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Limits of focused attention in three-dimensional space

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The present experiment examined the shape of the attentional gradient in three-dimensional space. Subjects performed a response-compatibility task in which they were instructed to respond to a centrally located target and ignore flanking distractors. The irrelevant distractors were presented at combinations of seven different depths, three different horizontal separations, and three different vertical separations relative to the target. Depth was varied in a stereoscopic display viewed through polarized glasses. Overall, the size of the response-compatibility effect decreased with increased separation in all three dimensions. Interestingly, the response-compatibility effect was larger for horizontal separations than for vertical separations and was larger for crossed disparities than for uncrossed disparities. The results suggest an elliptical focus of attention, with steeper gradients in the vertical dimensions than in the horizontal dimensions. In addition, the results suggest, along the vertical dimension, a steeper gradient for objects located beyond the focus of attention relative to that for objects located between the observer and the focus of attention.

Over the past two decades, there has been considerable interest in the dynamics of visual attention. An important focus of this body of research has been the relation between the size of the attentional focus and processing efficiency. For example, models based on a spotlight analogy have argued that stimuli that fall within the beam of the spotlight receive full processing, whereas stimuli that are located outside of the boundaries of the spotlight are ignored (Broadbent, 1982; Posner, Snyder, & Davidson, 1980; Shulman, Remington, & McLean, 1979). Within these models, the requirement to process information at different locations in the visual field necessitates movement of the spotlight.

Although the spotlight models provide a reasonable account of results obtained in spatial priming, focused attention, and dual-task studies (Bashinski & Bararach, 1980; B. A. Eriksen & C. W. Eriksen, 1974; Hoffman & Nelson, 1981), they cannot easily accommodate findings that suggest that efficient processing can occur over either a narrow or a wide area of the visual field. For example, LaBerge (1983; LaBerge & Brown, 1986; see also Jonides, 1983) found that the size of the attentional focus could be varied by using a single letter or a word to precue different size regions of the visual field. Similarly, other researchers have found that attention could be directed to either small or large areas of the visual field on the basis of cues such as color, contour, and proximity (Harms & Bundesen, 1983; Humphreys, 1981; Kramer & Jacobson, 1991; Pomerantz & Schwaitzberg, 1975).

Two related models have been proposed to accommodate these findings. C. W. Eriksen and St. James (1986; C. W. Eriksen & Yeh, 1985) argued that a zoom lens provides an apt analogy for the dynamic nature of attention in the visual field. Within the zoom-lens model, attention can be dynamically allocated along a continuum from a tightly focused area to a widely distributed area. The resolution of the attentional system is inversely related to the width of the attentional focus. Thus, while relatively easy discriminations can be made with a diffuse focus of attention, difficult discriminations require a concentrated beam of attention.

Gradient models are similar to the zoom-lens model in that they argue that processing efficiency varies over the visual field (Downing & Pinker, 1985; Hughes & Zimba, 1985; LaBerge & Brown, 1989). However, rather than shifting the focus from narrowly to widely distributed areas, gradient models suggest that processing efficiency declines in a continuous fashion from the center to the periphery of the attentional field. LaBerge and Brown (1989) have suggested that the shape of the attentional gradient is determined on the basis of information concerning the size and probable location of an expected object.

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Thus, the attentional gradient will be narrowly focused if the expected target is small and its location is precisely known. On the other hand, the gradient will be wide when the target location is not well defined.

Although at first glance it may appear that these two models can be discriminated on the basis of empirical data, two proposals—one concerning the zoom-lens model and the second concerning the gradient model—make it difficult to distinguish between these concepts of attention. C. W. Eriksen and St. James (1986), in their description of the zoom-lens model, have suggested that "the edge of the attentional focus is not a discontinuity, but is rather a graded drop-off in processing resources corresponding to William James's conception of a focus, a margin, and a fringe" (p. 233). Thus, even the zoom lens incorporates a gradient of processing. The fact that both classes of models incorporate the notion of a gradient makes it difficult to contrast the models, at least with regard to the selective processing of a subset of items in the visual field.

While the theory and data described above suggest that there is some consensus about the important properties of visual attention, it is important to note that our knowledge about attention is, for the most part, based on studies that have been conducted within a two-dimensional (2-D) world. Relatively little research has been conducted to examine how attention is distributed in 3-D space.

One exception is a study reported by Downing and Pinker (1985), who employed the valid/invalid cuing procedure popularized by Posner et al. (1980). The subjects' task was to respond whenever they detected a light flash at one of eight locations. The lights were arranged in two rows in depth, with the subject's fixation directed between the rows. Shortly prior to the flash, subjects were cued to shift their attention to one location. On 80% of the trials, the cue was valid; on 20% of the trials, the flash occurred at an uncued location. Relative to a control condition in which none of the locations were cued, attentional costs—defined as invalid reaction time (RT) minus control RT—were larger when subjects were required to shift to a different depth, relative to the same horizontal position at the same depth. Attentional costs were also greater when subjects were required to shift from near to far positions, relative to a shift from far to near positions.

A similar series of studies were reported by Gawryszewski, Riggio, Rizzolatti, and Ulmità (1987). In their first experiment, subjects responded to the occurrence of a light that could appear at either a near or a far position, relative to fixation. A valid/invalid cuing procedure was used similar to that used in the study by Downing and Pinker (1985). The RTs were greater for invalid as compared to valid cue trials, suggesting that subjects did not simultaneously attend to positions located at different depths. The valid/invalid RT differences were also significantly greater for attention shifts to a far location than to a near location. These results were interpreted in terms of a model in which attention is allocated, in a viewer-centered fashion, from the observer to the precued position in depth.

The characteristics of attention in depth have also been examined in a series of visual search studies. In one such study, Nakayama and Silverman (1986; see also Steinman, 1987) presented subjects with a stereoscopic display in which they searched for a target defined by a conjunction of disparity and motion. The RTs were relatively invariant across different distractor set sizes, suggesting that the subjects were able to restrict their attention to a single depth plane and discriminate between the target and distractors on the basis of a single feature. Thus, consistent with the spatial priming results described above, it appears that attention is distributed in a relatively restricted region in depth.

Although the spatial priming and visual search studies suggest a circumscribed distribution of attention in depth, the fact that these studies presented stimuli at only two different depths limits our knowledge of the shape of the attentional focus. This issue was addressed by Andersen (1990) in a response compatibility task in which subjects were instructed to respond to a centrally located target and ignore the surrounding distractors. On some trials, the distractors were compatible with the response of the target (e.g., identical to the target), whereas, on other trials, the distractors were incompatible with the response of the target (e.g., the distractors required a different response when they served as targets). Across trials, the distractors appeared at seven different depths: three locations between the observer and the target, the same depth as the target, and three depths farther than the target. The displays were random dot stereograms that were viewed through a stereoscopic prism viewer. The size of the interference effect (e.g., incompatible distractor minus compatible distractor RT) increased, in a monotonic fashion, with decreases in the disparity between the target and distractors. Interestingly, this interference effect was asymmetric with respect to the position of the target. Distractors that were located farther from the target (e.g., uncrossed disparity) produced a larger interference effect than did distractors located in front of the target (e.g., crossed disparity).

As a result of the asymmetric pattern of interference, Andersen (1990) suggested that depth of focus of attention might function in a manner similar to the depth of focus of a camera lens. That is, the depth of focus is narrower for near objects than it is for far objects. Andersen's finding of asymmetric depth effects is consistent, in general, with the asymmetric attention movement effects obtained in a valid/invalid cuing paradigm (Downing & Pinker, 1985; Gawryszewski et al., 1987). However, the asymmetries of the study by Andersen and of the studies by Downing and Pinker (1985) and Gawryszewski et al. (1987) are in opposite directions. Thus, while Andersen (1990) found larger interference effects for the distant distractors, suggesting a steeper gradient of attention between the observer and the attended object, Downing and Pinker (1985) and Gawryszewski et al. (1987) found greater RT costs when attention was moved from near to far than from far to near positions, suggesting a steeper gradient beyond the focus of attention in depth.

A potential explanation for the discrepancy in the sign of the asymmetric attentional effects in the valid/invalid and response compatibility studies concerns the viewing conditions employed in the studies. In the Andersen (1990) study, subjects viewed the stereo images through a prism stereoscope. Under these viewing conditions, the optical axes of the eyes are aligned in parallel and the convergence angle is zero. Without information from convergence, absolute distance might be derived from other sources of information, such as accommodation. Under the close viewing conditions used in the Andersen (1990) study, small variations in apparent distance would have a relatively large effect on the perceived size of the distractors. Thus, the size of the far distractors might have been overestimated, causing them to produce a larger interference effect than that produced by the near distractors (Watson, 1981).

In the study by Downing and Pinker (1985), subjects monocularly viewed the rows of lights. Depth cues available to the subject included texture, accomodation, and linear perspective. Since subjects in the Gawryszewski et al. (1987) study viewed the lights binocularly, convergence information was also available. Despite the availability of a variety of depth cues in these studies, it is conceivable that the differences in intensity of the lights located at the two depths might have biased the results to favor the near location (i.e., assuming that the near lights were perceived as brighter than the far lights and therefore were easier to perceive).

One of the goals of the present study was to further examine the nature of the asymmetric attentional effects. To that end, we had subjects view stereoscopic images on a computer screen through a pair of polarized glasses. Under these viewing conditions, the optical axes of the eyes converge on the display and absolute distance information can be derived. This allows for a direct derivation of the simulated relative distance between the items on the display. Furthermore, other less reliable sources of distance information (e.g., accommodation) would have little influence on the perceived absolute distance since the viewing distance in the present study was considerably greater (i.e., 140 cm) than the distance used in Andersen (i.e., 21 cm). Finally, the presentation of computer-generated stereoscopic images rather than actual objects eliminates the potential problem of changes in illumination with distance.

A second objective of the present study was to more finely map the distribution of attention in 3-D space. This is in contrast to previous studies of attention in depth that have examined vertical, horizontal, and depth axes in separate experiments (Gawryszewski et al., 1987), examined a limited range of depth with several horizontal positions (Downing & Pinker, 1985), or fixed the position of distractors in horizontal and vertical dimensions while investigating a large number of positions in depth (Andersen, 1990). In the present study, response distractors were located at seven positions in depth, three horizontal separations, and three vertical separations in an effort to provide a more extensive examination of the spatial characteristics of attention in 3-D space.

METHOD

Subjects

The subjects were 10 undergraduate students at the University of Illinois at Urbana-Champaign who were paid $4 per hour for their participation. All subjects had normal or corrected-to-normal vision and were naive as to the purpose of the study. All subjects were tested for stereoscopic vision using the Randot E test and were required to have disparity sensitivity of 20 sec of arc.

Design

Five independent variables were examined: type of target (X or O), type of distractor (compatible or incompatible), difference in disparity between the target and the distractors (−6.8, −3.4, −1.7, 0, 1.7, 3.4, and 6.8 min of arc), 2-D distractor direction (vertical or horizontal), and 2-D distractor separation (horizontal and vertical separations: 0.59° and 0.67° [close], 0.71° and 0.80° [intermediate], or 1.19° and 1.34° [far]).

Stimuli

The displays consisted of two images, alternately presented on a computer screen at 120 Hz, that were viewed through a polarized glass plate. The subjects viewed displays through a pair of polarized glasses such that one eye received one image and the other eye received the other image. The display consisted of achromatic elements displayed against a black background. The response display consisted of a target with two adjacent distractors, one on either side of it, presented either vertically or horizontally relative to the target. Trials were either compatible (distractors and target were identical) or incompatible (distractors and target were different). The position of the distractors was shifted in equal increments in both images to maintain a constant visual angle separation between the target and the distractors.

Variations in the depth positions of the distractors were produced by shifting the positions of the items relative to the target. Shifting the distractors in the nasal direction produced crossed disparity relative to the target; shifting the distractors in the temporal direction produced uncrossed disparity relative to the target. The disparity values of the distractors, relative to the target, were −6.8, −3.4, −1.7, 0, 1.7, 3.4, and 6.8 min of arc of disparity. Negative disparity values indicate crossed disparity; positive disparity values indicate uncrossed disparity. The disparity values used in the present study were within the range of Panum's fusion area (Schumer & Julesz, 1984).

Three types of stereoscopic displays were used on each trial: a fusion display, a precue display, and a response display (see Figure 1). The fusion display consisted of a colon ":" symbol. The dimensions of the ":" symbol were 0.44° wide horizontally × 0.51° high vertically. The precue display was either a vertical bar (0.44° high × 0.26° wide) or a horizontal bar (0.22° high × 0.51° wide). The response display consisted of a target (either an X or an O) and two distractors. The dimensions of the X and O were each 0.44° wide × 0.51° high. The distance between the subject and the monitor was 141 cm.

The duration of the precue was 50 msec. The duration of the response display was also 50 msec. The interstimulus interval between the displays was 3 msec. Thus, the total duration of each trial was 103 msec, which was below the minimum time required to initiate

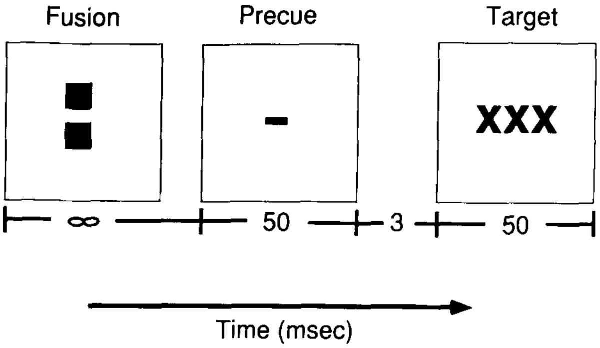

Figure 1. A schematic diagram of each trial, indicating the presentation order and duration of the fusion, precue, and response displays. The total display duration was 103 msec.

a vergence eye shift (Rashbass & Westheimer, 1961; Westheimer & Mitchell, 1969). The stimuli were presented on a Tektronix stereoscopic color monitor under the control of an IBM PC AT.

Procedure

The subjects were told to position their hands on the keyboard as if typing and to press the space bar on each trial as soon as they had a clear percept of the ":" symbol. Once the space bar was pressed, either a vertical or a horizontal bar appeared at the same location as the ":" symbol. If the subjects saw a vertical bar, they were not to respond to the target that would follow. Trials with a vertical bar precue served as catch trials and accounted for 6.6% of the total number of trials. The purpose of the catch trials was to ensure that the subjects were attending to the central position at the beginning of the stimulus presentation. The disparity value of the distractors for catch trials was equal (0 disparity) to the disparity of the target.

If the subjects saw a horizontal bar, they were to respond to the target that followed at the same location, pressing either the "z" key or the "/" key. For half of the subjects, the "z" key was used as the response for an O target, whereas the "/" key was used as the response for the "X" target. For the other half of the subjects, the response assignment was reversed. The subjects were instructed to respond as quickly as possible, but also to be as accurate as possible. They were also told that they might see other items located adjacent to the target, but that they should ignore these items.

The subjects received 40 blocks of trials over a 10-day period. The first block of trials on the first day was used for practice. Each block contained a single presentation of each display condition (2 target types × 2 distractor types × 7 disparity levels × 2 distractor directions × 3 distractor separations) and 12 catch trials (trials in which the vertical bar precued the target) for a total of 180 trials. Thus, the total number of trials over the 10-day period was 7,200 trials per subject. The catch trials consisted of 6 compatible and 6 incompatible distractor trials, with one trial for each of the close, intermediate, and far separations at vertical and horizontal locations. The subjects were given a rest halfway through each block and following the completion of each block. The subjects viewed the displays in a dark room. Trials in which the RT was less than 100 msec or exceeded 1 sec were not included and were replicated at the end of the block. Mean RT was computed for correct trials only.

RESULTS

A preliminary analysis of target type indicated no significant differences for RT or percentage of correct responses. Thus, all additional analyses were collapsed across this variable. The remaining analyses are organized in terms of mean RT and mean percentage of response errors.

Reaction Time

The mean RT for each subject for each condition was tabulated and analyzed in a four-way (type of distractor × disparity difference × 2-D distractor direction × 2-D distractor separation) analysis of variance (ANOVA). The main effect for distractor type was significant [$F(1,9) = 71.6, p < .01$], and so was that for 2-D distractor separation [$F(2,18) = 45.2, p < .01$]. Distractor type interacted significantly with 2-D distractor separation [$F(1,9) = 23.3, p < .01$], 2-D distractor direction [$F(2,18) = 14.9, p < .01$], and disparity [$F(6,54) = 2.3, p < .05$]. There were significant three-way interactions of distractor type, distractor separation, and disparity [$F(6,54) = 2.9, p < .05$] and of distractor type, distractor direction, and disparity [$F(12,108) = 2.4, p < .01$]. The four-way interaction of distractor type, distractor separation, distractor direction, and disparity was significant [$F(12,108) = 2.05, p < .05$]. There were no other significant main effects or interactions.

As shown in Figure 2, mean RT was longer for incompatible distractors (370 msec) than for compatible distractors (359 msec). The mean RTs for the close, intermediate, and far separations were 370, 364, and 361 msec, respectively. The increased RTs for incompatible trials decreased with increased horizontal, vertical, and depth separation between the distractors and the target. One interesting finding was the significant interaction between distractor type and distractor direction (see Figure 3). According to this result, there was greater overall interference (difference between RTs for the compatible and incompatible distractors) for horizontal distractors than for vertical distractors. This suggests that attention is not symmetrical in the horizontal and vertical directions. One could argue that this effect is due to the slightly different visual angle values used for the close, intermediate, and far separations for horizontal and vertical locations. However, the difference between horizontal and vertical locations at the three separations were 0.08°, 0.09°, and 0.15°. It is unlikely that these small differences could have resulted in the interaction.

A more rigorous test of this effect would be to compare the results for horizontal and vertical distractor conditions across different visual angles. Four different F ratios were calculated to examine these conditions. Two F ratios compared the close (0.67°) vertical condition with the intermediate (0.71°) horizontal condition for crossed and uncrossed disparities. The other F ratios compared the intermediate (0.80°) vertical condition with the far (1.19°) horizontal condition for crossed and uncrossed disparities. If significant differences were found for these comparisons, it would suggest horizontal distractors located at greater 2-D separations produced greater interference than did vertical distractors positioned closer to the target. The F ratios for crossed disparity conditions were nonsignificant

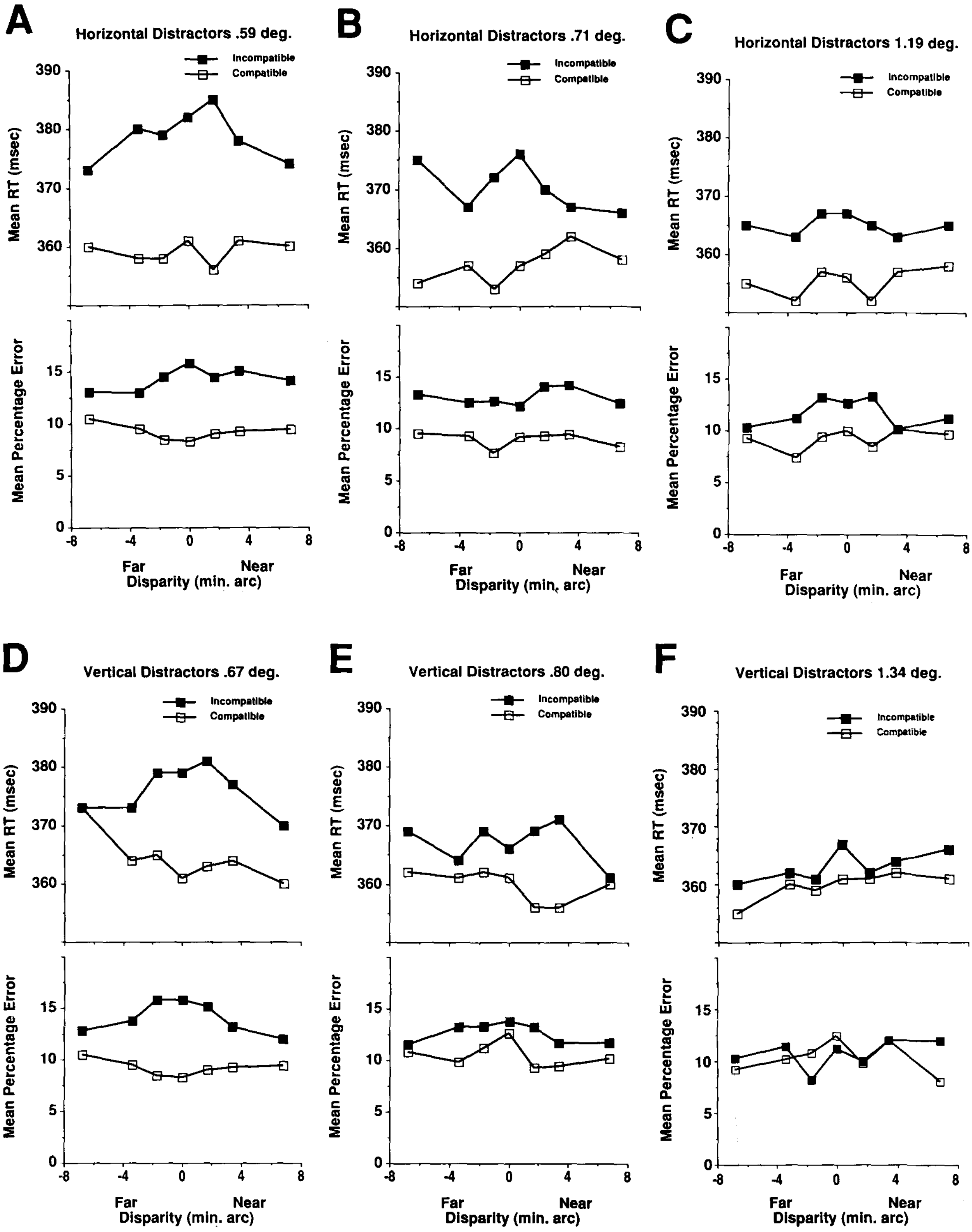

Figure 2. Effect of incompatible and compatible distractors on mean RT and mean percentage error as a function of disparity. Separate graphs are presented for horizontal distractors with 2-D spatial separations of (A) 0.59°, (B) 0.71°, and (C) 1.19°, and for vertical distractors with 2-D spatial separations of (D) 0.67°, (E) 0.80°, and (F) 1.34°. Positive and negative disparity refer to near and far distances, respectively.

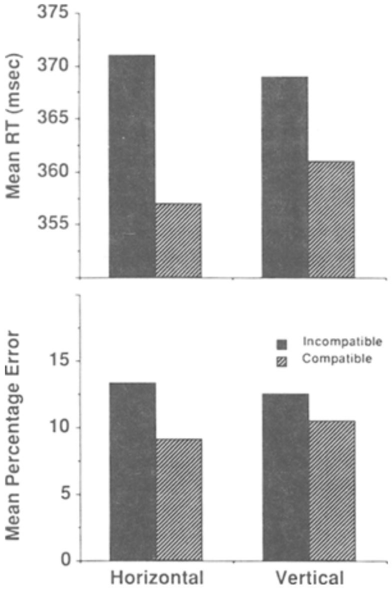

Figure 3. Effect of distractor type and distractor direction on mean RT and mean percentage error.

($p < .05$). However, a different pattern of results occurred for uncrossed disparity conditions. The comparison between close/vertical and intermediate/horizontal distractors was significant [$F(1,9) = 9.43, p < .025$]. The mean interference for the close/vertical and intermediate/horizontal conditions was 8 msec and 16.8 msec, respectively. The comparison between intermediate/vertical and far/horizontal condition approached significance [$F(1,9) = 4.51, p < .07$]. The mean interference for the intermediate/vertical and far/horizontal distractor conditions was 5.6 msec and 10.6 msec, respectively.

These results suggest that interference varied as a function of vertical, horizontal, and depth positions. In addition, the significant four-way interaction among the distractor type, distractor separation, distractor direction, and disparity variables suggests that the magnitude of interference varied for different positions along the horizontal, vertical, and depth dimensions. An important goal of the present study was to determine the change in interference for different separations between the distractors and target in the vertical, horizontal, and depth dimensions. In order to examine this issue, a series of additional analyses of partial interactions were conducted. The analyses examined contrast effects for the distractor conditions at different disparity values by subtracting the RTs for compatible and incompatible conditions as a function of disparity (see Keppel, 1991, for a discussion of contrast effects and interactions). The difference in mean RT for compatible and incompatible conditions provides a measure of the differential interference between these conditions and represents the facilitation of compatible distractors and the interference of incompatible distractors. This type of analysis was performed for each distractor direction in the horizontal and vertical dimensions.

Separate graphs of mean differential interference for different visual angles along the horizontal and vertical dimensions is presented in Figure 4. A significant effect of disparity was found for horizontal distractors at the close (0.59°) separation [$F(6,108) = 3.18, p < .05$] and intermediate (0.71°) separation [$F(6,108) = 5.02, p < .05$]. A significant effect of disparity was also found for vertical distractors at the close (0.67°) separation [$F(6,108) = 4.6, p < .05$] and intermediate (0.80°) separation [$F(6,108) = 2.97, p < .05$]. There were no significant effects found for either the horizontal-far or the vertical-far separations [$F(6,108) < 1$].

As shown in Figure 4, there was an overall decrease in the amount of interference according to the horizontal or vertical separation of the distractors. The greatest amount of interference occurred at the closest separation, with interference decreasing with an increase in the separation between the target and distractors. These results are similar to the results obtained by B. A. Eriksen and C. W. Eriksen (1974), who found a decrease in interference for increased 2-D spatial separations between distractors and targets.

Of particular interest in the present study was whether the pattern of results suggests that attention varied according to a gradient in the depth dimension for different 2-D spatial separations. In order to assess the overall interference of distractors varying in depth, a series of correlations were derived for different 2-D separations. If attention is distributed as a gradient along the depth dimension, then interference should be negatively correlated with distance. The strength of the correlations, as well as the slope of linear regression equations, should decrease with an increase in 2-D spatial separation between the target and distractors. Separate correlations and linear regression equations were derived for crossed and uncrossed disparity conditions for both distractor directions in order to determine whether interference varied for distractors located closer to or farther from the observer. The disparity values used for these analyses included the four absolute disparity values of 0, 1.7, 3.4, and 6.8 min of arc.

The results of the correlations, significance tests for the correlations, and slopes and intercepts of the regression equations are presented in Table 1. We will begin by contrasting the crossed and uncrossed disparity functions for the vertical distractor locations. As can be seen in Table 1, the correlations were significant for both the crossed and the uncrossed close distractor positions. However, the slope was substantially steeper for the uncrossed disparity. The difference in the slopes was not a function of speed-accuracy tradeoffs, since correlations between disparity values and error rates (see Table 2) were equivalent for the uncrossed and crossed disparities at the close distractor location (slopes = −.77 and −.70 for uncrossed and crossed disparities, respectively).

For the horizontal locations, the correlations were significant for the close, intermediate, and far crossed disparity conditions, as well as for the close uncrossed disparity condition. Furthermore, it can be seen in Table 1 that the slopes are more negative for the crossed horizontal

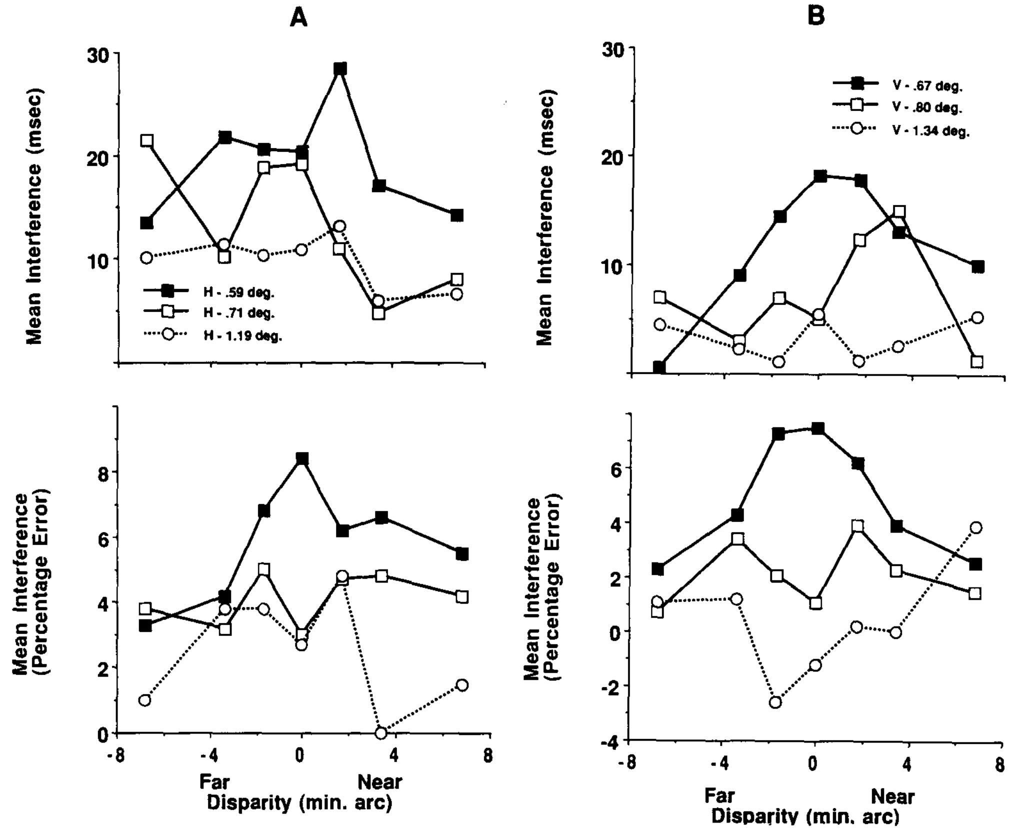

Figure 4. The differential interference (in milliseconds and percentage error) of attention as a function of the disparity value of distractors. Separate graphs are presented for horizontal (H) and vertical (V) distractor conditions at different 2-D spatial separations. Positive and negative disparity values refer to near and far distances, respectively.

location than for the uncrossed horizontal locations. At first glance, these results seem to belie our finding of a steeper attentional gradient for the uncrossed disparities at the vertical distractor locations. However, this apparent discrepancy between the gradients obtained for the horizontal and vertical locations can be resolved by an examination of the error rate data. As indicated above, the RT and error rate functions were consistent in indicating a steeper gradient (e.g., more negative slopes) for the uncrossed disparities for the vertical distractor locations. However, such is not the case with the horizontal locations. Although the RT functions suggest a steeper gradient at the crossed locations, the error rate slopes suggest a steeper gradient for the uncrossed locations. The slopes of the error rate regression functions for the uncrossed close, intermediate, and far horizontal locations

Table 1
Correlation and Linear Regression Analyses of Interference (in Milliseconds) as a Function of Distractor Location

	Horizontal Location			Vertical Location		
	Close	Intermediate	Far	Close	Intermediate	Far
		Crossed Disparity				
Mean *r*	−.65	−.70	−.70	−.95	−.34	.20
t score	2.45*	2.82*	2.8*	9.59*	1.04	0.57
Mean Slope	−1.38	−1.5	−0.83	−1.3	−0.77	0.15
Mean Intercept	24.2	15.2	11.6	18.7	10.7	3.2
		Uncrossed Disparity				
Mean *r*	−.79	.10	−.40	−.99	.22	.03
t score	3.69*	0.28	1.23	28.1	0.64	0.08
Mean Slope	−1.03	0.21	−0.01	−2.65	0.15	0.01
Mean Intercept	22.1	16.8	10.8	18.4	5.06	3.3

*Significant *t* score, $p < .05$.

Table 2
Correlation and Linear Regression Analyses of Interference (Error Rate) as a Function of Distractor Location

	Horizontal Location			Vertical Location		
	Close	Intermediate	Far	Close	Intermediate	Far
			Crossed Disparity			
Mean *r*	−.77	−.70	−.58	−.97	.08	.95
t score	2.94*	2.42*	2.12*	9.90*	0.20	7.50*
Mean Slope	−0.21	−0.26	−0.33	−0.70	0.03	0.71
Mean Intercept	7.4	3.3	3.1	6.9	2.2	−1.5
			Uncrossed Disparity			
Mean *r*	−.94	.39	−.79	−.96	−.36	.73
t score	6.77*	1.12	3.17*	8.40*	1.02	2.63*
Mean Slope	−0.84	0.02	−0.31	−0.77	−0.23	0.39
Mean Intercept	7.7	3.3	3.3	7.2	1.9	−1.8

*Significant *t* score, $p < .05$.

were −.84, −.02, and −.31. The slopes for the crossed close, intermediate, and far horizontal locations were −.21, .26, and −.33. Thus, it would appear that the steeper RT slopes for crossed horizontal locations were due to a speed–accuracy tradeoff.

In summary, the results of the vertical distractors provide evidence that attention is asymmetrically distributed along the line of sight, as was found in previous research (Andersen, 1990; Downing & Pinker, 1985; Gawryszewski et al., 1987). However, one important difference between the present results and those obtained by Andersen (1990) is the direction of the asymmetry. In the Andersen study, greater interference was obtained for uncrossed (far) disparity conditions. The results of the present study suggest that greater interference occurred for crossed (near) disparity conditions, consistent with the results of Downing and Pinker (1985) and Gawryszewski et al. (1987). An explanation for this pattern of results is provided in the Discussion section.

Errors

The mean percentage of errors for each subject for each condition was analyzed in a four-way (distractor type × disparity × 2-D distractor direction × 2-D distractor separation) ANOVA. The main effect for distractor type was significant [$F(1,9) = 28.8, p < .01$]. The mean percentage of errors for the compatible and incompatible distractors were 9.8 and 12.9, respectively. The main effect of 2-D distractor direction was also significant [$F(1,9) = 12.5, p < .01$], as was the main effect of disparity [$F(6,54) = 2.59, p < .05$]. As shown in Figure 2, error rates were greater for the vertical distractors than for the horizontal distractors. Error rate was greatest when distractors were located at the same distance as the target. Increasing the depth separation between the target and distractors resulted in a decrease in the error rate.

There were significant two-way interactions between distractor type and distractor separation [$F(2,18) = 11.6, p < .01$] and between distractor type and distractor direction [$F(1,9) = 11.5, p < .01$]. There were no other significant main effects or interactions.

One interesting finding was the significant interaction between distractor type and distractor direction (see Figure 3). According to this result, subjects had a greater difference in error rate (between compatible and incompatible distractor conditions) for horizontal distractors than for vertical distractors. This result provides further evidence that interference was not symmetrical along the horizontal and vertical axes.

DISCUSSION

Two related issues were investigated within the context of focused attention in depth. The first issue concerned the spatial dimensions of focused attention in 3-D space. This issue was addressed by instructing the subjects to respond to a centrally located target and ignore flanking distractors that could appear at combinations of seven different depths, three horizontal separations, and three vertical separations. The difference between RTs and error rates obtained for response-compatible and response-incompatible distractors served as the basis for evaluating the shape of the attentional focus.

Overall, our results are consistent with the notion of a gradient of attention in 3-D space (Andersen, 1990; Downing & Pinker, 1985; LaBerge & Brown, 1989).[1] The difference in RT and accuracy between response-compatible and response-incompatible trials decreased as distractors were located farther from the target. This effect was observed for the horizontal, vertical, and depth dimensions. It is interesting to note that the shape of the gradient was different in the horizontal and vertical dimensions. The response compatibility effect was significantly greater, for both RT and error rates, for distractors positioned along the horizontal dimension than for those positioned along the vertical dimension. This effect is consistent with the difference between valid and invalid cue trials for the horizontal and vertical conditions in the Gawryszewski et al. (1987) studies. The RT differences as a function of cue validity were 43 msec for the horizontal conditions and 13 msec for the vertical conditions. Thus, the results obtained in two different attention paradigms, cue validity and response compatibility, suggest that the shape of the attention gradient is elliptical, with a steeper gradient in the vertical dimension.

The second issue addressed in the present study concerned the discrepancy between the findings of asymmetries of attention along the depth axis. Investigations of attention using valid/invalid cuing paradigms have found that the reorientation of attention occurs more quickly when shifting from a distant location to a near location than when shifting from a near location to a distant location (Downing & Pinker, 1985; Gawryszewski et al., 1987). This pattern of results can be interpreted in terms of a steeper gradient beyond the focus of attention in depth. Thus, it might be assumed that attention is distributed, in a viewer-centered fashion, from the observer to fixation. Therefore, the processing of objects between the observer and fixation should be relatively easy, whereas the processing of objects beyond fixation may necessitate the redeployment of attention. It is important to note, however, that the differences in apparent illumination between near and far distractors might have been at least partially responsible for the asymmetry of cuing effects along the depth axis. Thus, it is conceivable that the brighter near lights might have been easier to perceive, thereby resulting in a faster shift from the far position to the near position than from the near position to the far position.

Contrary to the findings obtained in the valid/invalid cuing paradigm, Andersen (1990) found larger interference effects for further distractors in a focused attention paradigm. These results could be interpreted in terms of a steeper attentional gradient between the observer and fixation. However, the method used to view stereoscopic images in the Andersen (1990) study might have resulted in perceived size variations for distractors at different depths. Since subjects viewed the stereo images through a prism stereoscope, the optical axes of their eyes were aligned parallel, thereby producing a convergence angle of zero. Without convergence information, perceived absolute distance might have been determined from accommodation. Under the close viewing conditions used in the Andersen study, variations in perceived relative distance from disparity might have caused the subjects to greatly overestimate the size of the far distractors, thereby producing a larger interference effect for the far distractors than for the near distractors.

In the present study, we attempted to resolve the inconsistent findings obtained in the cue-validity and response-compatibility paradigms by instructing subjects to view stereoscopic images on a computer screen through a pair of polarized glasses. Under these viewing conditions, the optical axes of the eyes converge on the display and absolute distance can be derived. The presentation of computer-generated images rather than actual objects also eliminates the potential problem of changes in illumination across different depths.

Consistent with the results found in the cue-validity paradigm, we found larger response compatibility effects at crossed (near locations) disparities than at uncrossed (far locations) disparities. In addition, the slope relating interference to target/distractor separation in depth was significantly more negative for the uncrossed (far) disparities than for the crossed (near) disparities for the vertical distractors. The results for horizontal distractors were less clear, with a speed-accuracy tradeoff occurring across variations in disparity. The result for vertical distractors is consistent with a steeper gradient beyond the focus of attention in depth. Given these results, it would appear that the larger response compatibility effect obtained by Andersen (1990) for the uncrossed disparities may be attributed to an overestimation of the size of the far distractors.

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NOTE

1. An alternative explanation of the results is that the decrease in compatible RT minus incompatible RT with increasing target/distractor disparity can be attributed to decreases in distractor acuity. This nonattentional hypothesis was examined in an additional experiment. In this experiment, the subjects were presented with three stereoscopic displays on each trial: a fusion display, a precue display, and a response display. These displays were identical to those used in the original experiment with the following exceptions. The response display consisted of only two letters rather than three letters, as were used in the original experiment. These letters, which were either Os or Xs on any particular trial, were arrayed 0.59° (e.g., the closest horizontal separation used in the original study) to the left and the right of the fusion point. The subject's task was to press one response button if the letters were Os and another response button if the letters were Xs. Five subjects participated in a 1-h practice session and a second session in which they performed 60 trials of the letter identification task for each disparity value examined in the original experiment. If differential acuity for the distractors at the seven target/distractor disparities was responsible for the changes in compatible RT minus incompatible RT in the original study (i.e., the decreased compatible RT minus incompatible RT difference as a function of increased target/distractor disparity), we would expect increases in RT as the subjects were required to identify distractors at increasing disparities relative to the fusion point. On the other hand, if the compatible effects obtained in the original experiment were due to the restricted focus of attention, we would expect little or no change in RT or error rate at different disparity values. The data obtained in this experiment were consistent with the latter prediction. There were no significant differences in either RT or error rate as a function of the disparity of letters from the fusion point.

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Deadline for submissions to the *Bulletin of the Psychonomic Society* revised

After 1993, the Psychonomic Society will no longer be publishing the *Bulletin of the Psychonomic Society*. The Society's Publications Committee has decided that its original purpose—that of providing an outlet for quick, brief, unrefereed articles in experimental psychology at a time when publication lags were generally very long—has been fulfilled and is no longer needed.

The 1993 volume has been filled sooner than expected, and the deadline for submissions to the *Bulletin* has been revised accordingly. Manuscripts must be received by **June 30, 1993** to be considered for publication in the journal. The journal staff in Austin will make every effort to include all manuscripts received before the deadline in the final volume, but will return any manuscript received after that date to the author.

Authors who wish to submit manuscripts before the June 30 deadline should consult a recent issue of the *Bulletin* for information about publication policies.