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Attention switching in depth using random-dot autostereograms: Attention gradient asymmetries

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Random-dot autostereograms (RDASs) were used to investigate attention shifts along the sagittal plane in distractor-free tasks of high perceptual load. In three experiments using a *same/different* comparison task, the shape of the gradient over five different depths was examined and the conditions under which the gradient is and is not observed were compared. When the target set consisted of five similar objects, a robust asymmetric depth gradient was observed. When the target set consisted of two dissimilar objects, no gradient was observed. The results support a hypothesis of a viewer-centered asymmetric attention gradient in the depth plane that is dependent on perceptual or attentional load defined by target-set discriminability.

It is well established that attention can be allocated to different positions in a two-dimensional (2-D) visual field (Eriksen & St. James, 1986; LaBerge, 1983; Posner, 1980; Posner & Cohen, 1984). However, maneuvering through a three-dimensional (3-D) world also requires shifts of attention in depth. Moving toward a distant object, for example, may involve constant shifts of visual attention between objects in the immediate foreground and those in the distance.

Studies using *real* 3-D scenes have shown distance effects as well as directional asymmetries. These effects are measured as costs and benefits to validly and invalidly cued targets in a variation of the classic Posner (1980) task and suggest that attention can be allocated to different depth planes. For example, in experiments that present curved rows of lights at different depths (Downing & Pinker, 1985) or single lights aligned along the sagittal axis of the observer (Gawryszewski, Riggio, Rizzolatti, & Umiltà, 1987), responses are faster to validly cued targets and slower to invalidly cued targets. Moreover, there is an asymmetry: A faster reallocation of attention is found when observers switch attention from a far to a near (F–N) location than when they switch attention from a near to a far (N–F) location, suggesting that attention in depth operates from a body-centered awareness.

Criticisms of these studies have addressed the fact that target intensities may vary in depth in a real 3-D scene (Andersen & Kramer, 1993; Atchley, Kramer, Andersen, & Theeuwes, 1997). This may lead to behavioral differences that are based on discrimination owing to intensity rather than on differences in depth. Furthermore, the use of long cue-to-target stimulus onset asynchronies (SOAs) in these studies has prompted the criticism that reaction times (RTs) attributed to attention may also be reflecting time for accommodative and vergence eye movements (Iavecchia & Folk, 1994). Some researchers have used *simulated* 3-D stereographic displays to control for some of the variables inherent in real depth stimuli. One example of such displays are random-dot stereograms (RDSs), which eliminate monocular depth cues and allow a purer measure of depth perception owing mainly to retinal disparity (Julesz, 1964; for a review, see O'Toole & Kersten, 1992).

In traditional RDSs, two images of random dots are presented, one to each eye. The images are identical, except for a subset of the dots that define the depth object. Those dots are displaced laterally in one image relative to the other. Owing to the retinal disparity of the displaced pattern of dots, the object is perceived at a different depth than is the plane of the remaining dots. Because the images are presented separately, one to each eye, there is no need for convergence. Andersen and Kramer (1993) suggest that the lack of perception of absolute distance that is due to a lack of convergence of the eyes may produce a confound, because interpretation of object size is based on convergence as well as on retinal disparity (e.g., a large retinal disparity when the eyes are parallel would signal a large object, but the same retinal disparity when the eyes are converged would signal a smaller object; see Andersen, 1990). Andersen and Kramer dealt with this possibility by using polarized glasses to view stereoscopic images presented on a computer screen, thus providing a perceptual measure of absolute distance.

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However, not all studies have demonstrated the depth effect (e.g., Ghirardelli & Folk, 1996; Iavecchia & Folk, 1994), leading some researchers to suggest that the attentional spotlight is blind to depth. In these studies, however, the targets were easily distinguishable, and no distractors were present, which led Atchley et al. (1997) to hypothesize that the perceptual load (Lavie, 1995) was not great enough to require a precise attentional focus at the target location. In other words, in experiments with relatively low perceptual loads, a narrow attentional focus is not necessary, and as a result, attention is not reoriented between cued and target depth locations. Groups who have found attentional gradients in depth have presented distractors in their displays (Andersen, 1990; Andersen & Kramer, 1993). Presumably, the presence of distractors increases perceptual load and requires a narrower focus of attention directed to the target, thus revealing a gradient if one exists.

Atchley et al. (1997) systematically tested this hypothesis in two experiments that differed in that target-similar distractors were presented in one and not in the other. In both experiments, the participants were validly, invalidly, or neutrally cued to a potential target location by a luminance increase in one of four different locations—two at crossed disparities (near plane) and two at uncrossed disparities (far plane). Following the cue, a target appeared at one of the locations. In the first experiment, the participants had to identify the target (i.e., two line segments forming an x or a +) among feature-similar distractors (e.g., a horizontal line with a diagonal line bisecting it) occupying the other three locations. A progressive increase in RT was found as participants responded to validly cued, neutrally cued, invalidly cued same depth (ISD), and invalidly cued different depth (IDD) targets, respectively, revealing an attentional gradient in depth. In contrast, an effect of the gradient did not appear in the second experiment, which used the same targets but did not present distractors. Under these conditions, the experimenters found no effect of depth on RT. The results were interpreted as evidence for an attentional gradient in depth that is revealed with high perceptual load, which was manipulated by presenting target-similar distractors.

When the task involves visual search for a target among distractors, there is a potential problem for the interpretation that an increase in RT reflects a gradient of attention in depth. The fact that a search strategy exists may indicate that there is *attention* in depth; however, this is not the same as revealing an attentional *gradient* in depth. There is evidence to suggest that disparity information can be used as a featural cue for grouping objects perceived to be at the same depth (Theeuwes, Atchley, & Kramer, 1998). Items could be grouped on the basis of a perceived depth that is categorical (e.g., near vs. far) without implying an attentional gradient in depth, just as items could be grouped on the basis of similarities in color without implying an attentional gradient in color. For example, Holliday and Braddick (1991) demonstrated parallel processing of categorical depth information, using parallelograms that slanted toward or away from the observer. A singleton that differed from the distractors in the direction of stereoscopic slant showed a pop-out effect, demonstrating that disparity is an effective feature for preattentive processing. Other studies have also shown that in an array of distractors, disparity information can be used as a cue to select a group of objects for visual search (Nakayama & Silverman, 1986). Theeuwes et al. (1998) have suggested that there may be a parallel process that segregates spatially contiguous subsets of elements on the basis of feature similarity and that disparity is just one of the features by which this selection may occur.

In addition, a group of objects can be selected and searched before other objects on the basis of nonspatial features (Cave & Wolfe, 1990; Theeuwes, 1996; Wolfe, 1994). Information about location information in depth may not hold the same status as information about location in the x,y plane. For example, nonspatial stimulus dimensions (e.g., color) can have a greater effect on search time than does stereoscopic depth (Chau & Yeh, 1995). Items might be grouped according to their position above or below the horizontal meridian. We know that there are increased costs for shifting attention across either the horizontal or the vertical meridian (Egly & Homa, 1991; Eimer, 1997; Rizzolatti, Riggio, Dascola, & Umiltà, 1987) and that there are behavioral and electrophysiological differences for upper versus lower visual hemifield attention (Gunter, Wijers, Jackson, & Mulder, 1994).

In the Atchley et al. (1997) experiment, there were two salient and redundant features that could lead to grouping upper and lower items. The crossed (and uncrossed) disparity items were always on the same side of the horizontal meridian; therefore, items could be grouped on the basis of similarity in position above or below the fixation cross, in addition to appearing at the same categorical depth. These two features may have been enough to facilitate a guided search (Cave & Wolfe, 1990; Wolfe, 1994) that selected and searched through upper or lower items first. It is therefore unclear whether the increase in RT for IDD over ISD in the Atchley et al. experiment is due to an attentional depth gradient or to a search strategy in which participants examined same-depth locations before different-depth locations. The increase in RT would then be a result of searching through only two items in the ISD condition, versus searching through three or four items in the IDD condition, not because of the existence of an attentional depth gradient, but because the same-depth objects were grouped on the basis of 2-D location (upper or lower visual hemifield) or by categorical depth location.

We believe that Atchley et al.'s (1997) hypothesis is correct; perceptual load is an important factor for whether a depth gradient is observed. For example, Lavie (1995) demonstrated that attention is more effectively focused and distractors more efficiently ignored when the perceptual load is increased by increasing the set size of relevant items or by increasing the difficulty of the processing required in response to the target set.

We also predict that it should be possible to observe a strong influence of an attentional gradient in depth by making the task more perceptually and attentionally demanding without the use of distractors and without involving a search through multiple items. If there is a gradient of attention in depth, as there is across 2-D space, the narrowing of attention that is produced with more demanding targets should result in a narrowing of attention in depth, as well as across 2-D space, revealing the gradient and possible asymmetries in the gradient when attention must switch to a different depth plane. If attention is narrowly focused and successive depth targets are presented in a single 2-D location and if there are no distractors to examine, differences in RT could be entirely attributed to differences in depth.

In the following experiments, we do not present distractors. Perceptual or attentional load is increased by at least three factors: (1) The task involves a relatively difficult *same/different* comparison between pairs of successively presented stimuli, (2) there are five possible targets, which are highly similar and therefore difficult to discriminate, and (3) it is necessary to extract the objects embedded in visually complex, high-frequency random-dot patterns.

Our stimuli were constructed using random-dot autostereograms (RDASs; Tyler & Clarke, 1990). RDAS stimuli potentially solve the same confounds as RDSs, while at the same time avoiding the convergence problem that may result in an object-size confound. Like traditional Julesz RDSs (see Julesz, 1971), depth perception is attained by exploiting the property of retinal disparity. In RDAS, however, only a single image is necessary. The random dots are arranged in horizontal periodic patterns. An object is embedded in the image by an algorithmic manipulation of the dot periodicity representing the object. The object itself is not detectable in the 2-D arrangement of dots; thus, as with an RDS, retinal disparity is an important cue to depth. Unlike RDSs, which are presented separately to each eye, perception of depth in an RDAS requires the observer to establish a focal plane in front of or behind the display before fusing the corresponding patterns of dots represented on each retina. Once the focal plane has been established, however, repeated stimuli of the same background pattern width can be presented without requiring further vergence eye movements to reestablish the necessary focal plane. Using RDASs, target intensity and eccentricity can be held constant across depth planes while the convergence of the eyes at the focal plane provides a reference for absolute distance.

On the basis of previous depth studies, one might predict that RT would increase with switching distance. Furthermore, on the basis of experiments using real (Downing & Pinker, 1985; Gawryszewski et al., 1987) and stereographic (Andersen & Kramer, 1993) depth stimuli, one might expect an asymmetry in RT with respect to the direction of the attentional shift (i.e., F–N switches of attention along the depth plane will occur faster than N–F switches). However, studies reported in the literature can be categorized into those that report gradients in depth and do present distractors (Andersen, 1990; Andersen & Kramer, 1993; Atchley et al., 1997; Downing & Pinker, 1985; Gawryszewski et al., 1987; Theeuwes et al., 1998) and those that find no gradients in depth and do not present distractors (Atchley et al., 1997; Ghirardelli & Folk, 1996; Iavecchia & Folk, 1994). Therefore, the presence of distractors may very well be a critical factor for observing attentional gradients in depth. In that case, increasing the perceptual load by manipulating target discrimination alone may not result in performance differences based on stimulus depth.

Experiments 1 and 2 established that asymmetric attentional gradients are observed under our stimulus and task conditions, and Experiment 3 demonstrated that the observation of the attentional gradient is dependent on a high perceptual load, as defined by a difficult target-set discriminability.

EXPERIMENT 1
Three-Dimensional Switching With Short Stimulus Duration

Perceiving images in autostereograms requires practice. The necessary oculomotor skill is the adjustment of the focal plane. The type of learning that occurs may be partially kinesthetic, as one learns to realize and maintain the focal point in front of or behind the plane of the 2-D dot array, while maintaining accommodation appropriate for the plane of the 2-D dot array. Evidence suggests that it is a skill that improves quickly with practice and that the level of proficiency attained is very stable over time (Jewell & McBeath, 1996). Our volunteers were screened to select those who could already fuse RDASs and who had already been trained to fuse the autostereograms by diverging the eyes to a plane beyond the surface of the computer screen. Although it is possible to fuse autostereograms by either convergence or divergence, it was important to our depth-switching task that all the observers should use the same method. Whether the image is perceived via divergence or convergence dramatically changes the perception of our depth stimuli. When divergent fusion is obtained, an object appears to float in front of a background. In contrast, when convergent fusion is obtained, there appears to be a hole that describes the outline of the object cut out of a large surface, and the background can be seen through the hole. Furthermore, the meaning of near and far is reversed. When objects are presented at multiple depths (by altering disparity), the same object that appears to be farthest from the observer when perceived by divergence appears to be nearest to the observer when perceived by convergence. Our stimuli were designed to be perceived by divergence, in the sense that we intended to present objects floating in front of a background; therefore, our training consisted of divergence only. We instructed participants to use divergence and described to them what they should and should not see when successfully fusing the images; we confirmed that partici-

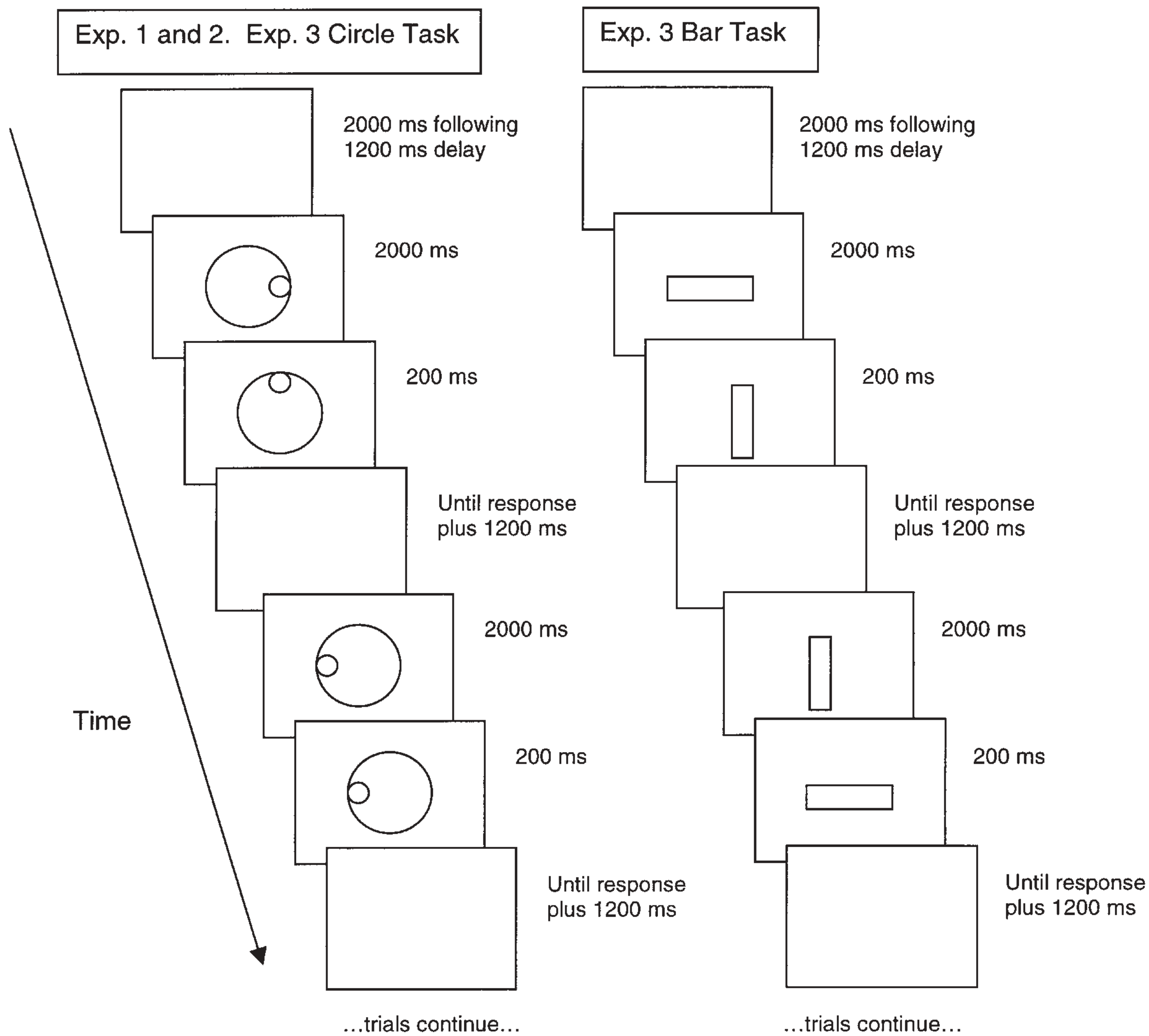

Figure 1. The time course for stimulus presentation for Experiments 1, 2, and 3 is shown, including representations of the circular objects and the bar objects as examples.

pants were diverging by asking them to report what they saw. All the participants reported perception of the objects floating in front of a background.

Our stimuli were circular disks in five possible configurations. Four of the circles had a circular gap appearing at the upper, right, lower, or left edge of the shape, and the fifth circle had no gap (see Figure 1 for examples). Each trial consisted of two sequentially presented frames, the first for a duration of 2 sec and the second for a brief duration of 200 msec. The task was to compare the circles presented in each frame to determine whether they were the same or different in terms of gap position; thus, there was a memory component linking the two frames.

For skilled observers, once the focal plane has been established, perception of depth becomes very stable, and similar stimuli can be presented repeatedly without requiring reestablishment of the focal plane. Even though we do not believe vergence eye movements contribute significantly to RT, the design of the *same/different* task ruled out that possibility entirely. The duration of the second frame was too brief for vergence eye movements to be useful, should they occur. Time is required for the initiation (160 msec) and completion (800 msec) of vergence eye movements (Rashbass & Westheimer, 1961; Westheimer & Mitchell, 1969). These same studies also report that vergence eye movements are interrupted upon early offset of a target.

Method

Participants. Six volunteers (2 males) participated in a 1-h session for $5. All the volunteers had participated in previous experiments and training sessions and were skilled at diverging their eyes to fuse the RDAS stimuli.

Stimuli. For each stimulus, the shape embedded in the autostereograms was a circle (diameter = 5.6 cm; visual angle of diam-

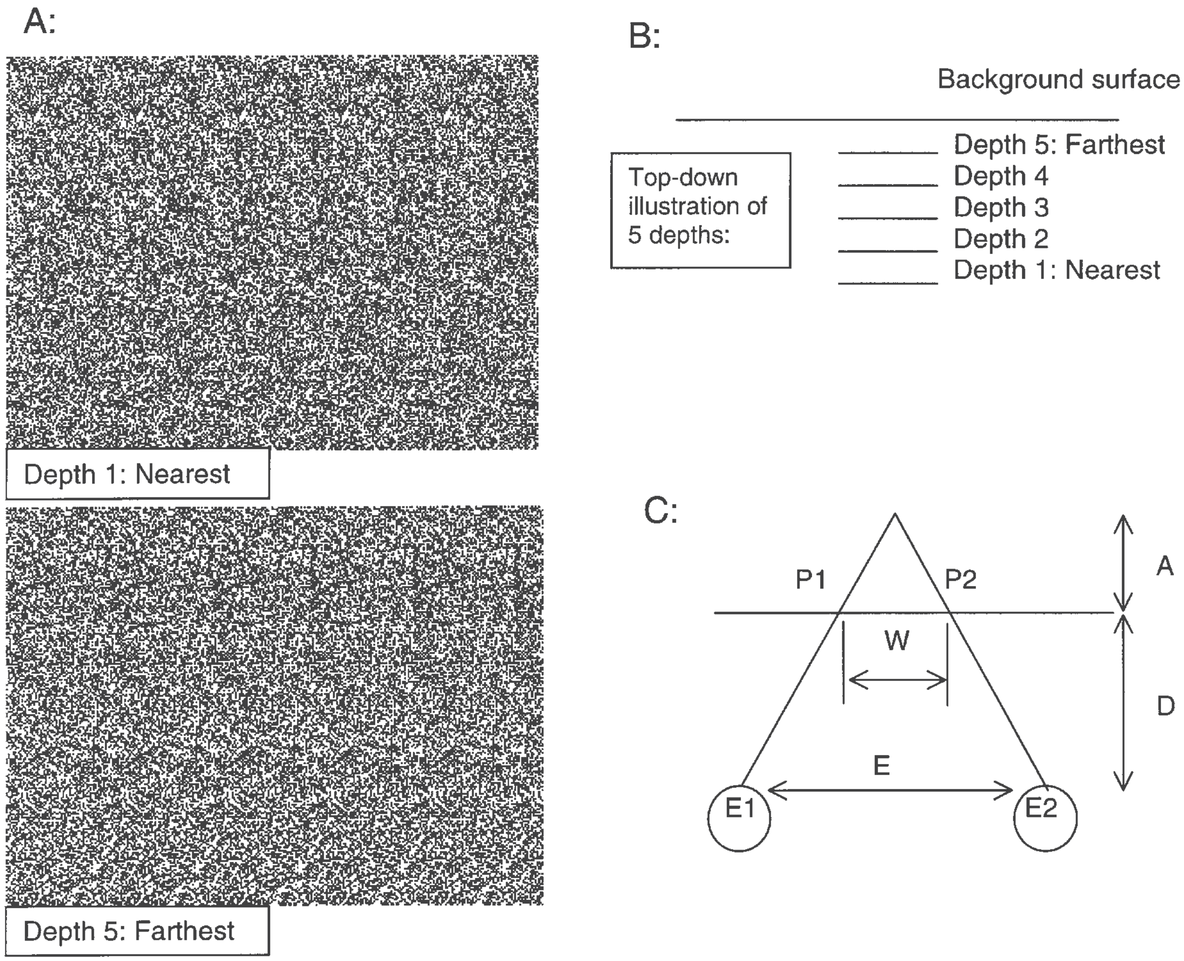

Figure 2. A: Example of a near (top) and far (bottom) circle stimulus embedded in a random-dot autostereogram. B: Circle stimuli were presented at five different apparent depths relative to the plane of the monitor. Divergence beyond the plane of the monitor resulted in the perception of a circle floating in front of a background. C: Apparent depth of each stimulus can be calculated. Distance between the monitor and the observer provides absolute distance. A = apparent depth, W = pattern width (distance between corresponding points P1 and P2), D = distance between eye and monitor (630 mm), E = distance between eyes (E1 and E2; estimate, 65 mm). A/W = (A+D)/E. Solving for A, A = DW/E-W. Apparent depth of objects beyond the plane of the monitor (with perceived distance from observer in parentheses): background = 369 mm (999 mm); farthest circle (Depth 5) = 340 mm (970 mm); far circle (Depth 4) = 314 mm (944 mm); middle circle (Depth 3) = 288 mm (918 mm); near circle (Depth 2) = 264 mm (894 mm); nearest circle (Depth 1) = 241 mm (871 mm).

eter = 5.1º) centered in the middle of the computer monitor in the center of the random-dot array. In total, five circle stimuli were created (see examples in Figures 1 and 2). Four of the five circle stimuli had a circular gap (diameter = 1.6 cm; visual angle of diameter = 1.5º) located at the inner edge (3, 6, 9, or 12 o'clock position), which appeared as a hole in the edge of the larger circle. The fifth circle did not contain a gap.

The RDAS images were computer generated directly from line drawings of the circles, using a simple algorithm (Hankinson & Hermida, 1994). For example, for each image, a random-dot field was generated with a horizontal repeating pattern width of 60 pixels, or 24 mm, displayed on a 15-in. VGA monitor at a resolution of 640 × 480 pixels. At 630 mm between the eyes and the monitor, this subtended a visual angle of 2.2º. The density of black dots on a white background was 50%. A lateral shift was applied to the dots representing the area of the circle, so that the pattern width was shortened by a specified number of pixels. The lateral shift in the dot pattern to create the five depths was 15 (6 mm; 32.7 arc min), 12 (4.8 mm; 26.2 arc min), 9 (3.6 mm; 19.6 arc min), 6 (2.4 mm; 13.1 arc min), or 3 (1.2 mm; 6.5 arc min) pixels.

Figure 2 illustrates the calculations for the perceived distance of the five different depths of the circle stimuli. The distance between the monitor and the observer provides the absolute distance (630 mm). With reference to the similar triangles in the diagram in Figure 2C, A/W = (A+D)/E, and solving for A, A = DW/E-W, where A = apparent depth, W = pattern width (distance between corresponding points P1 and P2), D = distance between eye and monitor (630 mm), and E = distance between eyes (E1 and E2; estimate, 65 mm). Thus, the apparent depths of the circle objects beyond the plane of the monitor are as follows (with perceived distance from observer in parentheses): nearest circle (Depth 1) = 241 mm (871 mm), near circle (Depth 2) = 264 mm (894 mm), middle circle

(Depth 3) = 288 mm (918 mm), far circle (Depth 4) = 314 mm (944 mm), farthest circle (Depth 5) = 340 mm (970 mm), and background = 369 mm (999 mm).

Thus, there were 25 different RDAS stimuli created (five different gap positions at five different equidistant depth planes). To minimize the contribution of learning the monocular dot patterns, three RDAS images with different random-dot patterns were generated for each of the 25 stimuli, and one was chosen randomly whenever that particular circle stimulus was presented. In the text and accompanying figures, the depth plane nearest to the observer is coded 1, and the depth plane farthest from the observer is coded 5. A single circle stimulus was presented on each frame in the center of the screen, always in the same central *x*, *y* position. Successful divergence and fusion resulted in the perception of a flat circle or disk floating above a flat background.

Procedure. After watching an instructional session, the observers were seated 630 mm from 15-in. VGA monitors. A vertically adjustable chinrest centered in front of the display served to stabilize the head at a fixed distance and ensure that eye level was even with that of the screen. The participants were instructed to maintain fixation in the middle of the screen and covertly shift attention.

The session consisted of a single practice block of 25 trials, followed by 16 test blocks of 25 trials each. Each trial consisted of two sequentially presented frames, each displaying one of the circles. Responses were made by a keypress with the right index finger if the two circles were the same in terms of gap position and with the left index finger if they were different. Hand of response was balanced across participants. The participants were also given an alternative response: If they were unable to make the judgment (e.g., owing to blinking or inability to perceive the target), they were to press the space bar. Gap position was random on Frame 1. On half the trials, the gap position on Frame 2 matched the gap position on Frame 1 (a *same* trial), and on the other half it did not (a *different* trial), in which case the gap position on Frame 2 was randomly chosen from the four remaining possibilities. The order of *same*/*different* trials was pseudorandom (maximum of four consecutive *same* or *different* responses). The depth of the circle on Frame 1 was also pseudorandom so that over all blocks, depths on Frame 1 were equally represented but the order of presentation was random. Importantly, the depth of the circle on Frame 2 was also random; thus, the direction and distance of the attentional switch on all the trials were random.

The observers initiated each block by pressing the space bar, after which there was a 1,200-msec delay (blank screen), followed by the RDAS background (no circle) for 2 sec before the trials began, allowing the observers to achieve the correct divergence prior to the first trial. Each trial consisted of Frame 1 for a duration of 2 sec, followed by Frame 2 for a duration of 200 msec, followed by the RDAS background (no circle) until response plus an additional 1,200 msec. The next trial began immediately (see the example in Figure 1). It is interesting and important to note that the fusion of the depth image is not interrupted by the change in the dot pattern. The subjective observation is that the "wall paper" pattern on the background field changes and the object floating above the background is replaced by another, but the background itself remains perceptually stable.

Feedback was provided at the end of each block, including the number of correct and incorrect responses and the mean RT for correct responses. The participants were allowed to rest as long as they wished between blocks. RT was measured as a function of the distance of the switch, as well as of the direction of the switch. For example, when switching from an object at Depth 5 (apparent depth = 970 mm) to an object at Depth 1 (apparent depth = 871 mm), the switching distance was 4 (apparent distance = 99 mm), and the direction was F–N. Thus, the data were coded in terms of five different switching distances (0, 1, 2, 3, and 4), as well as two different switching directions (N–F and F–N) for each of switching distances 1–4.

Results and Discussion

Reaction time. Only the correct responses were entered into the RT analysis. A repeated measures analysis of variance (ANOVA) of RT examined switching distance (1 through 4) × switching direction (F–N vs. N–F) × response (*same* vs. *different*), revealing a main effect of switching distance [$F(3,15) = 8.29$, $p < .001$], describing slower responses to larger switching distances (upper panel, Figure 3). There was also an interaction between switching distance and switching direction [$F(3,15) = 7.83$, $p < .01$]. For the smaller switching distances, there was no difference between N–F and F–N switching directions, but for larger switching distances, N–F switches were slower than F–N switches, evidence of the asymmetric gradient. A post hoc analysis revealed that this difference was significant only for the largest switching distance (Scheffé, $p < .01$). There was no effect of *same*/*different* response.

For a more detailed analysis of switching direction and distance, a repeated measures ANOVA examined RTs to depth level on Frame 2 (1 through 5) × previous level on Frame 1 (1 through 5), which produced significant main effects for depth level [$F(4,20) = 8.94$, $p < .001$] and previous level [$F(4,20) = 4.95$, $p < .01$] and an interaction between depth level and previous level [$F(16,80) = 5.58$, $p < .0001$; lower panel, Figure 3]. Post hoc comparisons showed that the N–F switch 1–5 was slower than 17 of the other switching conditions (1–1,2,3; 2–1,2,3; 3–1,2,3,4; 4–2,3,4; 5–2,3,4,5; Scheffé, $p < .05$).

Accuracy. Accuracy (Table 1) was analyzed with a repeated measures ANOVA of the factors switching distance (1 through 4) × switching direction (F–N vs. N–F) × response (*same* vs. *different*). There were two main effects, switching distance [$F(3,15) = 9.24$, $p < .01$] and response [$F(1,5) = 9.03$, $p < .05$], as well as an interaction between these same factors [$F(3,15) = 3.79$, $p < .05$]. Responses on *same* trials when the switching distance was 4 were less accurate than responses on *different* trials when the switching distance was 4, 3, 2, or 1 and also less accurate than on *same* trials when the switching distance was 1 (Scheffé, $p < .05$). This might reflect a tendency to respond *different* when the comparison did not lead to enough confidence to respond *same*, even though the third response option was available.

In addition to making a *same* or a *different* response, the observers were given the alternative to press the space bar if they could not reach a *same* or a *different* decision. This was rarely done, only for a proportion of .02 of total responses. Most of these were on N–F switching trials (.04); a few were on F–N switching trials (.007) or trials for which there was no switch in depth (.008). This is consistent with the asymmetric gradient hypothesis in which the N–F switches are the most difficult.

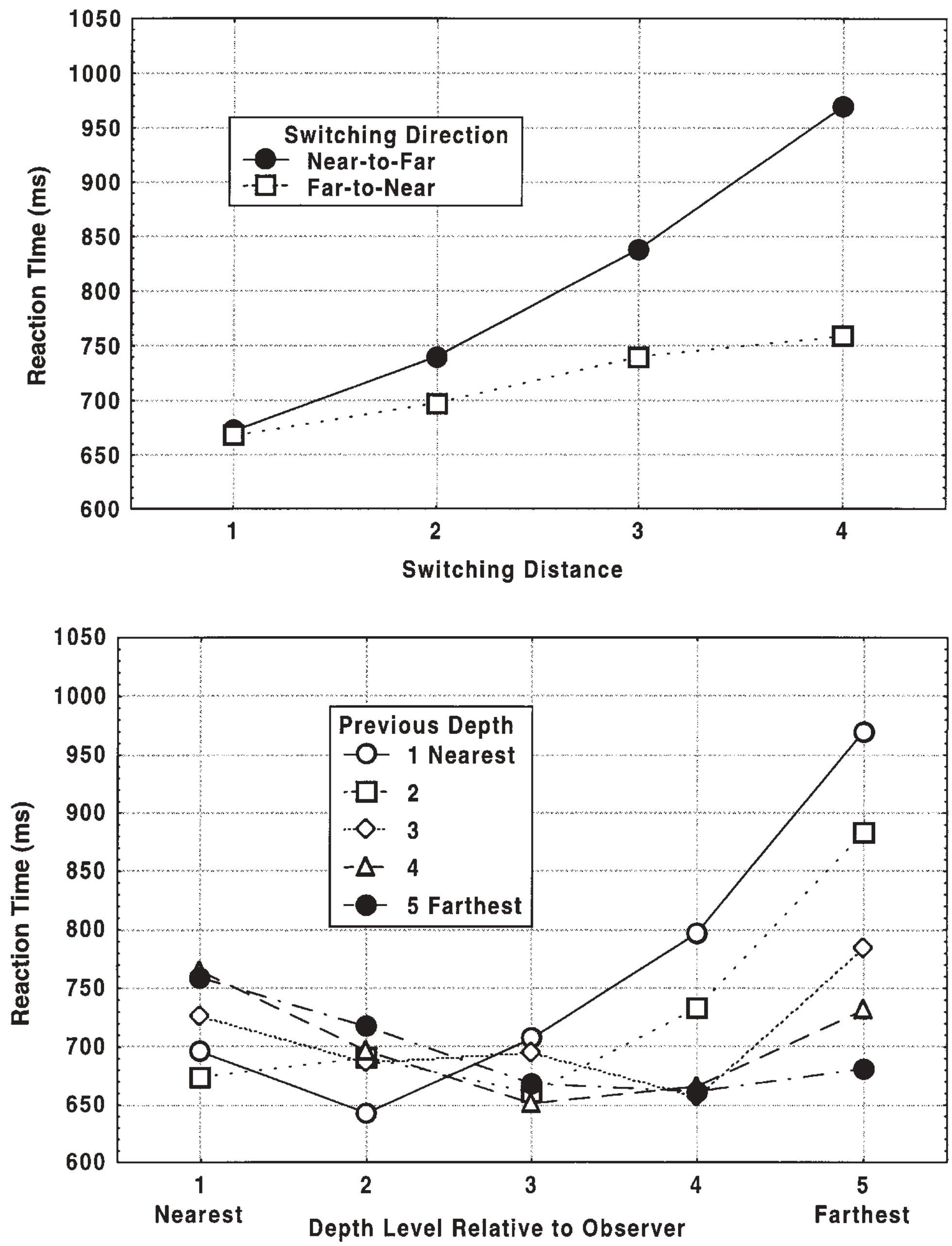

Figure 3. Experiment 1. Upper panel: Reaction time (RT) as a function of switching distance and direction. Lower panel: RT functions for all possible switching distances and directions.

It might be argued that the slower N–F switches to Depth 5 are slower simply because the farthest circle is more difficult to perceive than the other depths. However, note that responses were slowest to Depth 5 when attention was switching but that this depth actually produced the fastest responses when attention was fixed (lower graph of Figure 3). This argues against the hypothesis that the N–F effect was the result of the farthest depth level's being more difficult to perceive.

Experiment 1 clearly demonstrated an attentional gradient in depth without the use of overt distractors. The time to switch between objects increased with the distance along the depth plane. Moreover, the time to switch was asymmetric: F–N switches were faster, providing support for the viewer-centered nature of the gradient.

Despite the fact that the stimulus duration of Frame 2 was shorter than the time required for completion of vergence and accommodative responses, one might argue

Table 1
Proportion Correct and Standard Errors for Switching Direction, Switching Distance, and Response Type in Experiment 1

Switching Distance	*Same* Response				*Different* Response			
	N–F		F–N		N–F		F–N	
	M	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
1	.97	.04	.95	.07	.99	.05	.99	.05
2	.84	.12	.94	.06	.97	.09	.95	.05
3	.65	.25	.81	.21	.97	.06	.98	.05
4	.51	.40	.63	.23	.84	.16	.96	.03

Note—N–F, near–far; F–N, far–near.

that if the observer could predict the depth of the circle on Frame 2, it might be possible to begin or prepare eye movements during the 2-sec duration of Frame 1. The presentation of depth on Frame 2 was random; however, there is a potential problem in that there may have been some predictive value to Frame 1. Given that the depth of the circle on Frame 1 was far (e.g., 4 or 5), the probability was high that the circle depth on Frame 2 would be nearer (e.g., .6 or .8, respectively). It is possible that the observers might have been able to use these probabilities to prepare eye movements prior to the second stimulus onset. If these preparations were more efficient for F–N shifts than for N–F shifts, that might produce the RT functions we observed. There is a set of trials for which this is not a problem, for which the depth on Frame 1 is the middle depth. In that case, the probabilities of an N–F and an F–N switch are both .4. Although the trend was in the predicted direction for this subset of trials, we did not have the power to detect whether it was real. Experiment 2 was designed to solve this problem and rule out the hypothesis that the asymmetric gradient was due to the predictability of the direction of the attentional switch on some trials.

EXPERIMENT 2
Zero Predictability for Switching Direction

Method

Participants. Sixteen volunteers participated in a 1-h session for $5. Six of the volunteers had participated in Experiment 1 or in other experiments using the same stimuli, and the remaining 10 were trained during practice sessions to use divergence to fuse the autostereograms. Divergence was tested by presenting autostereograms with objects at multiple depths and asking the observers to report the nearest and the farthest objects.

Stimuli and Procedure. The stimuli and the procedure in Experiment 2 were identical to those in Experiment 1, except for the following. We presented only the subset of trials for which the circle depth on Frame 1 was the middle depth (Depth 3). The depth of the circle on Frame 2 was random, with a probability of .2 for any one of the five depths on any particular trial. Thus, there was nothing about the stimulus in Frame 1 that would motivate anticipatory eye movements.

Results and Discussion

Reaction time. A repeated measures ANOVA of RT examined switching distance (1 vs. 2) × switching direction (F–N vs. N–F) × response (*same* vs. *different*), revealing a main effect of switching distance [$F(1,15) = 8.3$, $p < .05$] and a main effect of switching direction [$F(1,15) = 9.8$, $p < .01$]. RT was greater for the longer switching distance and greater for the N–F switching direction. The interaction was not significant, and no differences were observed owing to *same/different* responses. Figure 4 illustrates the pattern of effects.

Accuracy. The repeated measures ANOVA for accuracy tested the same three factors, producing three main effects and all significant interactions: switching distance [$F(1,15) = 63.4$, $p < .001$], switching direction [$F(1,15) = 22.5$, $p < .001$], response [$F(1,15) = 41.3$, $p < .001$], response × switching distance [$F(1,15) = 46.9$, $p < .001$], response × switching direction [$F(1,15) = 15.9$, $p < .001$], switching distance × direction [$F(1,15) = 31.2$, $p < .001$], and response × switching distance × switching direction [$F(1,15) = 15.5$, $p < .001$]. The means for these cells can be found in Table 2. In general, the pattern is that the poorest accuracy occurred for the longer switching distance, for the *same* responses, and for the N–F switching direction.

These results confirm that the gradients observed in Experiment 1 cannot be fully explained by eye movements. Here, the N–F and the F–N switching directions are equally likely; yet, we still observe a strong effect of switching distance (responses are slower with increasing distance in both directions) and a strong effect of switching direction (N–F switches are slower than F–N switches), consistent with a viewer-centered attentional gradient.

EXPERIMENT 3
Low Versus High Perceptual Load

Having demonstrated a robust and asymmetric attentional gradient in depth and having shown that the contribution of eye movements is negligible, the next question was whether we could use the same procedure to demonstrate conditions under which the attentional gradient is not observed. We had not used distractors in our stimulus displays, believing that this removed a possible confound in which searching through distractors at the current depth contributed to the time to detect a target at another depth. Our task and stimuli carried a high perceptual load because of low perceptual discrimination

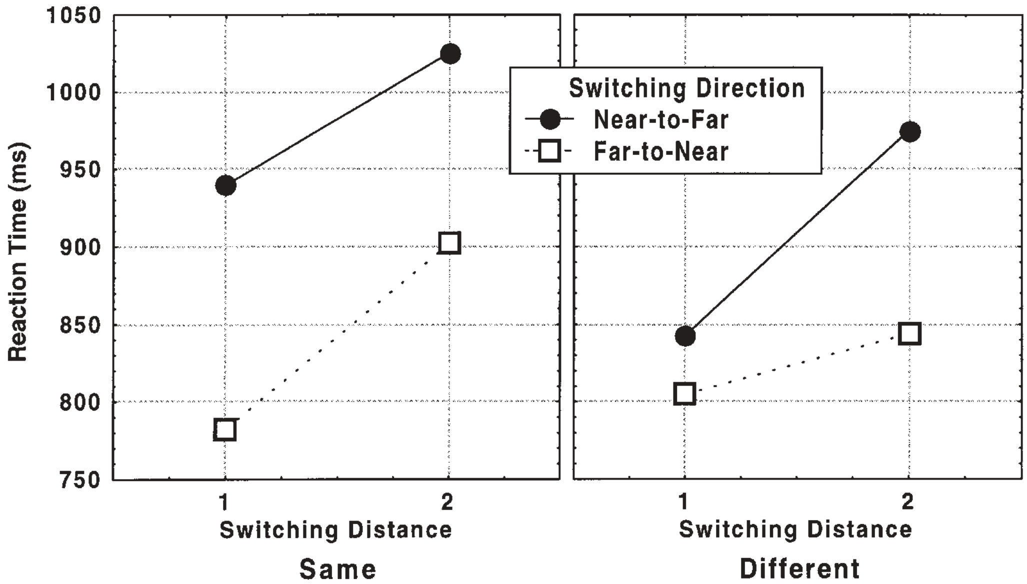

Figure 4. Experiment 2: Reaction time as a function of switching distance and direction, comparing *same* and *different* responses. The distance and direction of the attentional switch were not predictable.

between the five possible circle targets, the relatively "noisy" random-dot display, and the necessity to extract the object from the RDAS. If we could show that no gradient is observed when fewer and more discriminable targets are used, we would be more confident that the gradient observed was due to attention switching in depth. The hypothesis is that, given a very simple target discrimination, it would not be necessary to narrow the attentional focus to determine which target was presented. Thus, attention switching in depth would not occur, and the RT to detect an N–F target would not differ from the RT to detect an F–N target.

Experiment 3 replicated the stimuli and procedure of Experiment 2 exactly and added another session for which the procedure was the same but the stimuli were fewer (2 bars) and more easily discriminable (vertical vs. horizontal orientation).

Method

Participants. Eight volunteers (3 males) participated in two 1-h sessions. All 8 of the volunteers had been participants in at least two previous experiments, had extensive practice with the circle stimuli, and were highly trained to use divergence to fuse the autostereograms. All the volunteers had normal or corrected-to-normal vision.

Stimuli. There were two tasks presented in two different sessions, which we will call the circle task and the bar task. In the circle task, the five circle stimuli were identical to those described for Experiments 1 and 2. In the bar task, however, the stimuli were different. In contrast to the five circles, perceptual load was greatly reduced in the bar task by using only two stimuli that were highly discriminable, a vertical bar and a horizontal bar. We assert that the circle task has the higher perceptual load of the two tasks, because it has a larger number of possible targets and the five possibilities are very similar, whereas the bar task has only two possible targets and perceptually they are very dissimilar.

The bar task stimuli are described as follows. The horizontal bar subtended 5.6º × 1.18º and the vertical bar subtended 1.18º × 5.6º (width × height). The bars were presented at the center of the computer screen so that the center of a bar in the bar task was presented at the same position as the center of a circle in the circle task (see Figure 1 for approximate examples). As was the case for the circle stimuli, each bar image had a random-dot field generated with a horizontal repeating pattern width of 60 pixels, or 24 mm, displayed on a 15-in. VGA monitor at a resolution of 640 × 480 pixels. At

Table 2
Proportion Correct and Standard Errors for Switching Direction, Switching Distance, and Response Type in Experiment 2

Switching Distance	*Same* Response N–F *M*	*Same* Response N–F *SE*	*Same* Response F–N *M*	*Same* Response F–N *SE*	*Different* Response N–F *M*	*Different* Response N–F *SE*	*Different* Response F–N *M*	*Different* Response F–N *SE*
1	.93	.04	.98	.05	.95	.05	.98	.06
2	.50	.22	.90	.06	.84	.14	.98	.06

Note—N–F, near–far; F–N, far–near.

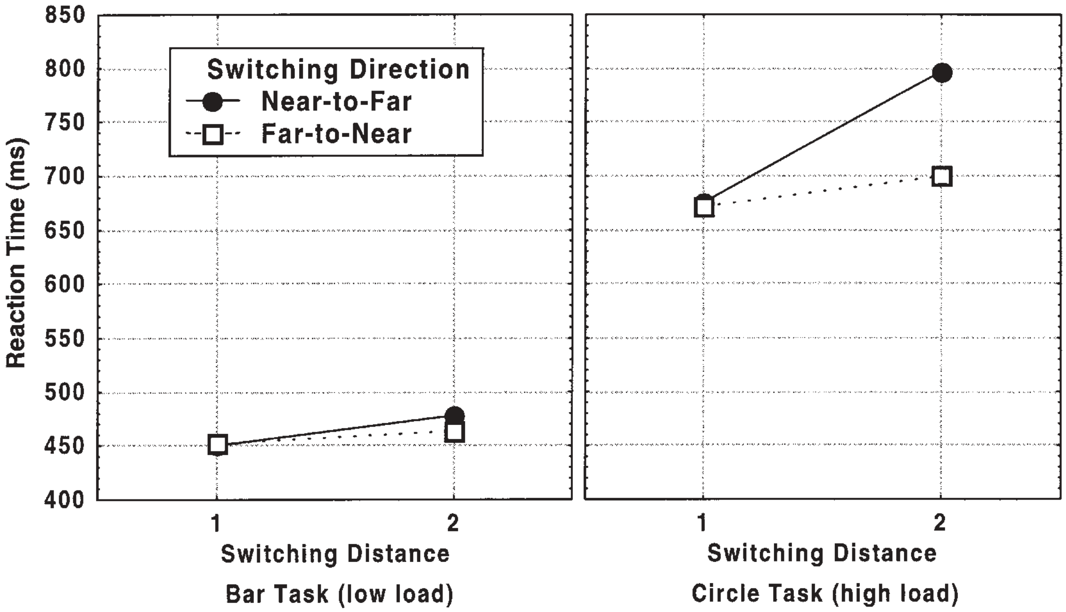

Figure 5. Experiment 3: Reaction time as a function of switching distance and direction, comparing low (bar task) and high (circle task) perceptual load (*same*/*different* responses are averaged together). The circle task replicates the results of Experiment 2, showing a robust asymmetric attentional gradient in depth. In contrast, the bar task shows no indication of the gradient in depth (refer also to Tables 3 and 4 for means and standard errors).

630 mm between the eyes and the monitor, this subtended a visual angle of 2.2º. The density of black dots on a white background was 50%. The bar stimuli were generated at five different depths, using the same procedure to generate the circles as that described in the Method section for Experiment 1. Thus, the perceived distance of the five different depths was identical to that of the circles, calculated as described in Figure 1. Specifically, the lateral shift in the dot pattern to create the five depths for the horizontal and vertical bars was 15 (6 mm; 32.7 arc min), 12 (4.8 mm; 26.2 arc min), 9 (3.6 mm; 19.6 arc min), 6 (2.4 mm; 13.1 arc min), or 3 (1.2 mm; 6.5 arc min) pixels. The distance between the observer and the computer screen was 630 mm; therefore, the perceived distance from the observer for each of the depths was 871, 894, 918, 944, and 970 mm for the bars and 999 mm for the background surface (calculations shown in the Method section of Experiment 1). There were 10 RDAS bar stimuli (two orientations at five different equidistant depth planes), each generated three times to produce three different dot patterns, as was also done for the circle stimuli.

Procedure. The procedure in both tasks was identical to that described in Experiment 2. For both the bar and the circle tasks, there was 1 practice block of 25 trials, followed by 16 test blocks of 25 trials each. Each trial consisted of two sequentially presented stimuli, and the task was to indicate whether the second stimulus matched the first stimulus (see Figure 1 for examples of the time course). In the bar task (or the circle task), responses were made by a keypress with the right index finger if the two bars (or circles) were the same in terms of orientation (or gap position) or by the left index finger if they were different. Hand of response was balanced across participants. Bar orientation (or gap position) was random on Frame 1. On half the trials, the stimulus on Frame 2 matched the stimulus on Frame 1 (a *same* trial), and on the other half it did not (a *different* trial). The order of *same*/*different* trials was pseudorandom (maximum of four consecutive *same* or *different* responses).

As in Experiment 2, to eliminate any motivation for anticipatory eye movements, we presented only the subset of trials for which the stimulus depth on Frame 1 was the middle depth (Depth 3). The depth of the stimulus on Frame 2 was random, with a probability of .2 for any one of the five depths on any particular trial. Thus, there was nothing about the stimulus in Frame 1 that would motivate anticipatory eye movements. Because all the participants had several hours of practice with the circle stimuli in previous experiments, an extra session of practice was provided with the bar stimuli prior to the bar task session. The practice session was identical to the test session.

The observers initiated each block by pressing the space bar, after which there was a 1,200-msec delay (blank screen), followed by the RDAS background (no stimulus) for 2 sec before the trials began, allowing the observers to achieve the correct divergence prior to the first trial. Each trial consisted of Frame 1 for a duration of 2 sec, followed by Frame 2 for a duration of 200 msec, followed by the RDAS background (no stimulus) until response plus an additional 1,200 msec. The next trial began immediately (see an example of the time course in Figure 1).

To underscore the similarity between the bar and the circle stimuli, both were identical in terms of density of dots, pattern width, and perceived distance of the five depths, as well as in terms of the procedure and the *same*/*different* comparison task performed by the volunteers. We hypothesized that the bar task carried a lower perceptual load than the circle task, in terms of both number of possible targets (2 vs. 5) and target similarity. The difference between the vertical and the horizontal bars was more discriminable than the difference between the five gap positions of the circles. In other words, the orientation of the bars was easier to distinguish than the position of the gap in the circles.

Results and Discussion

Reaction time. A repeated measures ANOVA of RT was performed to examine task (bar vs. circle) × switching distance (1 vs. 2) × switching direction (F–N vs. N–F)

Table 3
Comparison of Mean Reaction Times (in Milliseconds; With Standard Errors) for Low (Bar Task) and High (Circle Task) Perceptual Loads in Experiment 3, With Switching Direction, Switching Distance, and Response Type as Factors

	Same Response				*Different* Response			
	N–F		F–N		N–F		F–N	
Switching Distance	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
Bar Task: Low Perceptual Load								
1	444	21	449	20	456	20	454	465
2	485	20	462	22	471	17	20	22
Circle Task: High Perceptual Load								
1	649	39	657	47	702	49	686	43
2	811	67	703	43	783	57	696	46

Note—N–F, near–far; F–N, far–near.

× response (*same* vs. *different*). Some of the effects replicated previous results. For example, there was a main effect of switching direction, showing slower responses for N–F switching than for F–N switching [$F(1,7) = 11.6$, $p < .05$], and a main effect of switching distance, showing slower responses for the longer switching distance [$F(1,7) = 101.6$, $p < .001$]. An interaction between switching distance and direction showed that the slower N–F switches occurred primarily for the longer switching distance [$F(1,7) = 27.2$, $p < .01$]. Although the main effect of response type (*same*/*different*) was not significant, there was an interaction between response and switching distance, showing that *same* responses were slightly faster than *different* responses for the shorter switching distance but that this was not the case for the longer switching distance [$F(1,7) = 11.5$, $p < .05$]. A three-way interaction with task indicated that the interaction between response type and switching distance was observed only in the circle task, and not in the bar task [$F(1,7) = 8.5$, $p < .05$].

Moreover, and more important to our main point, there was a main effect of task, showing faster responses overall in the bar task [$F(1,7) = 34.4$, $p < .001$], and there were two significant interactions, between task and switching direction [$F(1,7) = 8.6$, $p < .05$] and between task and switching distance [$F(1,7) = 22.2$, $p < .01$]. These interactions indicated that the effects of switching distance and switching direction on the speed of response were observed only in the circle task, and not in the bar task.

This was further supported by the significant three-way interaction between task, switching direction, and switching distance [$F(1,7) = 10.0$, $p < .05$], which is illustrated in Figure 5 (see also Table 3). We examined this three-way interaction further, using Scheffé's post hoc comparison of means to test the difference between the means within each task. Not surprisingly, each of the four cells in the circle task was significantly different from each of the four cells in the bar task ($p < .01$). In the circle task, the mean for the cell representing the switching direction of N–F and the switching distance of 2 was significantly different from those for the other three cells ($p < .01$). None of the cells in the bar task was significantly different from the others ($p > .6$).

Accuracy. The same analysis was applied to accuracy, using a repeated measures ANOVA of the same four factors (refer to Table 4). The same three main effects occurred: the main effect of task, for which accuracy was higher in the bar task [$F(1,7) = 9.8$, $p < .05$]; the main effect of switching direction, for which accuracy was higher for F–N switches [$F(1,7) = 6.5$, $p < .05$]; and the main effect of switching distance, for which accuracy

Table 4
Comparison of Accuracy for Low and High Perceptual Loads in Experiment 3: Proportion Correct and Standard Errors for Switching Direction, Switching Distance, and Response Type

	Same Response				*Different* Response			
	N–F		F–N		N–F		F–N	
Switching Distance	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
Low Perceptual Load (Two Bars)								
1	.988	.005	.976	.010	.967	.013	.958	.009
2	.925	.024	.964	.010	.981	.006	.958	.014
High Perceptual Load (Five Circles)								
1	.975	.011	.975	.008	.963	.013	.968	.021
2	.802	.058	.942	.018	.954	.023	.960	.011

Note—N–F, near–far; F–N, far–near.

was higher for the shorter switching distance [$F(1,7) = 10.8$, $p < .05$]. Task interacted with switching direction [$F(1,7) = 11.4$, $p < .05$] and with switching distance [$F(1,7) = 5.6$, $p < .05$], and there was a three-way interaction between these factors as well [$F(1,7) = 6.6$, $p < .05$], showing that the direction and distance of the switch affected accuracy only in the circle task, and not in the bar task.

A further analysis of the three-way interaction examined the cells within each task, as was done for the RT analysis. With Scheffé's test, only one cell differed in accuracy from any of the other cells. This cell represented responses in the circle task, for which the switching direction was N–F and the switching distance was the longer of the two distances. This cell showed a poorer accuracy that was significantly different from each of the seven remaining cells ($p < .01$). None of the other comparisons reached significance ($p > .5$).

Other significant effects included an interaction between switching direction and distance [$F(1,7) = 6.6$, $p < .05$], showing poorer accuracy for N–F switching that was most apparent for the longer switching distance. There was an interaction between switching direction and response type, indicating poorer accuracy for *same* responses, but only for N–F switching [$F(1,7) = 7.5$, $p < .05$], and an interaction between switching distance and response type, showing poorer accuracy for *same* responses primarily for the longer switching distance [$F(1,7) = 8.7$, $p < .05$]. This was reinforced by a significant three-way interaction between response type, switching direction, and switching distance [$F(1,7) = 12.7$, $p < .01$], showing that accuracy for *same* responses was most affected when switching was in the N–F direction for the longer switching distance.

Essentially, we have demonstrated an asymmetric attentional gradient in depth when the perceptual load is high (circle task) and no apparent gradient when the perceptual load is low (bar task), supporting Atchley et al.'s (1997) perceptual load hypothesis. This contrast is demonstrated without presenting distractors in the high perceptual load condition, thus reducing the chance that the time to switch attention in depth includes the time to search through target-similar distractors at the cued depth, which may be grouped together on the basis of similarities of position in the visual hemifield or categorical depth. The contrast also lends support to the interpretation that the RT gradients we observed in the circle task are due to asymmetric attentional gradients in depth, rather than being an artifact of our autostereogram stimuli or eye movements.

GENERAL DISCUSSION

The results from these experiments provide evidence that (1) visual attention has a depth component, (2) RT increases with switching distance in depth, (3) the attentional gradient in depth is viewer centered, (4) distractors are not necessary to show effects of the gradient, and (5) perceptual load can account for whether an attentional gradient is observed. Furthermore, discrepant findings among different depth studies as to whether the gradient is viewer centered can be explained by (1) differences in perceptual load and (2) differences in the attentional requirements of the task.

Experiment 1 produced robust effects of an attentional gradient based entirely on the time required to identify the target presented at the attended depth versus unattended depths. The shape of this gradient is viewer centered, based on the observation that more time was required to identify a target presented at a location beyond the focus of attention than was required to identify the same target presented at a location between the focus of attention and the observer. Targets were briefly presented (200 msec), reducing the chance that vergence eye movements contributed to the RT. Experiment 2 eliminated another possible concern, that observers were able to predict the upcoming target location in depth and thus make anticipatory vergence eye movements. Experiment 3 demonstrated that the observation of the depth gradient depends on the difficulty of distinguishing between target items. This was done by comparing performance with the five perceptually similar target circles used in the first two experiments and performance with two perceptually dissimilar target bars, one vertical and one horizontal. When the targets were perceptually easy to discriminate, no effect of the attentional depth gradient was observed.

There have been various findings reported with respect to gradients and asymmetries. To understand the discrepancies, it may be useful to examine the extent to which processing is challenged in each of these studies. It is possible that perceptual or attentional load has a graded effect on the extent to which a gradient in depth is observed. In other words, as stimulus detection and identification become more difficult, observation of an attentional depth gradient become more likely.

Those studies demonstrating no effect of an attentional gradient in depth presented no distractors and used a small number of targets (Atchley et al., 1997; Ghirardelli & Folk, 1996; Iavecchia & Folk, 1994). Ghirardelli and Folk suggest that under those conditions, processing load owing to stimulus and task demands may not be great enough to require a deployment of attention in depth. In fact, error rates were less than 1% in all the conditions and 0% in more than half of the conditions (Ghirardelli & Folk, 1996). Other studies have shown an effect of attention in depth but were not designed to examine the shape of the gradient (Chau & Yeh, 1995; Nakayama & Silverman, 1986). For example, Nakayama and Silverman demonstrated that disparity can be used as a selection cue allowing parallel search for a singleton defined by conjunction of color and disparity, and Chau and Yeh reported an increase in search time as the number of depth planes increased, but they did not examine or report asymmetries.

Those studies that have shown effects of an attentional gradient in depth have increased perceptual load by presenting many distractors (Theeuwes et al., 1998), distractors that are similar perceptually to the targets (Atchley et al., 1997), or many possible distractor locations in 2-D and 3-D (Andersen, 1990; Andersen & Kramer, 1993). Most studies that do report an attentional gradient also report some form of asymmetry in the gradient, in terms of RT (Andersen, 1990; Andersen & Kramer, 1993; Downing & Pinker, 1985; Gawryszewski et al., 1987) or accuracy (Atchley et al., 1997). The direction of the asymmetry is the same for all of these studies (except for Andersen, 1990, for reasons discussed in Andersen & Kramer, 1993), with the gradient falling off more steeply beyond the focus of attention than between the focus and the observer. An exception to this group of studies is Theeuwes et al. (1998), who found a strong effect of cue validity, indicating that attention can be efficiently deployed in depth; however, they did not find evidence for a viewer-centered gradient in depth (although there was a trend in Experiment 3 for responses to far-plane targets to be more affected by distractor location; Theeuwes et al., 1998).

One explanation that they provided for the discrepancy between their findings and those that do show asymmetries in the depth gradient is that representations may be viewer centered when attention is directed to objects in depth and viewer independent when attention is spread across a whole depth plane, as it was in their task (Theeuwes et al., 1998). This explanation is consistent with our findings, in that our task involved directed attention to an object in depth and the RDAS stimuli provided an anchor for absolute distance; therefore, the object could have been represented in viewer-centered coordinates. In other words, the target object was represented in terms of where the object was relative to the observer. However, this explanation does not capture all of our results, because attention was directed to the bars in Experiment 3 in the same way as attention was directed to the circles; however, there was no evidence of an asymmetric gradient in the former.

This apparent inconsistency can be resolved by referring to the perceptual load argument. If the system is not challenged, it may not be necessary to deploy attention in depth. Distinguishing between the vertical and the horizontal bars in Experiment 3 was very easy, whereas distinguishing between the five gap positions in the circles was not easy, requiring that attention be focused more precisely at the depth plane of the circle objects. Why this should be the case may be related to the minimum amount of information needed to make a response. When the stimuli have a low degree of discriminability, it is necessary to focus attention narrowly to extract a greater amount of information by which to identify the current stimulus. Very simply, more information is needed. This is further compounded when there are a large number of possibilities. In contrast, when the stimuli are very different in shape or features and few in number, a minimum amount of perceptual information may be needed to reach a decision and make the response, and this information may be available without narrowing attention in depth.

Is it the case that functions describing attention in depth are similar to functions that describe attention in 2-D space? It has been shown that attention in a 2-D field can be defined as a gradient of processing resources; there is facilitation of information at the center of the focus of attention, which falls off with retinal distance from that focus (LaBerge & Brown, 1989). This attentional gradient can be measured as a function of interference by distracting information presented around the target position. Nakayama and Silverman (1986) suggested that attention in the third dimension could be focused on a target at a particular depth plane irrespective of the number of distractors at different depth planes. They hypothesized that retinal disparity information could be used to selectively focus attention to a specific depth plane, much as retinal location is used to attend to specific 2-D areas. However, their distractors were of a different color than that of the targets. Theeuwes et al. (1998) demonstrated that distractors at other depth planes could not be ignored when they were the same color as the targets. Distractor interference was reduced when both color and depth information guided attention to the target. This implies that objects at different depths can be tied together on the basis of nonspatial information that is similar between the objects. Chau and Yeh (1995) have also shown that the similarity of nonspatial stimulus features affects both perceptual segregation and selective attention in 3-D. It is possible that delays in processing owing to target-similar distractors might be due to the increased perceptual load's requiring a shift of a narrow focus of attention in depth. However, if targets and distractors are tied together because they have similar features, delays might involve deconvolving the items to confirm the separate location of the target. For this reason, it is interesting to demonstrate that the gradient is observed when no distractors are present.

Furthermore, the pattern of RTs to different depth objects when attention was not switching argues against the hypothesis that the farthest stimuli produced the greatest switching effects because they were more difficult to perceive. Responses were faster for the farthest, relative to the nearest, stimuli during the nonswitching trials (bottom panel, Figure 3). This suggests that the effect of the direction of the attentional shift was not due to difficulty in perceiving the farthest depth stimulus per se but can be explained by hypothesizing an attentional gradient. This is not to say that the farthest stimuli are as perceptually discriminable when attention is directed to a near plane as they are when attention is directed to the far plane. Clearly, the latter provides the best condition for detection of far stimuli.

Although it may be argued that stimuli presented at a plane other than the plane of focus may be degraded somewhat, thus introducing perceptual differences, the same is true for stimuli presented at the periphery of the visual field. Attention to locations in the retinal field is measured by comparing RT to stimuli in locations at the periphery when those locations are or are not attended upon stimulus onset. An increase in the time to respond to stimuli at unattended locations is interpreted as the time to orient attention to the location of the stimulus, independent of eye movements (Posner, Snyder, & Davidson, 1980). The same logic may be applied to attention in depth. However, the perceptual gradient owing to focus may be steeper than that described across the retinal field.

Neurophysiology provides further support for these gradient findings, distinguishing between neural mechanisms for near versus far processing. Cells in the striate cortex of the monkey can be classified as far and near neurons, tuned to relative disparities beyond or before the fixation plane (Poggio & Poggio, 1984). Moreover, cells in the monkey parietal cortex on the lateral bank of the intraparietal sulcus, which are involved in directing attention prior to saccadic and vergence eye movements, have been classified into groups that prefer near or far positions in depth (Gnadt & Mays, 1995). Neurophysiological studies on monkeys demonstrate that there are more receptors for detecting stimuli close to the body (Rizzolatti, 1983; Rizzolatti & Camarda, 1987). Furthermore, many studies indicate that specific cortical areas are excited by stimuli in peripersonal (within arm's reach) or extrapersonal space (Leinonen, Hyvarinen, Nyman, & Linnankoski, 1979; Leinonen & Nyman, 1979; Rizzolatti, Scandolara, Matelli, & Gentilucci, 1981). Studies of brain damage also indicate anatomical correlates for attention to near or far areas of the depth plane in humans (Bisiach, Perani, Vallar, & Berti, 1986; Coslett, Schwartz, Goldberg, Haas, & Perkins, 1993; Halligan & Marshall, 1991; Heilman, Chatterjee, & Doty, 1995; Vuilleumier, Valenza, Mayer, Reverdin, & Landis, 1998). It is, therefore, likely that shifts of attention in depth involve modulation of the flow of information along near and far channels in striate and extrastriate areas.

One can speculate about the function of an asymmetric attentional gradient in depth. Rapid awareness of objects moving into immediate personal space is of obvious survival benefit. When picking berries from a bush, attention shifts between clusters of berries that differ in depth, as well as across the 2-D plane. As you reach out for a particular cluster, the sudden appearance of a wasp may be more important if that wasp appears in near space (between you and the berries) than in far space (beyond the berries). Further experiments should examine whether, even within the broad categories of peripersonal and extrapersonal space, the allocation of attention can still be described in terms of near and far shifts, depending on the location of fixation within those spaces.

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