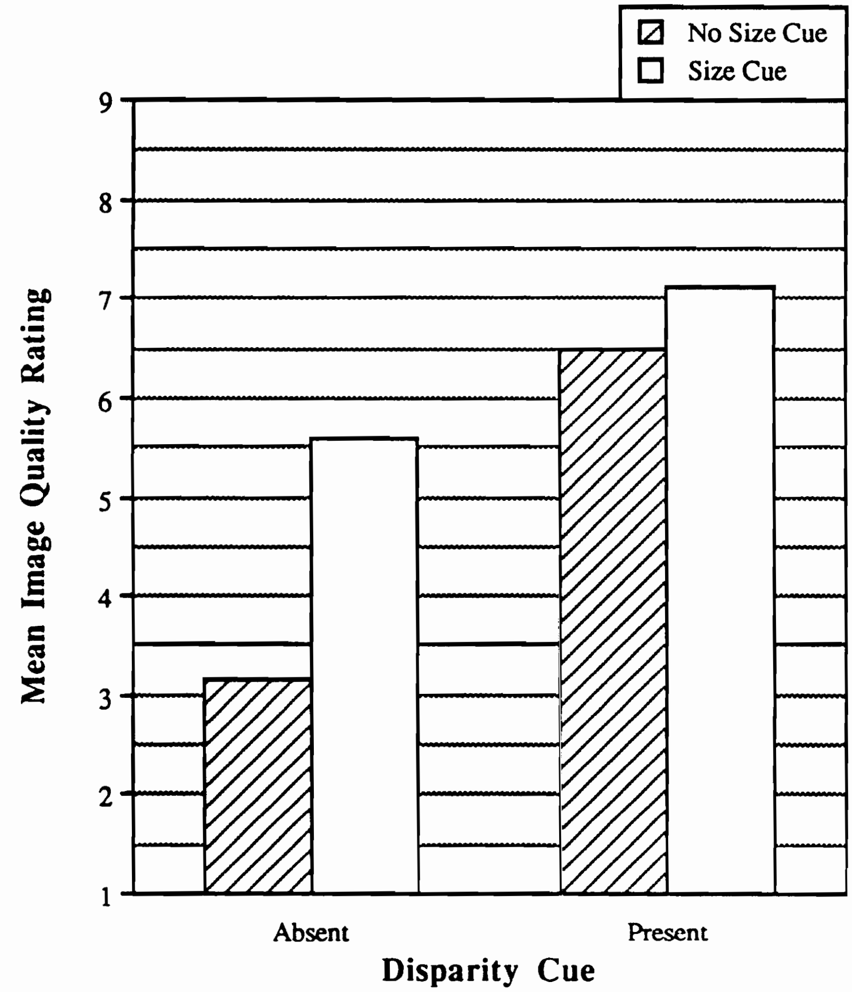


Figure M-45. Mean image quality rating as a function of Disparity and Size cues, Experiment 3.

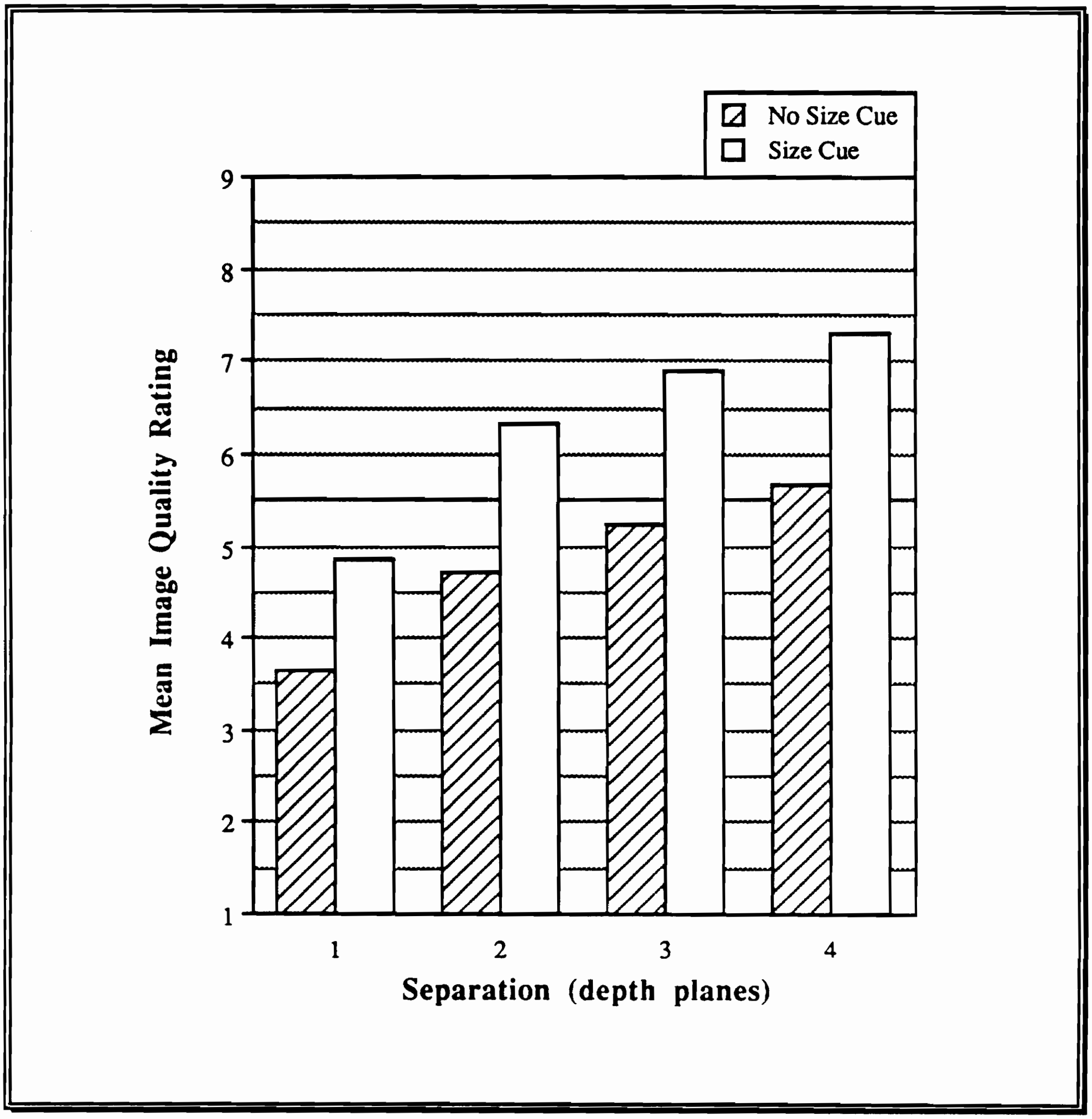


Figure M-46. Mean image quality rating as a function of Separation and Size cue, Experiment 3.

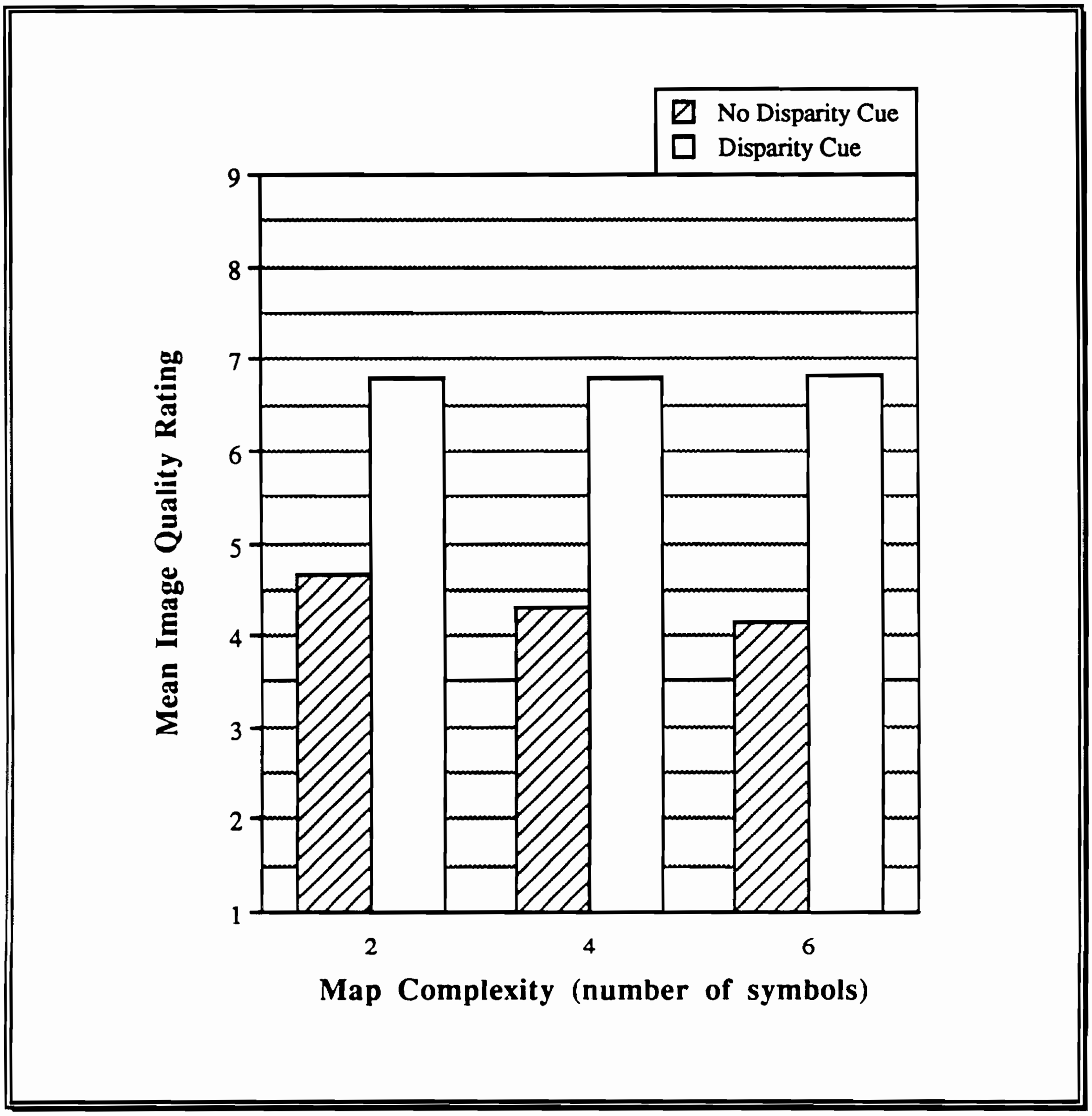


Figure M-47. Mean image quality rating as a function of Complexity and Disparity cue, Experiment 3.

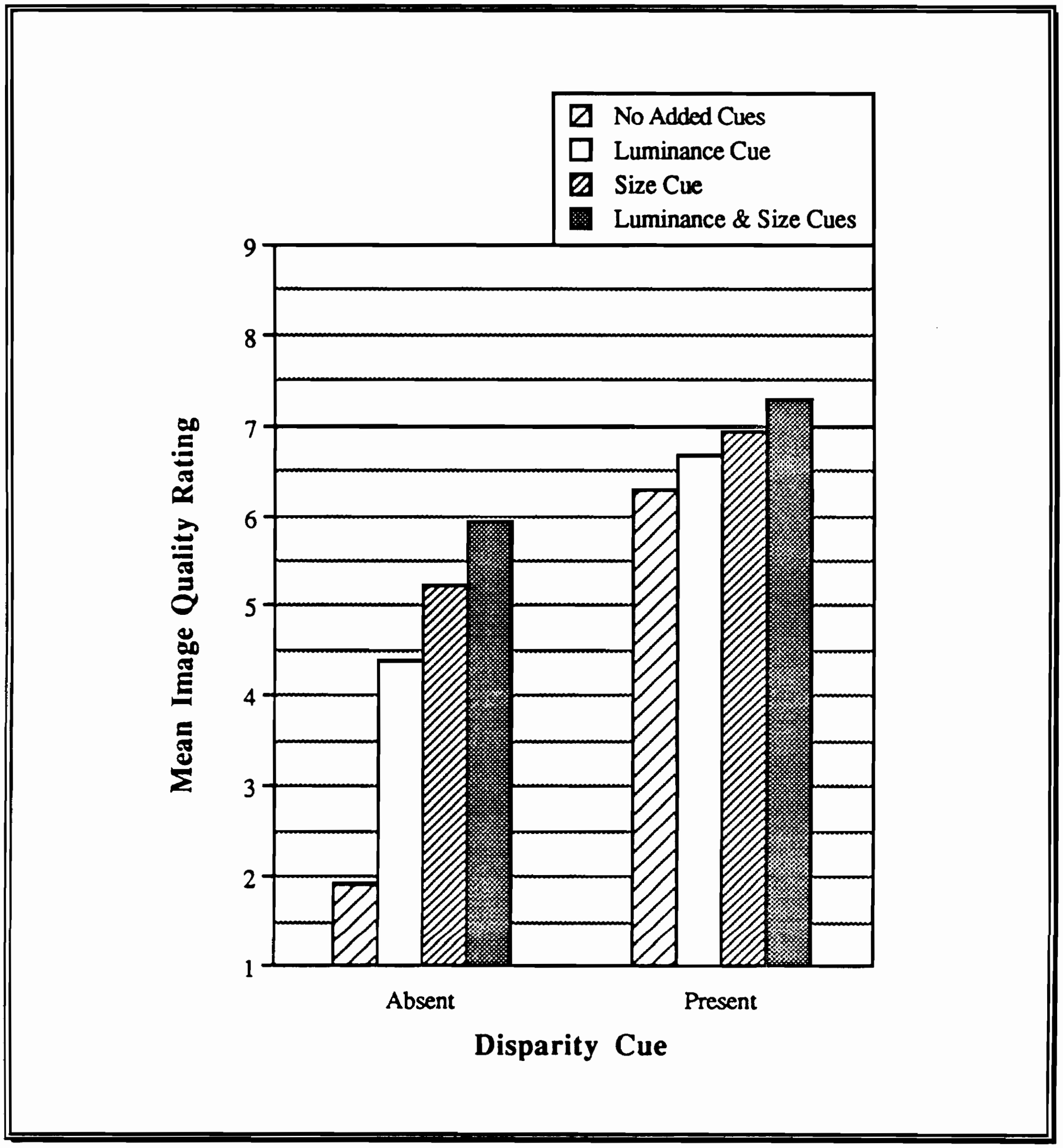


Figure M-48. Mean image quality rating as a function of Disparity, Luminance, and Size cues, Experiment 3.

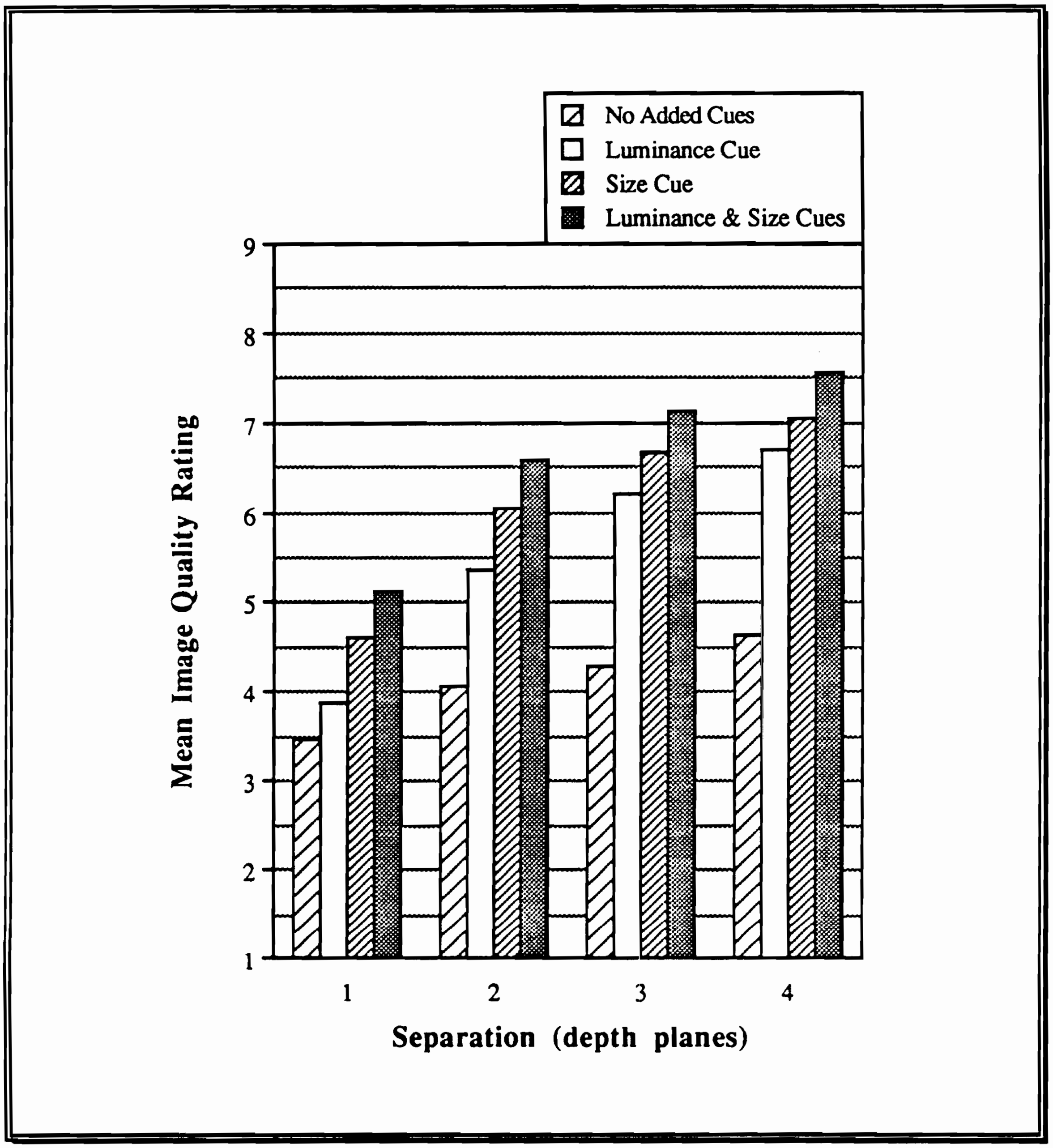


Figure M-49. Mean image quality rating as a function of Separation and Luminance and Size cues, Experiment 3.

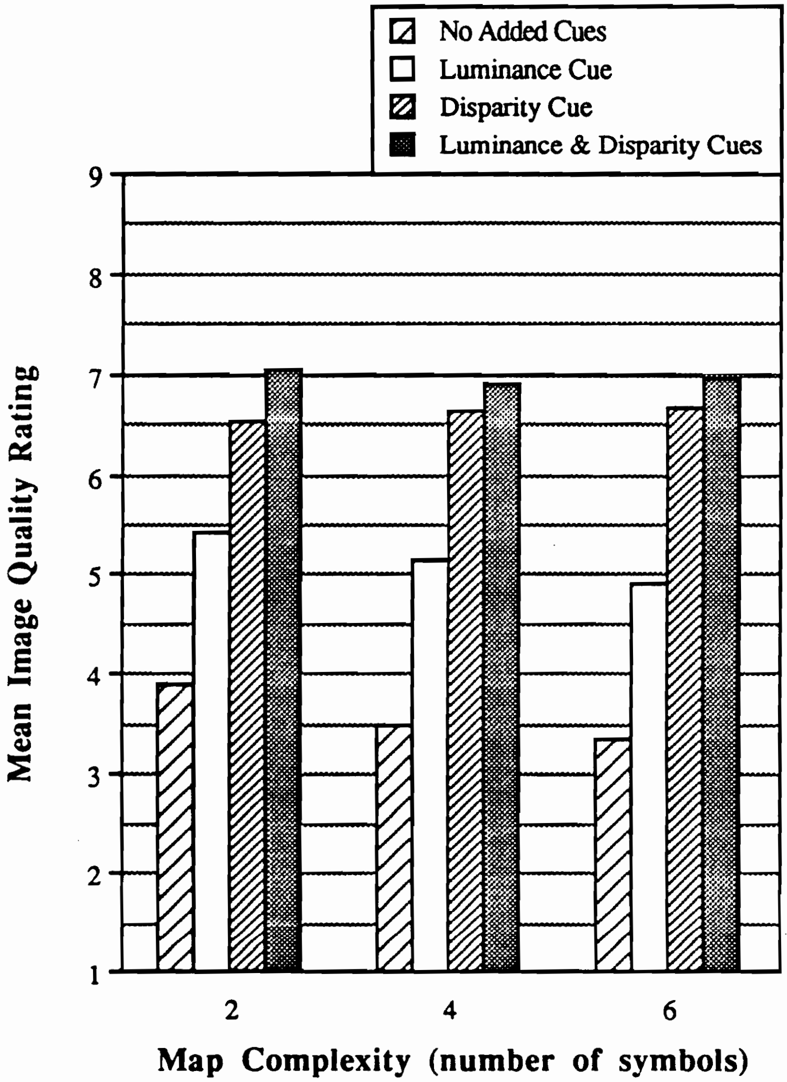


Figure M-50. Mean image quality rating as a function of Complexity and Luminance and Disparity cues, Experiment 3.

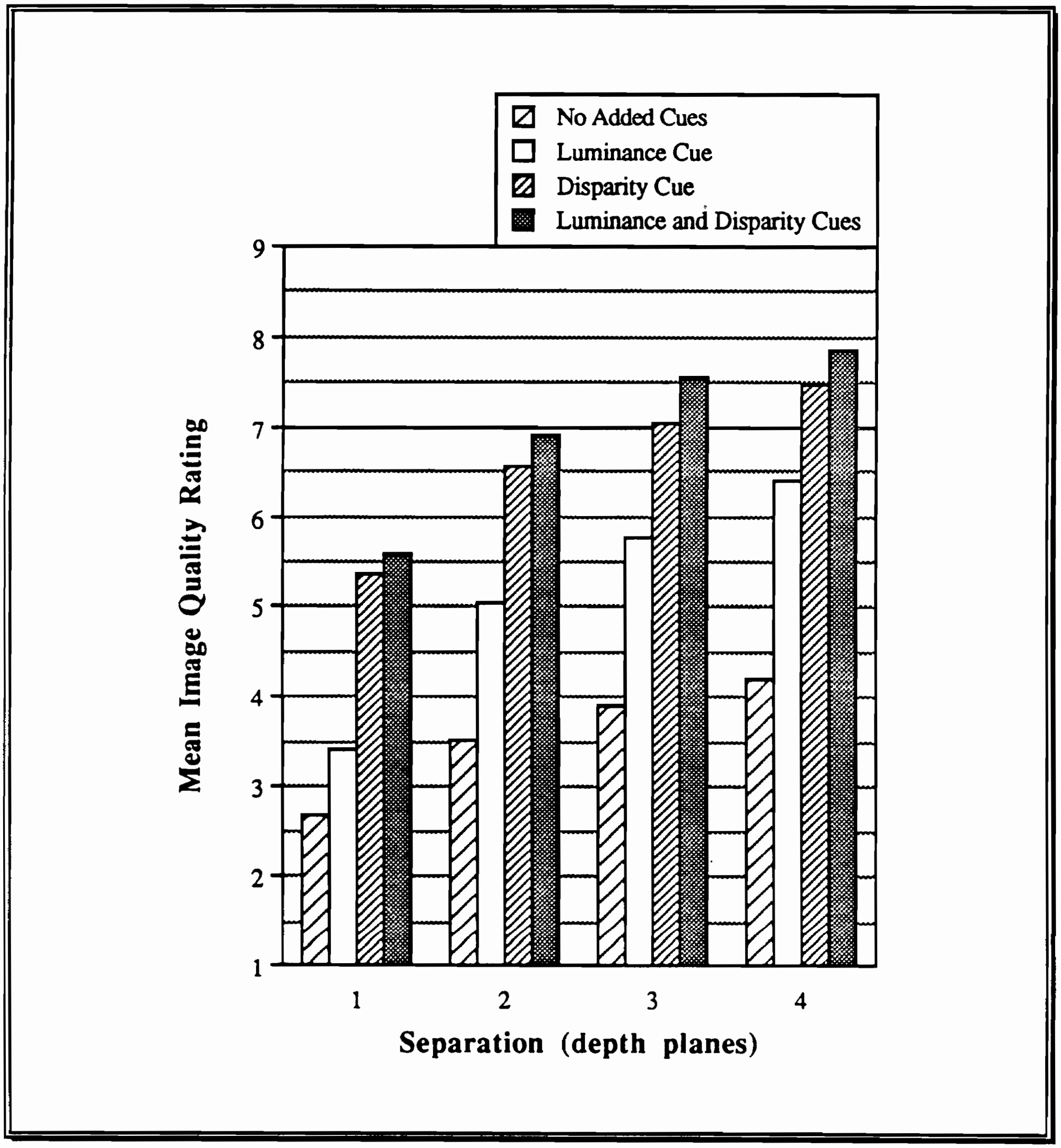


Figure M-51. Mean image quality rating as a function of Separation and Luminance and Disparity cues, Experiment 3.

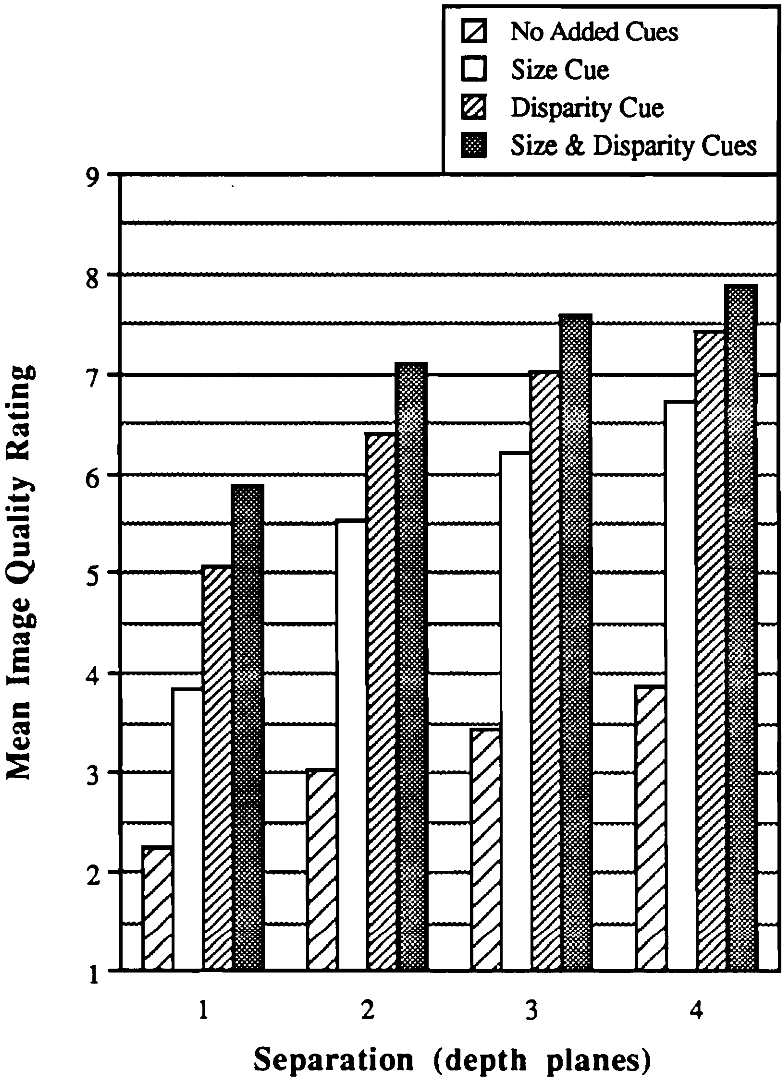


Figure M-52. Mean image quality rating as a function of Separation and Size and Disparity cues, Experiment 3.

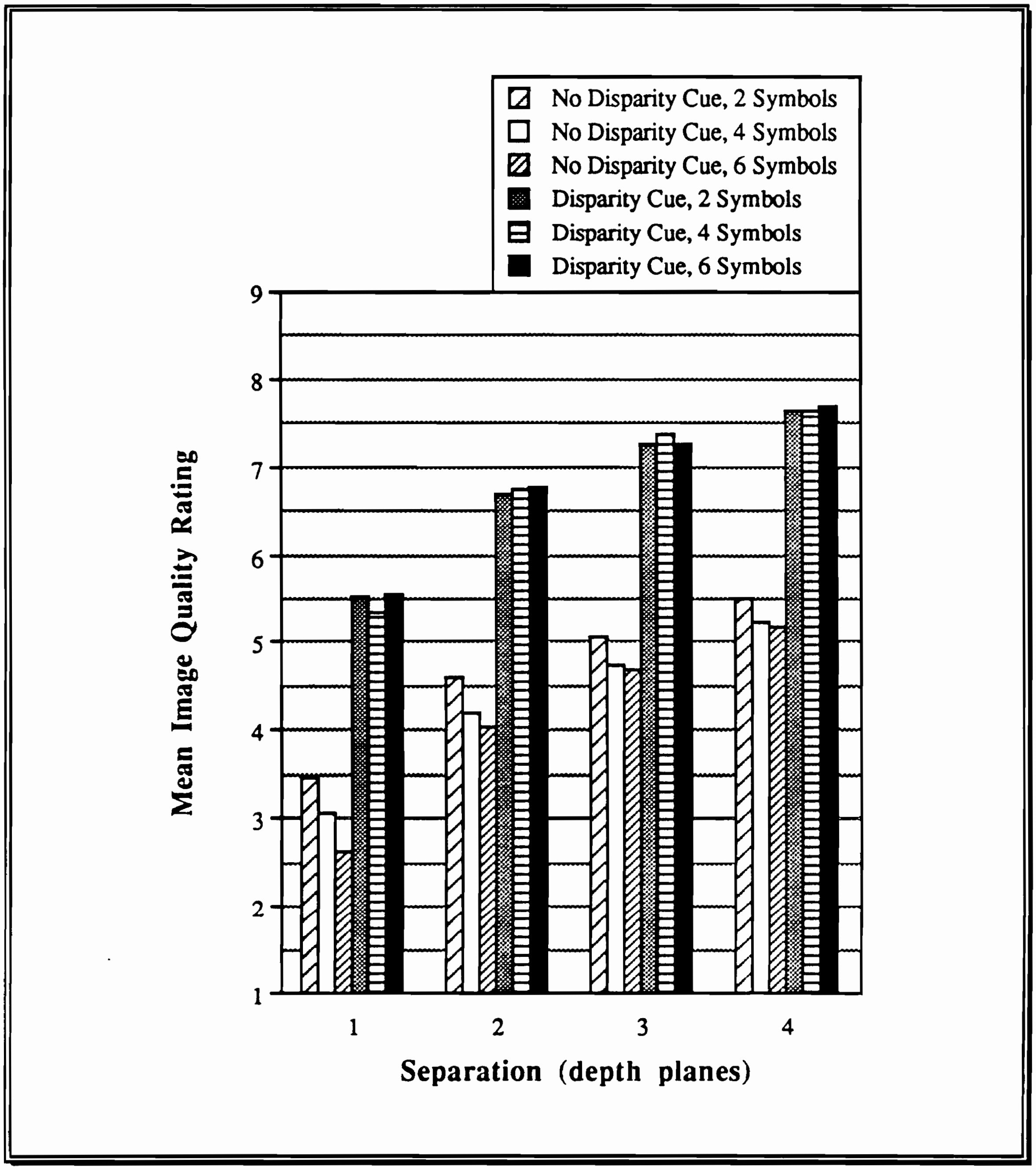


Figure M-53. Mean image quality rating as a function of Separation, Disparity cue, and Complexity, Experiment 3.

APPENDIX N

TABLES FROM POST-HOC ANALYSES, EXPERIMENT 3

TABLE N-1

Results of Newman-Keuls Test on Complexity (Search Time(s)) *

Number of Symbols:	2	4	6
Mean Value:	4.68	6.29	7.44

---

* Means with a common line do not differ significantly at $p \leq .05$

TABLE N-2

Results of Newman-Keuls Test on Separation (Search Time(s)) *

Separation (depth planes):	1	2	3	4
Mean Value:	9.94	5.82	4.56	4.24
			———	———

* Means with a common line do not differ significantly at $p \leq .05$

TABLE N-3

Results of Simple-Effect F-Tests on Complexity (C) for Each Value of Separation (Sp) (Search Time (s))

Source	*df*	*MS*	*F*	*p*
C (1 depth plane Sp)	2	974.5348	137.14	< .0001
C (2 depth planes Sp)	2	303.2085	42.67	< .0001
C (3 depth planes Sp)	2	151.7513	21.36	< .0001
C (4 depth planes Sp)	2	96.6204	13.60	< .0001
C*Sp*Sub	114	7.1059		

TABLE N-4

Results of Newman-Keuls Test on Complexity for a Separation of 1 Depth Plane (Search Time(s)) *

Number of Symbols:	2	4	6
Mean Value:	7.20	10.61	11.99

---

* Means with a common line do not differ significantly at $p \leq .05$

TABLE N-5

Results of Newman-Keuls Test on Complexity for a Separation of 2 Depth Planes (Search Time(s)) *

Number of Symbols:	2	4	6
Mean Value:	4.47	5.76	7.22

---

* Means with a common line do not differ significantly at $p \leq .05$

TABLE N-6

Results of Newman-Keuls Test on Complexity for a Separation of 3 Depth Planes (Search Time(s)) *

Number of Symbols:	2	4	6
Mean Value:	3.64	4.48	5.58

* Means with a common line do not differ significantly at $p \leq .05$

TABLE N-7

Results of Newman-Keuls Test on Complexity for a Separation of 4 Depth Planes (Search Time(s)) *

Number of Symbols:	2	4	6
Mean Value:	3.42	4.33	4.96

---

* Means with a common line do not differ significantly at $p \leq .05$

TABLE N-8

Results of Simple-Effect F-Tests on Luminance by Size by Disparity (L*Sz*D) Interaction for Each Value of Separation (Sp) (Search Time (s))

Source	*df*	*MS*	*F*	*p*
L*Sz*D (1 depth plane Sp)	1	25.2413	2.73	.1040
L*Sz*D (2 depth planes Sp)	1	317.7233	34.37	< .0001
L*Sz*D (3 depth planes Sp)	1	820.5940	88.78	< .0001
L*Sz*D (4 depth planes Sp)	1	1465.5525	158.56	< .0001
L*Sz*D*Sp*Sub	57	9.2430		

TABLE N-9

Results of Simple-Effect F-Tests on Luminance by Size Interaction (L*Sz) for Each Value of Disparity (D) Cue for a Separation (Sp) of 2 Depth Planes (Search Time (s))

Source	*df*	*MS*	*F*	*p*
L*Sz (D Absent, 2 depth planes Sp)	1	776.5911	84.02	< .0001
L*Sz (D Present, 2 depth planes Sp)	1	7.0720	0.77	.3839
L*Sz*D*Sp*Sub	57	9.2430		

TABLE N-10

Results of Simple-Effect F-Tests on Luminance by Size Interaction (L*Sz) for Each Value of Disparity (D) Cue for a Separation (Sp) of 3 Depth Planes (Search Time (s))

Source	*df*	*MS*	*F*	*p*
L*Sz (D Absent, 3 depth planes Sp)	1	1922.3228	207.98	< .0001
L*Sz (D Present, 3 depth planes Sp)	1	11.1070	1.20	.2779
L*Sz*D*Sp*Sub	57	9.2430		

TABLE N-11

Results of Simple-Effect F-Tests on Luminance by Size Interaction (L*Sz) for Each Value of Disparity (D) Cue for a Separation (Sp) of 4 Depth Planes (Search Time (s))

Source	*df*	*MS*	*F*	*p*
L*Sz (D Absent, 4 depth planes Sp)	1	3183.8486	344.46	< .0001
L*Sz (D Present, 4 depth planes Sp)	1	5.2254	0.57	.4534
L*Sz*D*Sp*Sub	57	9.2430		

TABLE N-12

Results of Simple-Effect F-Tests on Luminance (L) for Each Value of Size (Sz) Cue with No Disparity (D) Cue and a Separation (Sp) of 2 Depth Planes (Search Time (s))

Source	*df*	*MS*	*F*	*p*
L (Sz Absent, D Absent, 2 depth planes Sp)	1	2656.6438	287.42	< .0001
L (Sz Present, D Absent, 2 depth planes Sp)	1	147.1904	15.92	.0002
L*Sz*D*Sp*Sub	57	9.2430		

TABLE N-13

Results of Simple-Effect F-Tests on Luminance (L) for Each Value of Size (Sz) Cue with No Disparity (D) Cue and a Separation (Sp) of 3 Depth Planes (Search Time (s))

Source	*df*	*MS*	*F*	*p*
L (Sz Absent, D Absent, 3 depth planes Sp)	1	4483.0909	485.03	< .0001
L (Sz Present, D Absent, 3 depth planes Sp)	1	24.5092	2.65	.1091
L*Sz*D*Sp*Sub	57	9.2430		

TABLE N-14

Results of Simple-Effect F-Tests on Luminance (L) for Each Value of Size (Sz) Cue with No Disparity (D) Cue and a Separation (Sp) of 4 Depth Planes (Search Time (s))

Source	*df*	*MS*	*F*	*p*
L (Sz Absent, D Absent, 4 depth planes Sp)	1	6880.9137	744.45	< .0001
L (Sz Present, D Absent, 4 depth planes Sp)	1	9.9441	1.08	.3031
L*Sz*D*Sp*Sub	57	9.2430		

TABLE N-15

Results of Newman-Keuls Test on Complexity (Total Search Errors) *

Number of Symbols:	2	4	6
Mean Value:	0.419	0.431	0.489
	———	———	

* Means with a common line do not differ significantly at $p \leq .05$

TABLE N-16

Results of Newman-Keuls Test on Separation (Total Search Errors) *

Separation (depth planes):	1	2	3	4
Mean Value:	0.779	0.375	0.342	0.290
		———	———	
			———	———

* Means with a common line do not differ significantly at $p \leq .05$

TABLE N-17

Results of Simple-Effect F-Tests on Luminance by Size Interaction (L*Sz) for Each Value of Disparity (D) Cue (Z Positioning Error)

Source	*df*	*MS*	*F*	*p*
L*Sz (D Absent)	1	12.1260	93.49	< .0001
L*Sz (D Present)	1	0.0141	0.11	.7514
L*Sz*D*C*Sp	6	0.1297		

TABLE N-18

Results of Simple-Effect F-Tests on Luminance (L) for Each Value of Size (Sz) Cue and No Disparity (D) Cue (Z Positioning Error)

Source	*df*	*MS*	*F*	*p*
L (Sz Absent, D Absent)	1	27.9929	215.83	< .0001
L (Sz Present, D Absent)	1	0.1341	1.03	.3493
L*Sz*D*C*Sp	6	0.1297		

TABLE N-19

Results of Newman-Keuls Test on Complexity (Image Quality Rating) *

Number of Symbols:	2	4	6
Mean Value:	5.72	5.54	5.48

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* Means with a common line do not differ significantly at $p \leq .05$

TABLE N-20

Results of Newman-Keuls Test on Separation (Image Quality Rating) *

Separation (depth planes):	1	2	3	4
Mean Value:	4.26	5.52	6.07	6.49

* Means with a common line do not differ significantly at $p \leq .05$

TABLE N-21

Results of Simple-Effect F-Tests on Luminance by Size by Disparity Interaction (L*Sz*D) for Each Value of Separation (Sp) (Image Quality Rating)

Source	*df*	*MS*	*F*	*p*
L*Sz*D (1 depth plane Sp)	1	2.7000	5.57	.0217
L*Sz*D (2 depth planes Sp)	1	9.5391	19.68	< .0001
L*Sz*D (3 depth planes Sp)	1	36.8521	76.02	< .0001
L*Sz*D (4 depth planes Sp)	1	66.7521	137.70	< .0001
L*Sz*D*Sp*Sub	57	0.4847		

TABLE N-22

Results of Simple-Effect F-Tests on Luminance by Size Interaction (L*Sz) for Each Value of Disparity (D) Cue for a Separation (Sp) of 1 Depth Plane (Image Quality Rating)

Source	*df*	*MS*	*F*	*p*
L*Sz (D Absent, 1 depth plane Sp)	1	0.5352	1.10	.2987
L*Sz (D Present, 1 depth plane Sp)	1	2.5352	5.23	.0259
L*Sz*D*Sp*Sub	57	0.4847		

TABLE N-23

Results of Simple-Effect F-Tests on Luminance by Size Interaction (L*Sz) for Each Value of Disparity (D) Cue for a Separation (Sp) of 2 Depth Planes (Image Quality Rating)

Source	*df*	*MS*	*F*	*p*
L*Sz (D Absent, 2 depth planes Sp)	1	25.7852	53.20	< .0001
L*Sz (D Present, 2 depth planes Sp)	1	0.5042	1.04	.3121
L*Sz*D*Sp*Sub	57	0.4847		

TABLE N-24

Results of Simple-Effect F-Tests on Luminance by Size Interaction (L*Sz) for Each Value of Disparity (D) Cue for a Separation (Sp) of 3 Depth Planes (Image Quality Rating)

Source	*df*	*MS*	*F*	*p*
L*Sz (D Absent, 3 depth planes Sp)	1	98.3894	202.99	< .0001
L*Sz (D Present, 3 depth planes Sp)	1	1.7796	3.67	.0604
L*Sz*D*Sp*Sub	57	0.4847		

TABLE N-25

Results of Simple-Effect F-Tests on Luminance by Size Interaction (L*Sz) for Each Value of Disparity (D) Cue for a Separation (Sp) of 4 Depth Planes (Image Quality Rating)

Source	*df*	*MS*	*F*	*p*
L*Sz (D Absent, 4 depth planes Sp)	1	135.0000	278.52	< .0001
L*Sz (D Present, 4 depth planes Sp)	1	0.0042	0.01	.9207
L*Sz*D*Sp*Sub	57	0.4847		

TABLE N-26

Results of Simple-Effect F-Tests on Luminance (L) for Each Value of Size (Sz) Cue with Disparity (D) Cue and a Separation (Sp) of 1 Depth Plane (Image Quality Rating)

Source	*df*	*MS*	*F*	*p*
L (Sz Absent, D Present, 1 depth plane Sp)	1	0.0009	0.01	.9207
L (Sz Present, D Present, 1 depth plane Sp)	1	5.2083	10.75	.0018
L*Sz*D*Sp*Sub	57	0.4847		

TABLE N-27

Results of Simple-Effect F-Tests on Luminance (L) for Each Value of Size (Sz) Cue with No Disparity (D) Cue and a Separation (Sp) of 2 Depth Planes (Image Quality Rating)

Source	*df*	*MS*	*F*	*p*
L (Sz Absent, D Absent, 2 depth planes Sp)	1	140.1120	289.07	< .0001
L (Sz Present, D Absent, 2 depth planes Sp)	1	21.6750	44.71	< .0001
L*Sz*D*Sp*Sub	57	0.4847		

TABLE N-28

Results of Simple-Effect F-Tests on Luminance (L) for Each Value of Size (Sz) Cue with No Disparity (D) Cue and a Separation (Sp) of 3 Depth Planes (Image Quality Rating)

Source	*df*	*MS*	*F*	*p*
L (Sz Absent, D Absent, 3 depth planes Sp)	1	299.7787	618.48	< .0001
L (Sz Present, D Absent, 3 depth planes Sp)	1	10.8000	22.28	< .0001
L*Sz*D*Sp*Sub	57	0.4847		

TABLE N-29

Results of Simple-Effect F-Tests on Luminance (L) for Each Value of Size (Sz) Cue with No Disparity (D) Cue and a Separation (Sp) of 4 Depth Planes (Image Quality Rating)

Source	*df*	*MS*	*F*	*p*
L (Sz Absent, D Absent, 4 depth planes Sp)	1	411.9343	849.87	< .0001
L (Sz Present, D Absent, 4 depth planes Sp)	1	14.9343	30.81	< .0001
L*Sz*D*Sp*Sub	57	0.4847		

TABLE N-30

Results of Newman-Keuls Test on Mean Questionnaire Cue Ratings *

Questionnaire Item:	2(a) Luminance	2(b) Size	2(c) Disparity
Mean Value:	6.55	7.25	8.70
	———	———	
		———	———

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* Means with a common line do not differ significantly at $p \leq .05$

Vita

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Personal History

Birthdate: October 8, 1961
Birthplace: Golden Valley, Minnesota
Residence: 36 D Terrace View Apartments
Blacksburg, Virginia 24060
Marital Status: Married

Education

April, 1987- May, 1990	Ph.D. Department of Industrial Engineering and Operations Research Human Factors Engineering Option Virginia Polytechnic Institute and State University
October, 1986- March, 1987	Department of Psychology Virginia Polytechnic Institute and State University
September, 1981- May, 1985	Bachelor of Arts, Psychology Augsburg College Minneapolis, Minnesota

Experience

April, 1987 - Present **Graduate Research Assistant**

Displays and Controls Laboratory
Department of Industrial Engineering and Operations Research
Virginia Polytechnic Institute and State University
Blacksburg

Experience: Design and execution of human factors research with human subjects; spatial and temporal characterization of visual displays; investigation of field-sequential stereoscopic CRT display, conceptual display technologies, mental workload, and working memory; display interface design, prototyping and usability testing; extensive experience with review and summary of research literature; data analysis including use of IBM 3090-300 computer, SAS statistical package, and microcomputer-based analytic tools; oral and written presentation of research findings to staff and outside contractors; computer programming experience including "C," PASCAL, BASIC, and HyperCard.

January, 1987 - March, 1987 **Graduate Teaching Assistant**

Human Perception Laboratory
Department of Psychology
Virginia Polytechnic Institute and State University
Blacksburg

Experience: Supervision of laboratory course topics including elementary statistical hypothesis testing, psychophysical methodology, auditory perception, and analysis of visual illusions; supervision of student projects; evaluation of laboratory reports; assessment of student progress.

October, 1986 - December, 1986 **Graduate Teaching Assistant**

General Psychology Discussion Section
Department of Psychology
Virginia Polytechnic Institute and State University
Blacksburg

Experience: Presentation and leadership in class discussion of material relevant to introductory psychology, such as research methodology, learning, perception, motivation, and memory; leadership of class review sessions; assignment of course grades.

September, 1985 - September, 1986 **Youth Counselor**

Plymouth Christian Youth Center
Wilderness Canoe Base
Grand Marais, Minnesota

Experience: Leadership of retreat groups including runaway adolescents and mentally retarded adults; skills training in winter survival, canoeing, backpacking, rock climbing, etc.; direction of small group team building exercises; American Red Cross certification in Basic First Aid, CPR, and Water Safety (lifesaving).

June, 1984 - August, 1985 **Research Associate**

Honeywell, Inc.
Technology Strategy Center
Golden Valley, Minnesota

Experience: Control room design review of the Prarie Island and Monticello nuclear power facilities; human computer hardware and software interface development in CRT cursor control; research addressing alphanumeric keyboard assignment for the Multi-Position Letter Sorting Machine (MPLSM) conducted for the United States Postal Service; display prototyping with the Florida Graphics Computer.

January, 1984 - May, 1984 **Independent Research**

Department of Psychology
Augsburg College
Minneapolis, Minnesota

Experience: Independent investigation of microcomputer-based simulation of human control systems; self-direction of Psychology Honors Thesis: Control systems analysis of computer pointing devices; use of MINITAB and SPSS statistical packages.

October, 1983 - December, 1983 **Research Assistant**

Department of Psychology
University of Minnesota
Minneapolis

Experience: Animal learning investigation of memory-expectancy and specificity of inhibition theories; operation of mainframe-controlled animal testing chambers; use of SUPERSKED Process Control/ State Notation interface language; collection and recording of data; handling of laboratory animals.

Honors and Professional Affiliations

Alpha Pi Mu, Industrial Engineering Honor Society
Departmental Representative for College of Engineering Master's Research Award Committee, 1989-1990
Ergonomics Society, Student member
Human Factors Society, Student member
Phi Kappa Phi, Honor Society
Pi Gamma Mu, National Social Sciences Honor Society
President, VPI&SU Student Chapter of the Human Factors Society, 1989
Psychology Honors Graduate, Augsburg College
Sigma Xi, Student Member
Society for Information Display, Student member
Society of Photo-Optical Instrumentation Engineers, Student member

Publications

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