

# Focused Attention Distorts Visual Space: An Attentional Repulsion Effect

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Attention was focused at a specific location either by a briefly flashed cue (cue-induced attention) or by a voluntary effort (voluntary attention). In both cases, briefly presented probes appeared displaced away from the focus of attention. The results showed that the effect of cue-induced attention was transient whereas the effect of voluntary attention was long lasting. The repulsion effect was most evident with brief probe durations ( $<200$  ms). Control experiments ruled out nonattentional hypotheses based on classic figural aftereffects and apparent motion. Although a number of studies have demonstrated enhancements of visual perception at attended locations, the present studies show that focused attention can distort the encoding of nearby positions. Speculation is offered that the repulsion effect is one of the costs involved in the allocation of more resources to the focus of attention.

Attention is often regarded as a mechanism by which our brains selectively gate a subset of sensory stimulation into consciousness. In the visual modality, we normally attend to sensory signals coming through the central region of the retina in and around the fovea. In casual terms, we normally “see” what we are looking at. Because of the high cone density and cortical magnification factor, the fovea affords the highest sensitivity and acuity under photopic conditions. It thus makes sense that our visual systems normally gate the highest quality signals coming through the small region centered around the fovea into conscious processing. Stimuli of interest are brought into the fovea by way of saccadic and smooth-pursuit eye movements.

However, most of us can voluntarily direct attention away from the fovea and focus it at some location in the periphery. Common introspection is that voluntarily focused attention in the periphery somehow helps us see and react faster to events in the attended region. In fact, as early as in the late 19th century, Helmholtz (1896) reported enhanced contrast sensitivity at voluntarily attended locations.

The focus of attention can also be attracted to abrupt spatial-temporal discontinuities. A sudden flash of intense

light or a smudge on an otherwise immaculately finished wall just cannot help being “seen,” regardless of one’s conscious effort. A number of studies have shown that transient enhancement of processing occurs at the location to which attention has been directed by a salient stimulus.

For example, Eriksen and colleagues (Eriksen & Collins, 1969; Eriksen & Rohrbaugh, 1970) flashed a cue at the location of the target letter immediately preceding its presentation in order to “grab” attention at the target location. They found that the accuracy of the target letter identification improved as a function of the stimulus onset asynchrony (SOA) between the cue and the target letter up to  $\sim 200$  ms, and then the performance leveled off. In a follow-up study, it was shown that response time followed the same trend; response time improved during the first 200–300 ms of the cue–stimulus SOA and then leveled off (Colegate, Hoffman, & Eriksen, 1973). More recently, Nakayama and Mackeben (1989) reported that the accuracy of vernier offset discrimination also improved as a function of the cue–stimulus SOA up to about 200 ms, and then the performance declined at longer intervals. These studies indicate that visual acuity does improve at the location where a sudden flash of a cue “grabs” attention, and it takes about 200 ms for the enhancement to occur. In addition to visual acuity, Hawkins et al. (1990) showed that luminance sensitivity (in terms of  $d'$ ) was also enhanced at cued locations. They used a fixed cue–stimulus SOA of 167 ms.

Physiological studies have shown that voluntary attention modulates the response of V4, parietal, and inferior temporal (IT) visual neurons to their preferred stimuli (e.g., Bushnell, Goldberg, & Robinson, 1981; Mountcastle, Motter, Steinmetz, & Sestokas, 1987; Spitzer & Richmond, 1991). Of particular interest are those recent studies which have demonstrated that attention modulates the spatial properties of individual receptive fields in V4 (Connor, Gallant, & Van Essen, 1994; Moran & Desimone, 1985) and IT (Desimone, Wessinger, Thomas, & Schneider, 1990) cells. These find-

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ings suggest a possible neural mechanism underlying the perceptual enhancement at the focus of attention.

Moran and Desimone (1985) found that some V4 cells responded to their preferred stimuli only if the monkey attended to those stimuli. Similar behavior was subsequently found in IT cells as well (Desimone et al., 1990). The authors postulated that receptive fields shrank toward the focus of attention. More recently, Connor et al. (1994) mapped receptive fields of V4 neurons 100–200 ms following the flash of a task-relevant cue; the receptive fields did not shrink but shifted toward the cued location—the receptive fields shifted toward the focus of attention. Shrinking or migration of receptive fields toward the focus of attention could potentially give rise to enhanced visual processing through sharpening of spatial tuning or increased overlap of receptive fields. In the latter case, the signal coming through the focus of attention would be detected by an increased number of cells and would result in an increased sampling density.

Much as it might enhance visual processing, however, this type of receptive field shrinking or migration toward the focus of attention may incur a cost because of the loss of receptive field coverage in neighboring regions. The current study demonstrates that perception of position is distorted around the focus of attention in a way predicted by such a loss in the receptive field coverage adjacent to the attended location (see the General Discussion for details). Briefly presented stimuli appear displaced away from the focus of attention—the attentional repulsion effect. The use of briefly presented test stimuli is an essential component for revealing these distortion effects. The tests must be brief because spatial attention has a very strong transient component; no matter how hard one voluntarily attends to something, the sudden appearance of a new stimulus draws attention away within ~200 ms (e.g., Eriksen & Collins, 1969; Hikosaka, Miyauchi, & Shimojo, 1993a, 1993b; Nakayama & Mackeben, 1989). The onset of a test stimulus used to probe the spatial distortions due to focused attention would inevitably and quickly draw attention to itself. Thus, if one wanted to measure perceptual distortions of the test stimulus that were due to the previous allocation of attention, the measurement would have to be completed rather quickly (well under 200 ms) before attention could switch to the test stimulus.

The probe stimulus we used to demonstrate the attentional repulsion effect consisted of a vernier, two vertical lines aligned across a wide gap. Attention was focused at a given location either by a transient cue (Experiment 1) or by a voluntary effort (Experiment 4). The vernier was then flashed briefly (60 ms). The results showed that the line nearer the attentional focus was repelled, which created a vernier offset. The direction and the amount of this apparent offset were taken as a measure of the direction and the amount of the repulsion effect. As expected, the effect dropped rapidly as the vernier was exposed for a longer duration (Experiment 6).

We conducted a series of experiments to show that focused attention was indeed responsible for the repulsion effect. In Experiment 1 we demonstrated the basic effect; a

flash of a transient cue made the subsequently flashed vernier line appear displaced away from the cued location—the cue-induced repulsion effect. Two alternative hypotheses based on nonattentional effects were evaluated first. In Experiment 2 we evaluated the hypothesis that the repulsion effect might be a special case of the figural aftereffect with extremely short adaptation probed by a brief test stimulus. In Experiment 3 we evaluated the hypothesis that the repulsion effect might be due to the perception of apparent motion from the cue to the nearer vernier line. The results showed that these nonattentional effects could not account for the repulsion effect. In Experiment 4 we demonstrated that voluntarily sustained attention also produced the repulsion effect with no transient cues immediately preceding the vernier, which ruled out the involvement of image interactions. We measured the amount of the repulsion effect as a function of the SOA between the cues and the vernier in Experiment 5. If the cue-induced repulsion effect was due to involuntary attention momentarily being captured by flashed cues, the effect should have had a characteristic peak at an SOA of 100–200 ms, as is the case for the enhancement of visual acuity at the cued location (e.g., Eriksen & Collins, 1969; Eriksen & Rohrbaugh, 1970; Nakayama & Mackeben, 1989). The expected peak was obtained. Last, we varied the vernier exposure duration to find out how the repulsion effect diminished with longer viewing of the probe stimulus (Experiment 6). As discussed earlier, if the repulsion effect was due to attention, one would expect the effect to fall substantially within a 100–200 ms exposure of the vernier because by then attention would have shifted toward the vernier. The repulsion effect would then be centered around the vernier and would no longer affect the perception of the vernier offset. The repulsion effect indeed fell substantially within 100–200 ms of the vernier exposure. A point of interest was to see if we might observe the initially displaced vernier lines relaxing back to their veridical positions with longer viewing of the vernier. In Experiment 7 we demonstrated that such “recovery” motion is not visible, which suggests (a) that the repulsion effect arises beyond the point at which position information feeds into the motion processing mechanism and (b) that temporal summation (see Barlow, 1958; Cohn, 1990) operates in such a way that initially distorted representations of position are irrevocably replaced by the subsequent, more accurate, representation.

## General Method

The basic paradigm is shown in Figure 1. The observer fixated the cross at the center of the screen. A cue stimulus (circle) was flashed briefly (30 ms) in one of the quadrants (see Figure 1, second frame, on the left). After an SOA of 180 ms, a vernier stimulus was presented briefly (60 ms) along the vertical meridian,<sup>1</sup> followed by a random-dot mask. It turned out that the vernier

<sup>1</sup> Although we used a vertical vernier stimulus in all of the experiments presented in this article, a pilot study showed that repulsion effects of comparable magnitude were obtained with a horizontal vernier stimulus as well.

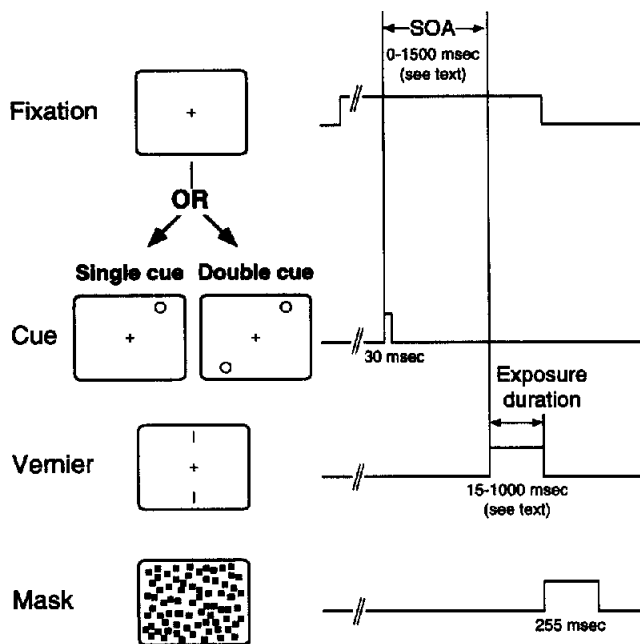


Figure 1. Trial events for Experiments 1, 5, and 6, in which the cue-induced repulsion effect was demonstrated. The left path shows the single-cue paradigm, and the right path, the double-cue paradigm (see General Method section for details). SOA = stimulus onset asynchrony.

always appeared offset away from the cue. For example, if the cue was flashed in the upper right quadrant as shown in Figure 1, the vernier would appear offset counterclockwise. This effect could be strengthened by flashing two cues in diagonally opposite quadrants (see Figure 1, 2nd frame, on the right). Six observers were formally tested as described in Experiment 1.

All stimuli were displayed on a 13-in. (33-cm) color monitor (66 Hz), and all experiments were controlled with a Macintosh IIfx computer with the software Shell & Macglib (micro ML inc., Quebec, Canada). The experiments were conducted in a dimly lit room, and the observers were tested individually. Undergraduate and graduate students from Harvard University participated in the experiments. All observers were naive as to the purpose of the experiments (except the first author, S.S.) and had normal or corrected-to-normal vision. Stimuli were drawn against a dark background ( $0.02 \text{ cd/m}^2$ ). A random-dot field of 1-pixel squares was used as the mask. The bright squares randomly covered 50% of the screen in each trial.

The experiments were run in either the single-cue or the double-cue paradigm. In the single-cue paradigm, a single attention cue was flashed in a randomly chosen quadrant (Figure 1, left path) with the constraint that each of the four locations be cued every four trials. In the case of the voluntary-attention condition, an additional distractor cue was flashed symmetrically across the vertical meridian (as shown later in Figure 7, left path). The luminance of the bright squares of the mask was  $9.1 \text{ cd/m}^2$ . The observer was seated 46 cm from the monitor such that each pixel subtended  $2.7'$  of visual angle. A chin rest was used to restrain the observer's head movement.

In the double-cue paradigm, two attention cues were flashed in either of the diagonally opposite pairs of quadrants (see Figure 1, right path). The cue locations were switched between these two

pairs of quadrants randomly across trials with the constraint that each pair of quadrants be cued twice every four trials. In the case of the voluntary-attention condition, two additional distractor cues were flashed in the remaining two quadrants (see Figure 7, right path). The luminance of the bright squares of the mask was increased to  $53.5 \text{ cd/m}^2$ . We used the higher intensity masking to further ensure that the processing of the vernier stimulus was strongly disrupted by the mask. The observer was seated farther away, 60 cm, from the monitor such that each pixel subtended  $2.1'$ . We used the longer viewing distance to increase the resolution of the vernier offset drawn on the monitor. The double-cue paradigm was used primarily in order to enhance the vernier offset induced by the repulsion effect. Diagonally opposite foci of attention<sup>2</sup> would repel the upper and lower vernier lines in opposite directions and thus enhance the vernier offset that was due to the repulsion effect. A pilot study showed that the observed effect was indeed stronger with two cues.

All stimuli were drawn with 1-pixel-wide curves ( $2.7'$  and  $2.1'$  at viewing distances of 46 and 60 cm, respectively). The observer always viewed the cross ( $2.5 \text{ cd/m}^2$ ) located at the center of the monitor. The fixation cross was  $7 \times 7$  pixels ( $0.6^\circ \times 0.6^\circ$  at 46 cm and  $0.5^\circ \times 0.5^\circ$  at 60 cm). The cue circles and the vernier lines ( $9.1 \text{ cd/m}^2$ ) were 36 pixels ( $1.7^\circ$  at 46 cm and  $1.3^\circ$  at 60 cm) in diameter and length, respectively. The cue squares used in Experiments 4, 5, and 6 to test the effect of sustained voluntary attention were  $32 \times 32$  pixels ( $1.5^\circ \times 1.5^\circ$  at 46 cm and  $1.1^\circ \times 1.1^\circ$  at 60 cm) so that their area matched that of the cue circles. The vertical distance between the two vernier lines was 280 pixels center to center ( $12.8^\circ$  at 46 cm and  $9.8^\circ$  at 60 cm).

At the beginning of each trial, a fixation cross appeared at the center of the screen at the sound of a warning beep; the observer fixated the cross for 1,800 ms before the trial events started. The fixation was maintained throughout the trial (except during the mask). The trial events consisted of a flash of the cue circle(s), a blank interval, the vernier presentation, and the random-dot mask. The observer indicated whether the vernier appeared to be offset clockwise or counterclockwise in a two-alternative forced-choice manner. The observer responded by pressing the appropriate keys on the computer keyboard. Trials were separated by 1,300 ms.

We used staircase methods to find the physical vernier offset required to null the repulsion effect (except in Experiments 2 and 7). The vernier lines were always veridically aligned in the first trial. In the single-cue paradigm, the step size of the staircase was  $2.8'$  (1 pixel). Every time the observer's response indicated a repulsion effect, the vernier line nearer the cue was shifted one step further toward the cue in the following trial, and vice versa. The vernier line farther from the cue was always aligned with the central cross. A single staircase was run for all four cue locations—the *one-staircase method*. The staircase was terminated after 10 reversals, and we obtained the repulsion effect by aver-

<sup>2</sup> Evidence exists that attention can be focused simultaneously at multiple loci. As for cue-induced attention, Yantis and Johnson (1990) showed that up to four onset stimuli are processed simultaneously prior to any nononset stimuli, which indicates that attentional benefits occur at multiple loci simultaneously. As for voluntary attention, attentive tracking studies (e.g., Intriligator, Nakayama, & Cavanagh, 1991; Pylyshyn et al., 1994; Pylyshyn & Storm, 1988) demonstrated that up to about five identical targets that are also identical to the distractors can be attentively tracked. Furthermore, measuring the facilitation of detection reaction time, Intriligator and Cavanagh (1992) and Pylyshyn et al. (1994) showed that attention can be focused at individual tracked targets without spanning the regions between them.

aging over the 10 upper and lower extreme values. Because the attention cue appeared in each of the four quadrants with equal probability, any effect of bias in the perceived vernier offset subtracted out; the staircase would yield the repulsion effect in excess of the bias, or zero if the effect was less than the bias. For some observers, we ran four staircases simultaneously for each of the four cue locations to increase the sensitivity of the measurement—the *four-staircase method*. The staircases were terminated after each had gone through at least four reversals; we obtained the repulsion effect by averaging over the extreme values from all four staircases. An advantage of the four-staircase method was that it would reveal the repulsion effect even if the effect was smaller than the bias.

In the double-cue paradigm, the step size of the staircase was 2.1' (1 pixel). Because the two vernier lines were repelled in opposite directions in this case, the nulling shifts of the vernier lines were made symmetrically; the upper and lower vernier lines were shifted in alternate trials. Two staircases were run simultaneously for the two diagonal pairs of the cues—the *two-staircase method*. The staircases were terminated after each had gone through at least eight reversals; we obtained the repulsion effect by averaging over the extreme values from both staircases. The two-staircase method also had the sensitivity to reveal a repulsion effect that was less than the bias.

### Experiment 1: The Basic Effect

In this experiment, we demonstrated the cue-induced repulsion effect: Flashed cues displace subsequently flashed vernier lines away from them. The physical vernier offset required to null the repulsion effect was obtained as a measure of the repulsion effect. We also showed that the repulsion effect was fairly independent of the distance between the cues and the vernier.

### Method

**Observers.** Six observers participated in the experiment.

**Stimuli.** The double-cue paradigm was used. See also the General Method section.

**Procedure.** A pair of cue circles was flashed (30 ms) randomly in either of the two diagonal pairs of quadrants (see Figure 1, right path). The cues were also presented at three different distances (in horizontal direction) from the vernier: 2.1°, 4.9°, and 7.7°. The distance was varied across blocks of trials. After an SOA of 180 ms, the vernier was presented for 60 ms along the vertical meridian, was masked for 255 ms, and was followed by a blank screen.

We used the two-staircase method to find the physical vernier offset required to null the repulsion effect. The amount of this nulling offset was measured for each of the three cue-vernier distances in a separate block. Each observer performed a total of six such blocks in two sessions. In the first session, half of the observers performed three blocks in the increasing order of cue-vernier distance, and the other half performed three blocks in the decreasing order of distance. The order assignments were reversed in the second session. We obtained the final value of the repulsion effect for each distance by averaging the results from the two sessions.

### Results and Discussion

In Figure 2, the amount of the repulsion effect is shown as a function of the horizontal distance between the cues and

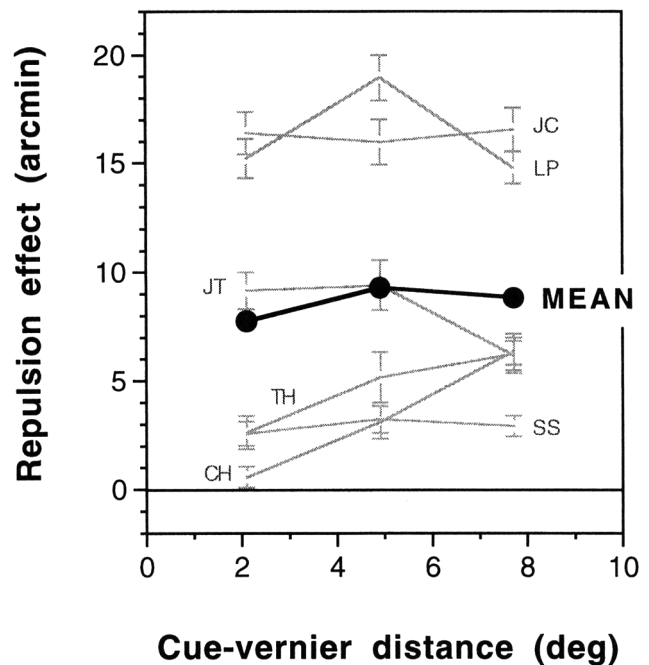


Figure 2. The repulsion effect (in minutes of arc; arcmin) as a function of the horizontal distance (in degrees of arc; deg) between the cues and the vernier. The gray curves are the data from the individual observers, and the black curve is the mean. The vertical error bars represent  $\pm 1$  SE. The effect is significantly above zero at all distances. The observers were tested in the double-cue paradigm with the two-staircase method (see General Method section).

the vernier lines. The mean (black curve) is plotted along with the data from the individual observers (gray curves). The repulsion effects for all cue-vernier distances were significantly above zero:  $F(1, 5) = 7.6, p < .05$ , for the 2.1° distance;  $F(1, 5) = 11.3, p < .03$ , for the 4.9° distance; and  $F(1, 5) = 15.6, p < .02$ , for the 7.7° distance. However, the repulsion effects for the three distances did not differ from one another. Despite the individual differences in the absolute magnitude of the effects, the repulsion effect was obtained for all observers.

Although we will eventually argue that the cue-induced repulsion effect is due to involuntary attention momentarily captured by the flashed cues, we consider nonattentional alternative hypotheses first. There are at least two possibilities that are based on previous studies. The first is that the repulsion effect is an extension of a classic figural aftereffect, but one produced with extremely short adaptation (30 ms) and probed by a briefly flashed test stimulus (60 ms). Wolfe (1984) showed that the tilt aftereffect (Blakemore & Campbell, 1969) was much stronger for brief test stimuli. The second possibility is that the repulsion effect is based on observers' seeing apparent motion from the cues to the nearer vernier lines and that this motion produced representational momentum (e.g., Finke & Shyi, 1988; Freyd & Johnson, 1987). We evaluated these two hypotheses in the following two control experiments.

## Experiment 2: Is the Repulsion Effect Quick Adaptation?

Numerous studies have shown that if one views an adapting stimulus for a sufficient duration of time, the subsequent stimuli presented near it appear displaced away. The effect, known as the figural aftereffect, has a fairly sharp spatial tuning, with the optimum distance between the adapting and the test stimuli varying from  $8'$  to  $3^\circ$  across 13 studies (e.g., Fox, 1951; Kohler & Wallach, 1944; Sagara & Ohyama, 1957). Note that the repulsion effect obtained in Experiment 1 showed little spatial dependence over a much wider range of cue-vernier distances ( $2^\circ$ – $8^\circ$ ). The figural aftereffect has also been shown to decay exponentially with increasing delay of the test stimulus following adaptation (Hammer, 1949; Sagara & Ohyama, 1957). Longer duration of adaptation slows the temporal decay of the effect (Sagara & Ohyama, 1957), but whether it also increases the magnitude of the effect (Hammer, 1949) or not (Sagara & Ohyama, 1957) seems to depend on the specific stimulus parameters.

Although our cue duration, 30 ms, is orders of magnitude shorter than the adaptation lengths normally used in figural aftereffect experiments, one might still argue that brief test stimuli are more susceptible to figural aftereffects induced by brief adaptation (see Wolfe, 1984). To evaluate this possibility, we pitted the effect of adaptation against the effect of "attention-grabbing" transient cues. A pair of adapting circles was presented in one diagonal pair of quadrants, and they remained on throughout the trial until the mask was presented (see Figure 3, second frame). After a 1-s adaptation to these circles, a pair of transient cues was flashed (30 ms) in the opposite diagonal pair of quadrants (see Figure 3, third frame). The vernier was then presented (60 ms) after a 180-ms SOA, followed by a mask. If the repulsion effect we found in Experiment 1 was a classic figural aftereffect with brief adaptation, the vernier should appear offset away from the pair of adapting circles, to which the observer had adapted 30 times longer than to the transient cues. On the other hand, if the effect was induced by attention drawn to the transient cues, the vernier should appear offset in the opposite direction, that is, away from the transient pair of cues.

## Method

**Observers.** Twelve observers participated in the experiment.

**Stimuli.** The double-cue paradigm was used, and the horizontal distance between the cue or adapting circles and the vernier lines was fixed at  $4.9^\circ$ . See also the General Method section.

**Procedure.** The sequence of events for a trial is shown in Figure 3. The adapting circles were presented randomly in either of the two diagonal pairs of quadrants. The transient cues were always presented in the opposite diagonal pair of quadrants. In this experiment, the vernier was veridically aligned in all trials. The observer indicated the direction of perceived vernier offset in a two-alternative forced-choice manner at the end of each trial. Each observer performed at least 20 trials.

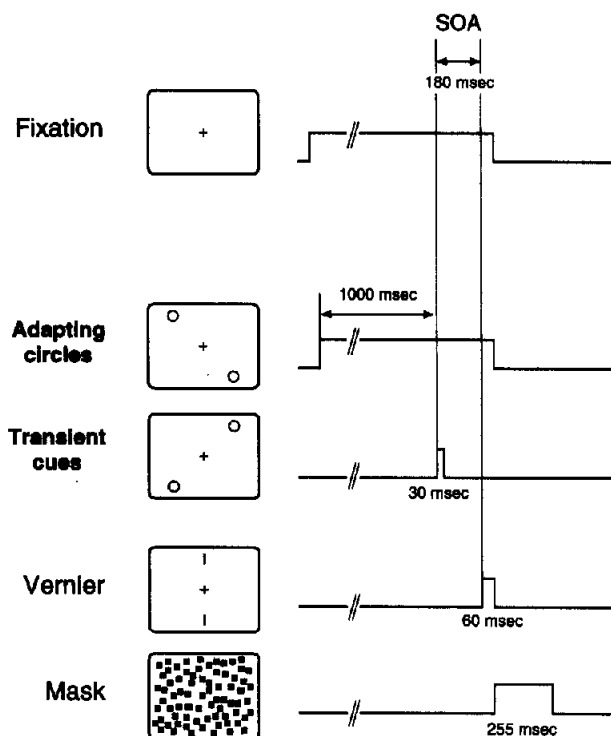


Figure 3. Trial events for Experiment 2, in which the effect of transient cues was pitted against the effect of a long adaptation. SOA = stimulus onset asynchrony.

## Results and Discussion

Figure 4 shows the percentage of trials in which the vernier appeared offset away from the transient cues rather than away from the adapting circles, averaged over the 12 observers. Chance performance would have yielded 50%; anything above 50% would indicate that transient cues won over long adaptation, whereas anything below 50% would

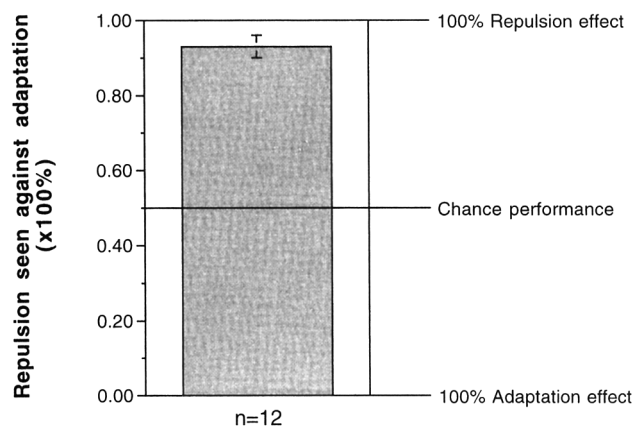


Figure 4. Transient, "attention-grabbing" cues versus long adaptation: Adaptation wins if less than 50%; transient cues win if greater than 50%. Random responses would yield 50%. The vertical error bar represents  $\pm 1$  SE.

indicate that long adaptation won over transient cues. The result clearly shows that the repulsion effect was seen away from the transient cues against a 30-times-as-long adaptation,  $F(1, 11) = 177.1$ ,  $p < .001$ .

Classic figural aftereffects thus cannot account for the cue-induced repulsion effect demonstrated in Experiment 1. In the next experiment we evaluated the apparent motion hypothesis of the repulsion effect.

### Experiment 3: Is the Repulsion Effect Due to Apparent Motion?

It has been shown that the perceived location at which a moving object has just disappeared is nonveridically displaced in the direction of the motion. This phenomenon is called *representational momentum*. The amount of displacement has been shown to increase in proportion to the speed of the object (Finke & Shyi, 1988; Freyd & Johnson, 1987) and to the delay in response following the disappearance of the object (Freyd & Johnson, 1987), much like physical momentum. The displacement reverses in anticipation of a collision (Hubbard & Bharucha, 1988) or a reversal of motion in a periodic motion sequence (Verfaillie & d'Ydewalle, 1991), which suggests that the effect involves higher level cognitive processing. We need to consider the

possibility that the repulsion effect is a two-frame version of the representational momentum effect.

We modified the experiment so that any apparent motion would always be away from the vernier lines. We accomplished this by presenting a pair of motion distractors along with the vernier (see Figure 5). In a motion competition display like this (where proximity is equal for the two alternatives), apparent motion is seen between a pair of objects that are most similar to each other in terms of overall size, luminance, color, and shape (e.g., Green, 1986, 1989; He & Nakayama, 1994; Prazdny, 1986; Ullman, 1980). Because the distractor circles were identical to the cues, all of these factors favored seeing motion from the cues to the distractor circles (as shown by the arrows in Figure 5) rather than to the vernier lines. Thus, apparent motion was made to go in the direction opposite that of the repulsion effect. If the cue-induced repulsion effect was due to apparent motion, the effect should disappear in this case.

### Method

**Observers.** Six observers participated in the experiment.

**Stimuli.** The double-cue paradigm was used. The motion distractors were presented  $4.9^\circ$  peripheral to the cue circles so that the vernier lines and the motion distractors were both an equal dis-

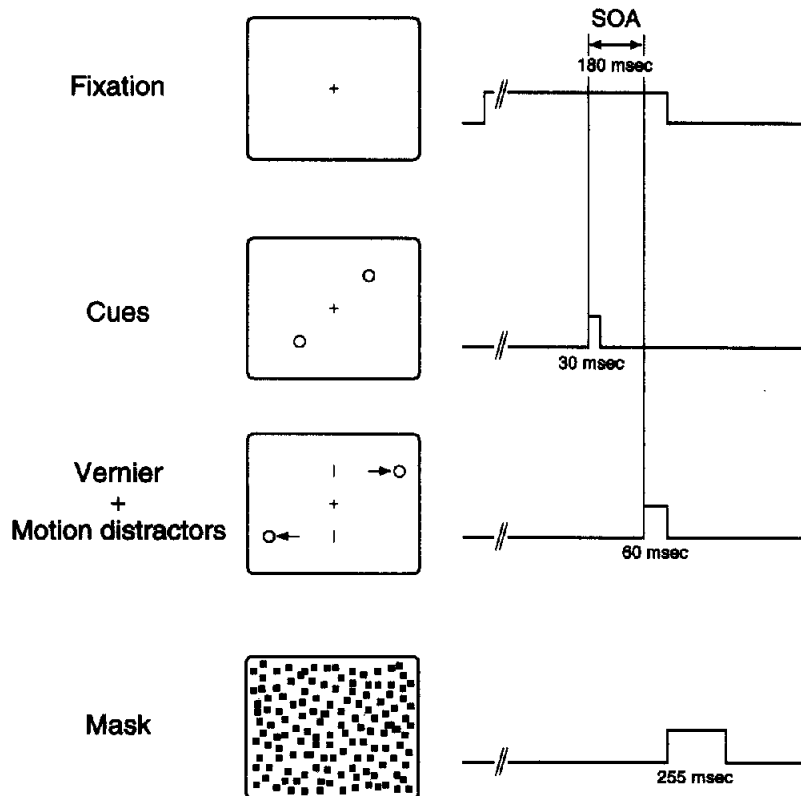


Figure 5. Trial events for Experiment 3, in which the repulsion effect was pitted against apparent motion in the opposite direction. Arrows in the third frame indicate the perceived directions of the apparent motion, from the cues to the motion distractors. SOA = stimulus onset asynchrony.

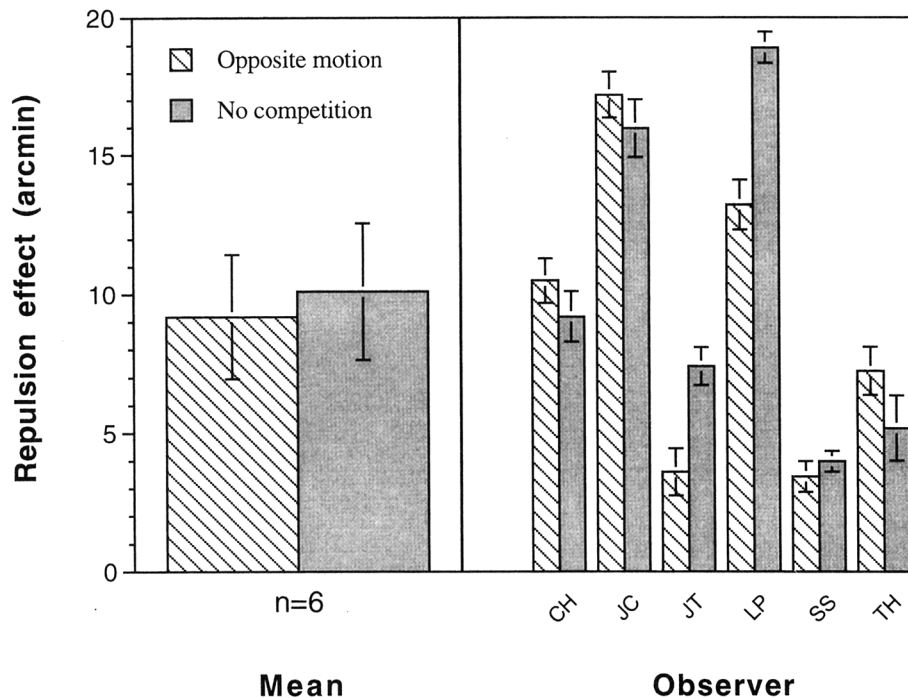


Figure 6. The repulsion effect with (striped bars) and without (gray bars) apparent motion in the opposite direction. All observers saw apparent motion from the cues to the distractor circles 100% of the time when forced to report any motion. The vertical error bars represent  $\pm 1$  SE. The observers were tested in the double-cue paradigm with the two-staircase method (see General Method section). arcmin = minutes of arc.

tance ( $4.9^\circ$ ) away from the cue circles. See also the General Method section.

**Procedure.** The trial events are shown in Figure 5. The cue circles were flashed for 30 ms, as before. After an SOA of 180 ms, the vernier and the motion distractors were presented for 60 ms, followed by the mask. We used the two-staircase method, as in Experiment 1, to determine the amount of the repulsion effect. The effect was measured twice for each observer, and the results were averaged. The observers were also tested in the control condition without the motion distractors.

## Results and Discussion

As shown in Figure 6 (striped bars), despite the motion distractors, not only was the repulsion effect significant,  $F(1, 5) = 16.9$ ,  $p < .01$ , but it was also obtained from all observers. None of the observers spontaneously reported seeing any apparent motion at all. However, 3 observers (J.T., L.P., and S.S.) reported seeing unambiguous motion from the cues to the motion distractors when asked to report any motion. Observers C.H., J.C., and T.H. indicated motion only when forced to report whether the cues appeared to move either to the vernier lines or to the motion distractors; all chose the motion to the distractors.<sup>3</sup> Thus, the repulsion effect was obtained despite the presence of apparent motion going in the opposite direction. Figure 6 further shows that the amount of the repulsion effect is equivalent with (striped bars) or without (gray bars) the motion dis-

tractors,  $F(1, 5) = 0.5$ , *ns*; the competing apparent motion does not noticeably reduce the repulsion effect.

We have seen that neither classic figural aftereffects nor apparent motion can account for the repulsion effect. In the following experiments we attempted to show that the repulsion effect is due to attention focused at the cued locations. In the next experiment we tested to see if the repulsion effect could be obtained with voluntarily sustained attention. No transient cues preceded the vernier.

## Experiment 4: What About Voluntary Attention?

It is well known that flashed cues briefly capture attention at the cued locations, automatically, regardless of the observer's intentions. Such cuing momentarily enhances visual acuity (e.g., Eriksen & Collins, 1969; Eriksen & Rohrbaugh, 1970; Nakayama & Mackeben, 1989), sensitivity (e.g., Hawkins et al., 1990), and salience (e.g., Yantis & Johnson, 1990). Similar enhancement of visual perception has also been demonstrated with voluntarily sustained attention; the response time required to detect a target stimulus is reduced at the attended location (e.g., Downing & Pinker, 1985; Posner, Snyder, & Davidson, 1980). If the

<sup>3</sup> None reported a split motion in which the cue circle appeared to move in two separate directions simultaneously, toward the nearer vernier line and toward the distractor circle.

cue-induced repulsion effect is due to attention, voluntary attention should also produce the repulsion effect.

## Method

**Observers.** Six observers participated in the experiment.

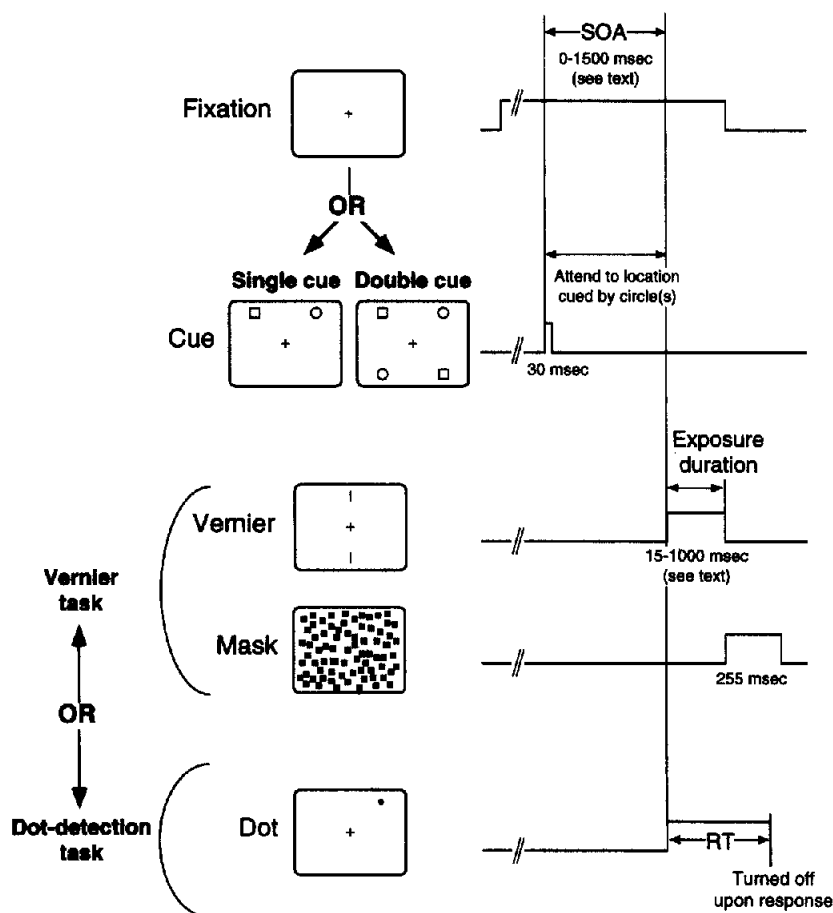
**Stimuli.** The double-cue paradigm was used. See also the General Method section.

**Procedure.** The trial events are shown in Figure 7 (right path). Four cues were flashed simultaneously for 30 ms: a pair of circles in one diagonal pair of quadrants and a pair of squares in the other quadrants. A blank screen followed this presentation. The observer maintained attention on the blank screen at the locations cued by the prespecified shape (circle or square) for as long as 1.5 s while keeping fixation at the central cross. The vernier was then presented for 60 ms, and the observer indicated the direction of its apparent offset in a two-alternative forced-choice manner as before. If voluntary attention caused the repulsion effect, the vernier should appear offset away from the attended locations. Because of

the bilateral symmetry of the display, image interactions could not produce the repulsion effect.

To check to see if the observer was actually attending to the cued locations, in half of the trials we presented a dot either at one of the attended locations (indicated by the prespecified shape) or at one of the other two locations (indicated by the other shape). The cue validity was 50%. The observer responded as quickly as possible as to whether the dot was presented in the left or the right visual field by pressing the corresponding keys. The dot remained on until a response was made. We expected the response time to be faster when the dot was presented at one of the attended locations. The observer was told that the dot-detection task was the primary task and that only accuracy was important when the vernier was presented. The instruction for voluntary attention was to "view the fixation cross, but *be prepared* to respond to a dot appearing at one of the locations indicated by the prespecified shape *by attending hard* to those locations." The dot and vernier trials were randomly mixed.

We used the two-staircase method to determine the amount of



**Figure 7.** Trial events for Experiments 4, 5, and 6, in which the voluntary-attention-induced repulsion effect was demonstrated. The left path shows the single-cue paradigm, and the right path, the double-cue paradigm (see General Method section for details). The dot-detection task was randomly mixed with the vernier task in Experiment 4; the two tasks occurred with equal probability across trials. In a dot-detection trial, the dot appeared at one of the attended locations 50% of the time (cue validity = 50%). The vernier task alone was used in Experiments 5 and 6. SOA = stimulus onset asynchrony; RT = response time.



the repulsion effect that was due to voluntary attention. As before, the cues were presented at three possible horizontal distances from the vernier: 2.1°, 4.9°, and 7.7°. The staircases were run separately for each of the three cue-vernier distances in a separate block. Each observer was tested in a total of six such blocks in two sessions. In the first session, half of the observers performed three blocks in the increasing order of cue-vernier distance, and the other half performed three blocks in the decreasing order of distance. The order assignments were reversed in the second session. All observers attended to the locations indicated by the circles in the first session and to those indicated by the squares in the second session. We obtained the final value of the repulsion effect for each distance by averaging the results from the two sessions.

### Results and Discussion

In Figure 8a, the amount of the repulsion effect is shown as a function of the horizontal distance between the attended loci and the vernier lines (equivalent to the horizontal eccentricity of the attended loci). The mean (black curve) is plotted along with the data from the individual observers (gray curves). The repulsion effects for all cue-vernier distances were significantly above zero:  $F(1, 5) = 10.9, p < .03$ , for the 2.1° distance;  $F(1, 5) = 9.9, p < .03$ , for the 4.9° distance; and  $F(1, 5) = 7.7, p < .04$ , for the 7.7° distance. However, they did not differ from one another. Despite the

individual differences in the absolute magnitude of the repulsion effects, all observers saw the effect for at least two of the three distances.

The response time data from the dot-detection trials are shown in Figure 8b. The difference in response time between the trials in which the dot was presented at an unattended location and the trials in which the dot was presented at an attended location is plotted as a function of the horizontal eccentricity of the attended loci. Positive values indicate that attention speeded the dot detection. The mean (black curve) is plotted along with the data from the individual observers (gray curves). The main effect of attention was not significant,  $F(1, 5) = 2.6, ns$ , because of the large negative contribution from J.T.; without J.T.'s data, the effect was significant,  $F(1, 4) = 15.7, p < .05$ . Separate analyses for the three cue-vernier distances yielded a significant effect only for the largest distance:  $F(1, 5) = 2.1, ns$ , for the 2.1° distance;  $F(1, 5) = 0.29, ns$ , for the 4.9° distance; and  $F(1, 5) = 10.5, p < .03$ , for the 7.7° distance.

Thus, voluntarily sustained attention as well as transient cues can produce the repulsion effect. Furthermore, note that the effect of voluntary attention was more reliable statistically for the repulsion effect (Figure 8a) than for the speeding of detection at the loci of attention (Figure 8b). This suggests that the repulsion effect is a more sensitive

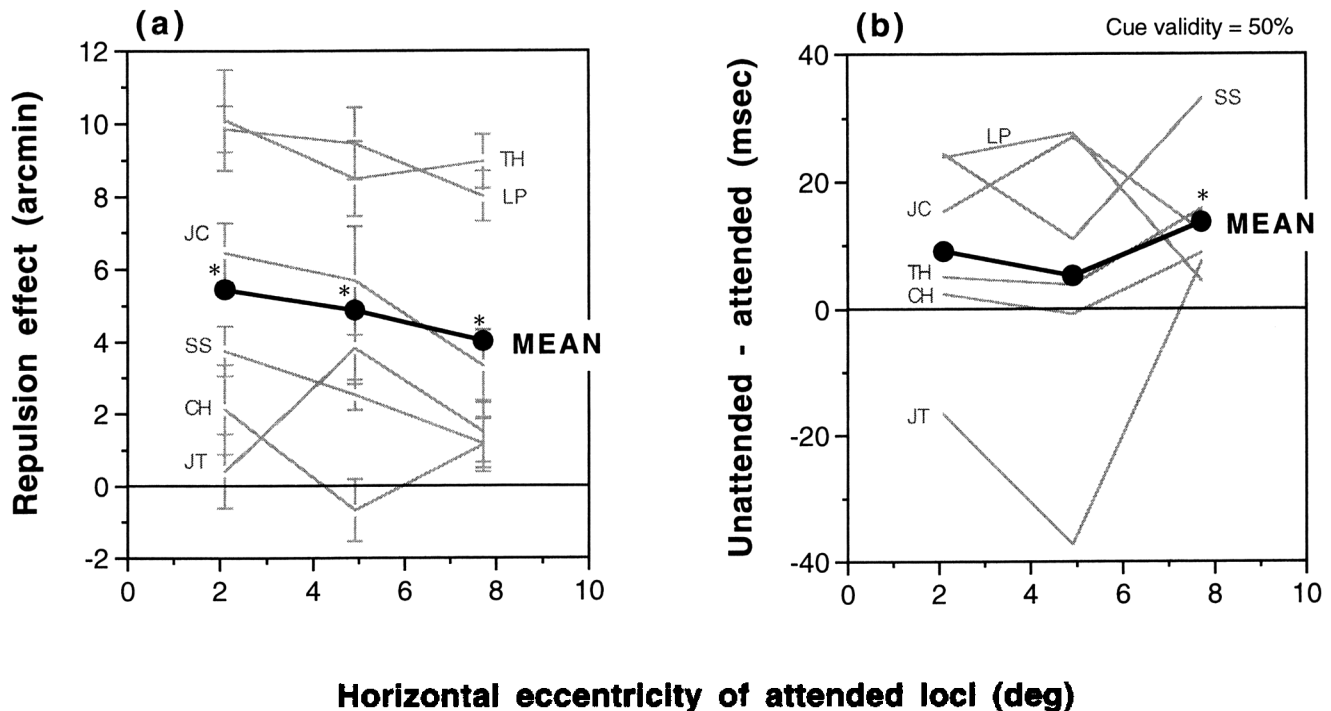


Figure 8. The effect of voluntary attention (a) on the repulsion effect (in minutes of arc; arcmin) and (b) on the dot-detection time, as a function of the horizontal eccentricity of the attended loci (in degrees of arc; deg). The gray curves are the data from the individual observers, and the black curve is the mean. The vertical error bars represent  $\pm 1$  SE. The asterisks indicate that the effects are significantly above zero. The observers were tested in the double-cue paradigm with the two-staircase method (see General Method section).

measure of voluntary attention, at least in our paradigm. In the next experiment we examined whether the cue-induced repulsion effect was due to attention being captured by the transient cues.

### Experiment 5: Is the Cue-Induced Repulsion Effect Due to Involuntary Attention?

It has been shown that the capturing of involuntary (obligatory) attention by the onset of a cue stimulus is transient. Nakayama and Mackeben (1989) demonstrated that the accuracy of vernier offset discrimination at cued locations improves as a function of the cue-stimulus SOA up to about 200 ms and that performance declines as the SOA is further increased. An extremely short SOA would allow too little time for attention to shift to the cued location, but attention would drift away if the SOA was too long. If the cue-induced repulsion effect is caused by such involuntary attention being briefly captured by flashed cues, the effect should behave similarly as a function of the cue-vernier SOA.

### Method

**Observers.** Two observers participated in the experiment.

**Stimuli.** The single-cue paradigm was used (Figure 1, left path), and the cue-vernier distance was  $6.4^\circ$ . See also the General Method section.

**Procedure.** The cue was flashed for 30 ms, as before. The SOA between the cue and the vernier was varied between 0 and 1,500 ms. The vernier was presented for 60 ms. In the special case where the SOA was zero, the cue and the vernier were presented simultaneously for 60 ms.

The repulsion effect was measured separately for each of the 13 SOAs (0–1,500 ms) in a separate block. The one-staircase method was used. The effect was measured at least twice for each SOA, once in the ascending and once in the descending order of SOA; the results were averaged for each SOA. An experimental session consisted of a warm-up block with no cues followed by a complete ascending or descending sweep of 13 blocks for the 13 SOAs. J.C. performed two such sessions in the order of (a) ascending and (b) descending. S.S. performed four sessions in the order of (a) descending, (b) ascending, (c) descending, and (d) ascending.

### Results and Discussion

The results are shown in Figure 9. Although the absolute magnitude of the effect was much smaller for S.S., a common pattern of dependence of the repulsion effect on the cue-vernier SOA was obtained for both observers. The repulsion effect peaked around an SOA of 200 ms, though the buildup was almost absent for S.S.<sup>4</sup> The effect decayed halfway to its asymptotic level by ~450 ms of SOA. This behavior of the repulsion effect as a function of the cue-stimulus SOA is comparable to the behavior of the acuity enhancement effect at the precued location reported by Nakayama and Mackeben (1989). The two results corroborate the hypothesis that both effects are due to involuntary attention being captured momentarily by flashed cues. The asymptotic (nonzero) effects obtained at long SOAs might

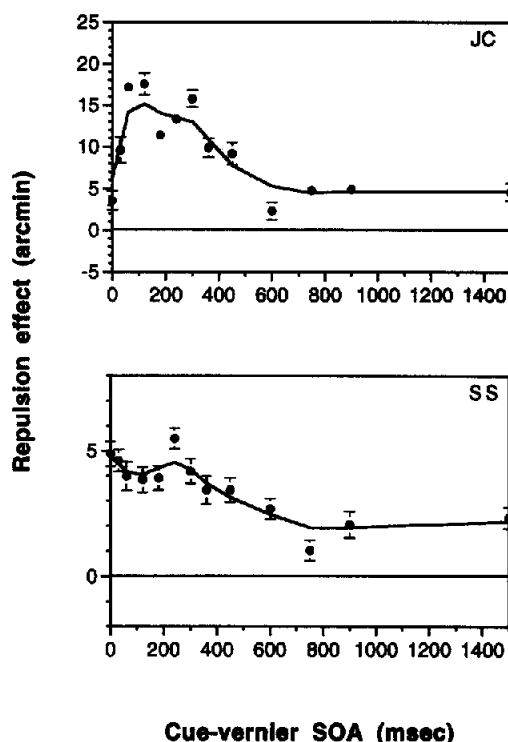


Figure 9. The cue-induced repulsion effect (in minutes of arc; arcmin) as a function of the cue-vernier stimulus onset asynchrony (SOA). The vertical error bars represent  $\pm 1$  SE. The smooth curves are the five-channel binomial fits. The observers were tested in the single-cue paradigm with the one-staircase method (see General Method section).

be due to a sustained component of the cue-induced attention, as suggested by Nakayama and Mackeben (1989). Some component of captured attention might linger until the next "attention-grabbing" event or a saccade takes place.

Early results (Experiment 1) suggested that the cue-induced repulsion effect had no systematic dependence on the distance between the cues and the vernier lines within the range tested ( $2^\circ$ – $8^\circ$ ; see Figure 2). To assert that the effect is distance independent, however, one must also show the peak SOA to vary little with the cue-vernier distance. The reason is that the peak SOA and the overall magnitude might covary with distance so as to cancel each other's dependence on distance. To evaluate this possibility, we tested an additional observer, L.P., in order to obtain the whole SOA curves of the repulsion effect for three different cue-vernier distances ( $2.1^\circ$ ,  $4.9^\circ$ , and  $7.7^\circ$ ). We used the double-cue paradigm to enhance the magnitude of the repulsion effect. The two-staircase method was used. The effect was measured twice for each SOA, once in the

<sup>4</sup> Because S.S. is a highly trained observer in attention experiments (the first author), the near-peak repulsion effects obtained at faster SOAs might be due to his increased vigilance and concentration. An additional untrained observer, L.P., showed the same pattern of results as J.C., as described in the following paragraphs.

ascending and once in the descending order of SOA, for each of the three cue–vernier distances.

We found that the peak SOA does not shift with the cue–vernier distance. The three SOA curves of the repulsion effect corresponding to the three cue–vernier distances ( $2.1^\circ$ ,  $4.9^\circ$ , and  $7.7^\circ$ ) virtually overlap, as shown in Figure 10. Also note that the SOA dependence of the repulsion effect for L.P. is almost identical to that for J.C. (see Figure 9).

This result, in combination with the result from Experiment 1, indicates that the cue-induced repulsion effect does not depend systematically on the cue–vernier distance in the

range tested ( $2^\circ$ – $8^\circ$ ). Note that the voluntary-attention-induced repulsion effect also does not depend on the cue–vernier distance (see Figure 8a).

To be thorough, we also obtained a complete SOA curve for the voluntary-attention-induced repulsion effect from J.C. and S.S. The main question addressed was how fast selective attention could be engaged. A flash of two shapes would inevitably draw involuntary attention to both shapes. The observer then would need to recognize the two shapes and selectively attend to the prespecified shape. The amount of time required for the shape recognition and the engagement of selective attention should be reflected in the additional amount of time it takes for the repulsion effect to build up in the voluntary-attention condition relative to the cue-induced (involuntary-attention) condition.

The single-cue paradigm was used (Figure 7, left path). Two cues (a circle and a square) were flashed (for 30 ms) in either the upper or lower two quadrants; the horizontal eccentricity of the cues was  $6.4^\circ$ . The observer was told to maintain attention on the blank screen at the location cued by the prespecified shape (circle or square) throughout the duration of the SOA (0–1,500 ms). Because of the bilateral symmetry of the display, image interactions could not produce the repulsion effect. Thus, any repulsion effect obtained should be due to voluntary attention. We measured the effect for each SOA in a separate block of trials, using the one-staircase method. J.C. performed 13 blocks (for 13 SOAs ranging from 0 to 1,500 ms) in the ascending order of SOA while attending to the location indicated by the square in the first session. In the second session, the block order was reversed and attention was focused on the location indicated by the circle. S.S. first performed the blocks in the descending order of SOA with attention to the circle; both the block order and the attended shape were again switched in the second session. Because in Experiment 4 we demonstrated the robustness of the voluntary-attention-induced repulsion effect, we did not use the concurrent dot-detection task here.

The results from the 2 observers are plotted in Figure 11. For both observers, it took 120 ms for the repulsion effect to rise significantly above zero. The cue-induced repulsion effect, on the other hand, rose above zero within 30 ms of SOA (see Figures 9 and 10). The difference ( $120 - 30 = 90$  ms) roughly indicates the time it takes to identify and attend to the target shape. Unlike the cue-induced effect, the voluntary-attention-induced effect is relatively independent of the cue–vernier SOA beyond the first 120 ms.

In summary, three main conclusions can be drawn from the present experiment. First, the SOA curve of the cue-induced repulsion effect mimics the SOA curve of the acuity enhancement effect at precued locations reported by Nakayama and Mackeben (1989), which supports that the cue-induced repulsion effect is due to involuntary attention being momentarily captured by the flashed cues. Second, neither the magnitude nor the peak SOA of the cue-induced repulsion effect depends on the cue–vernier distance ( $2^\circ$ – $8^\circ$ ) in any significant way. Last, the buildup of the voluntary-attention-induced repulsion effect is slower than that of the cue-induced repulsion effect by about 90 ms,

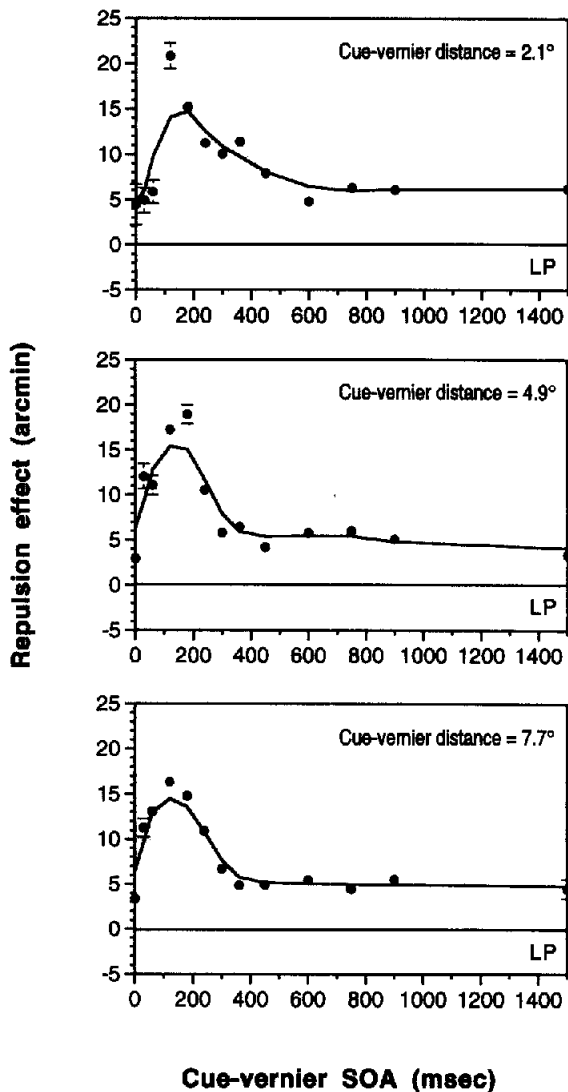
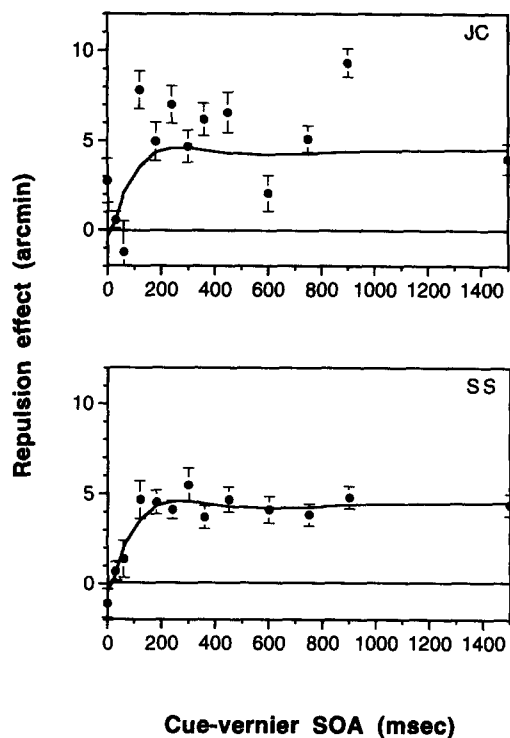


Figure 10. The cue-induced repulsion effect (in minutes of arc; arcmin) as a function of the cue–vernier stimulus onset asynchrony (SOA), obtained for three different cue–vernier distances for L.P. The vertical error bars represent  $\pm 1$  SE. The smooth curves are the five-channel binomial fits. The observer was tested in the double-cue paradigm with the two-staircase method (see General Method section).



**Figure 11.** The repulsion effect (in minutes of arc; arcmin) due to voluntary attention as a function of the cue-vernier stimulus onset asynchrony (SOA). The vertical error bars represent  $\pm 1$  SE. The smooth curves are the five-channel binomial fits. The observers were tested in the single-cue paradigm with the one-staircase method (see General Method section).

which suggests that that much time is required to recognize and selectively attend to the target shape.

So far we have taken for granted that the repulsion effect is observed only if the vernier is presented briefly, but we have not tested explicitly just how brief presentation must be for the effect to be observed. In the next experiment we addressed this basic question.

#### Experiment 6: How Brief Is Brief Enough to See the Repulsion Effect?

In this experiment, we varied the exposure duration of the vernier to determine how brief an exposure would be brief enough for the repulsion effect to be seen. If the effect was due to focused attention, one would expect it to decay substantially within 100–200 ms of the onset of the vernier. The reason is that the vernier itself would act as an attention cue and capture attention within 100–200 ms of its onset. The repulsion effect would then be centered around the vernier and would not affect the representation of its own position. An interesting question arose as to whether we would see the process of the initially offset vernier relaxing back to its veridical alignment when a long enough viewing time was allowed. Both involuntary- and voluntary-attention conditions were tested.

#### Method

**Observers.** Five observers participated in the experiment. Three observers (J.C., S.S., and E.Y.) performed in both the cue-induced and voluntary-attention conditions. P.T. performed only in the former condition and N.R. in the latter.

**Stimuli.** The single-cue paradigm was used for both the cue-induced and voluntary-attention conditions (Figures 1 and 7, right paths). See also the General Method section.

**Procedure.** The trial events were identical to those in the single-cue paradigm used in Experiment 5 except that the exposure duration of the vernier was varied while the cue-vernier SOA was fixed in this case. The range of the vernier duration tested was 15–960 ms. The cue-vernier SOA was 180 ms for the cue-induced condition and 1,500 ms for the voluntary-attention condition.

The effect was measured with the one-staircase method for P.T. and E.Y.; the four-staircase method was used for the rest of the observers (J.C., N.R., and S.S.). In each attention condition, the repulsion effect was measured at least twice (two blocks) for each vernier duration, once in the ascending and once in the descending order of the duration, and the results were averaged. In the voluntary-attention condition, the observer attended to the location indicated by the square in one order of blocks and that indicated by the circle in the other.

#### Results and Discussion

The repulsion effect is plotted separately for the cue-induced (Figure 12a) and voluntary-attention (Figure 12b) conditions. In both conditions, the repulsion effect decreased rapidly with increasing vernier duration, falling by half (relative to the asymptotic values) within 100–200 ms. As discussed earlier, this temporal profile of fall-off would be expected if the repulsion effect was due to attention. Because the magnitude of the repulsion effect varied across observers for the cue-induced condition, 3 additional observers were tested with the double-cue paradigm and the two-staircase method. All demonstrated the rapid fall-off like that shown in Figure 12a; furthermore, the magnitudes of the effects also lay within the range of those shown in Figure 12a (see Figure 13a).

Note that in the cue-induced condition, the effect appears to reach asymptote at nonzero values for some observers. A straightforward possibility is that for those observers whose attention was strongly attracted to the cued locations, some attention might linger there even after the onset of the vernier probe. The data appear to be consistent with this idea in that the repulsion effect tended to be longer lasting for those who showed stronger effects overall (see Figure 13a), that is, for those whose attention presumably was more strongly captured by the cues. Later, in the *Results and Discussion* section of the next experiment, we discuss another factor that could also contribute to the long tails in Figure 13a, that is, the possible involvement of temporal summation of position.

Given the rapid decrease in the repulsion effect within the first few hundred milliseconds, we can ask whether there is a corresponding, visible change in position for a vernier probe that is presented for longer than 200 ms. As soon as the vernier appears, it might have a large displacement away

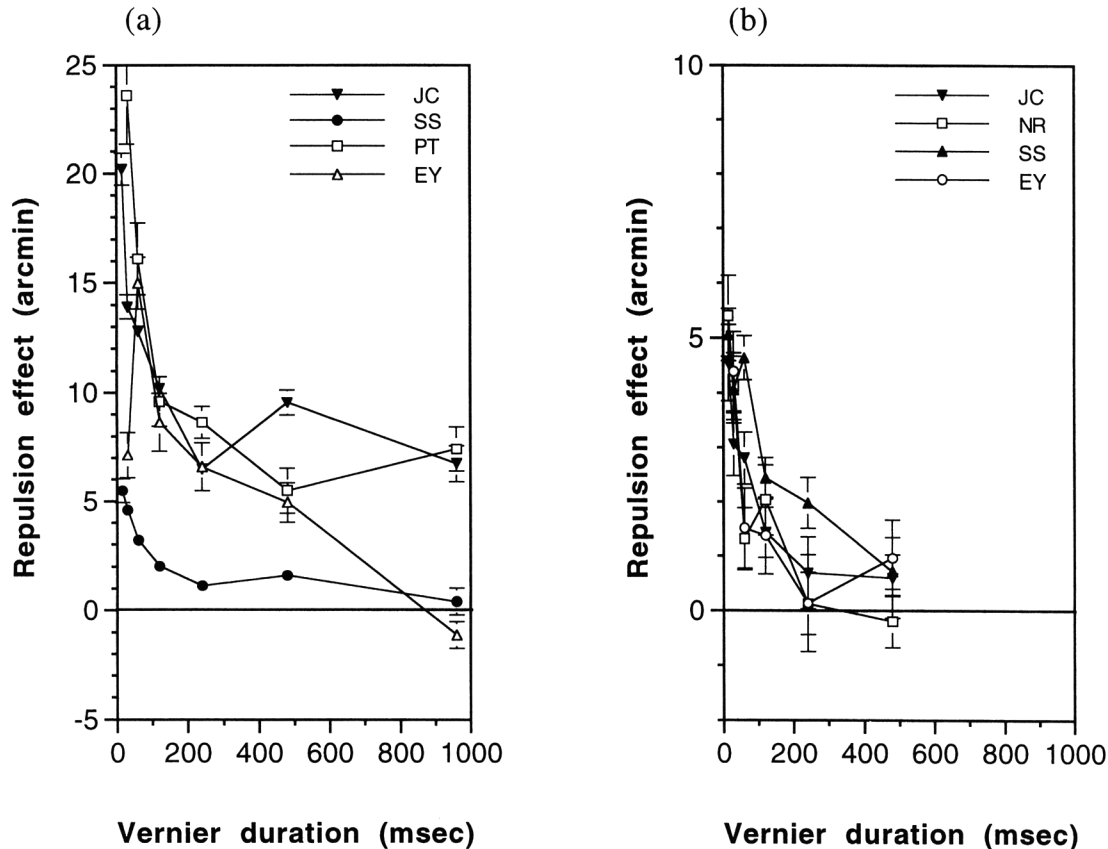


Figure 12. The repulsion effect (in minutes of arc; arcmin), (a) cue induced and (b) voluntary attention induced, as a function of the exposure duration of the vernier stimulus. The vertical error bars represent  $\pm 1$  SE. The observers were tested in the single-cue paradigm with the one-staircase (E.Y. and P.T.) and four-staircase (J.C., N.R., and S.S.) methods.

from the attention cues, which would then rapidly decrease. Is this change in position actually seen? None of the observers reported such a "recovery" motion of the vernier lines. There are at least three possible reasons why the motion was invisible. One is that the recovery motion was simply below threshold, although a study by Cropper and Derrington (1994) suggests otherwise. The second possibility is that the small recovery motion from the cues to the nearer vernier lines, though we have shown that this apparent motion is not responsible for the repulsion effect itself (see Experiments 3 and 4). Last, the recovery motion might not exist at all. It might be that the repulsion effect arises beyond the processing level at which position information feeds into the motion processing mechanism.

#### Experiment 7: Does Recovery Motion Exist?

Figure 13a shows that the cue-induced repulsion effect drops 4–17' within the first 200 ms of vernier exposure across observers. A linear approximation yields a rate of 20–85'/s, which would have been the speed of the recovery motion had it been visible. In this experiment, we simulated

(i.e., generated a motion display of) the lowest estimated recovery motion to see if it was visible in the experimental conditions we used to measure the repulsion effect. Figure 13a shows the simulated recovery motion (dotted line) along with the temporal fall of the repulsion effect obtained in Experiment 6 (the data from the 3 additional observers, indicated by asterisks, are also included). It is apparent that the simulated motion is comparable to the slowest temporal recovery profile obtained from the observer who showed the smallest overall repulsion effect. Thus, if the recovery motion was not observed because of its weakness of signal, the simulated motion should certainly not be observed.

The simulated motion was added to the vernier line during a typical cue-induced-attention trial, and it could be in either direction (toward or away from the attention cues) so that it either added to or subtracted from the putative recovery motion. If, on the one hand, the recovery motion was not seen because it was below threshold, then when it combined with the simulated motion, the total would remain below threshold when the two motions were in opposite directions but might rise above threshold when they were in the same direction (toward the attention cues). On the other hand, the recovery motion signal might be above threshold if it could

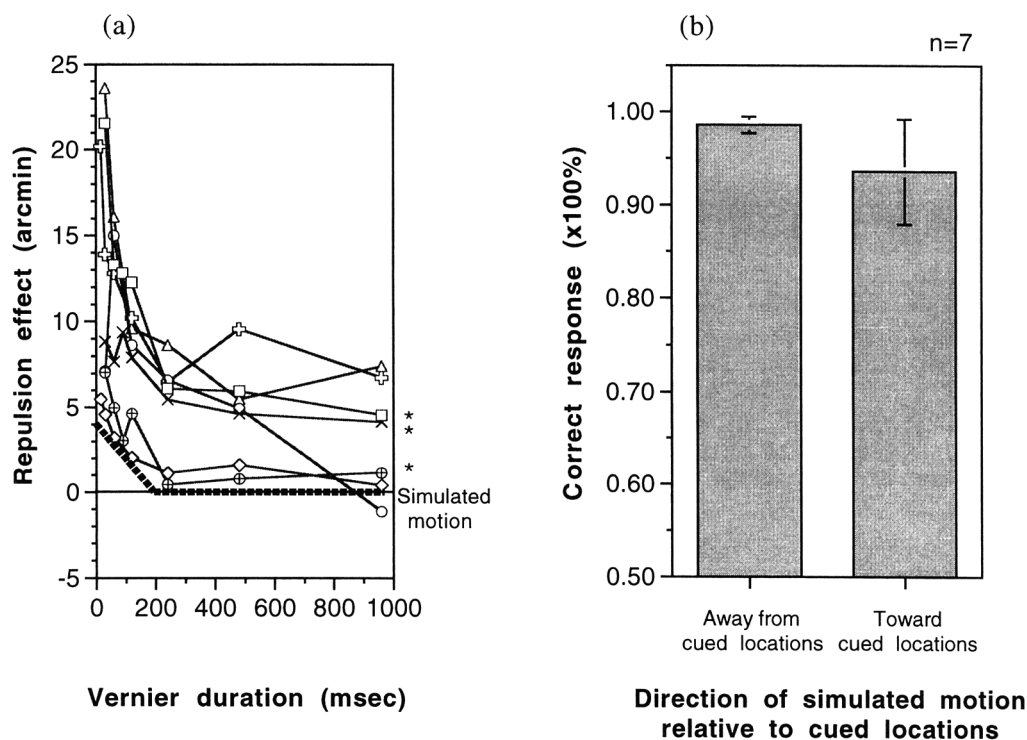


Figure 13. (a) The simulated vernier motion (dotted curve) is plotted along with the data from Figure 12a and those from the 3 additional observers (asterisks), from which the recovery motions were estimated. (b) Proportion of correct responses for the discrimination of direction of the simulated vernier motion, toward or away from the cued locations. The vertical error bars represent  $\pm 1$  SE. arcmin = minutes of arc.

be produced in isolation, but in the attention-cue display it may be masked by the large apparent motion signal between the attention cues and the vernier probe. In this case, the simulated motion should also be masked but more in one direction than the other. Typically, same-direction masks are far more effective than opposing-direction masks (e.g., Ball & Sekuler, 1979; Sekuler, Ball, Tynan, & Machamer, 1982), so we would expect to see such an asymmetry in the detectability of the simulated motion—it should be more visible in the recovery direction (returning toward the attention cues) than in the opposite direction. Both of these possibilities make the same prediction—better visibility of the simulated motion toward the attention cues. If no significant directional difference is found for the simulated motion and if its detectability is significantly above chance, then it may be that the rapid decrease in the position distortion indicated in the results of Figure 12 simply does not trigger any sensation of motion. That is, the position shifts may arise beyond the point at which position information feeds into motion mechanisms.

### Method

**Observers.** Seven observers participated in the experiment.

**Stimuli.** The vernier lines were initially offset by 2 pixels across the vertical meridian, and we brought them to veridical

alignment by moving each line toward the meridian by 1 pixel (2.1'); the vernier motion was completed in the first 180 ms (12 frames of monitor refreshment) of the 960-ms exposure. The observer, thus, could not infer the motion from the final positions of the vernier lines. To make the motion appear continuous, we moved the approximate luminance centroid of each vernier line in four steps of one quarter of a pixel (0.5'), with each step lasting 3 frames (45 ms). We generated the first quarter step by reducing the luminance of the vernier line to 75% and presenting another line of 25% luminance 1 pixel away (abutting the first line). This procedure moved the luminance centroid of the vernier line by roughly one fourth of a pixel. In the next step, the luminance of the first line was further reduced to 50% and that of the second line was increased to 50%, which moved the centroid to the one half of a pixel position. Then the luminances were shifted to 25% and 75% in the third step, which moved the centroid roughly to the three quarters of a pixel position. In the final step, we fully shifted the vernier line to the adjacent pixel by turning off the first line and brightening the second to 100% luminance. The motion thus generated appeared smooth. Note that the motion step of 0.5' is also less than the spacings between the photoreceptors in the retina at the corresponding eccentricity of 4.9° (Wassle, Grünert, Rohrenbeck, & Boycott, 1990). The double-cue paradigm was used. See also the General Method section.

**Procedure.** The cues were flashed in a diagonal pair of quadrants. The vernier appeared following 180 ms of SOA, remained on for 960 ms, and was masked. The vernier lines were moved either toward or away from the cued locations during the first 180

ms of their exposure. The direction of motion was varied randomly across trials. The observer indicated whether the perceived motion was clockwise or counterclockwise. Each observer performed 80 trials. The first 40 trials were practice trials without the cues in order to familiarize the observer with the fine motion discrimination task.

### Results and Discussion

The results indicate that the simulated vernier motion both toward and away from the cued locations was seen accurately (Figure 13b). The observers saw the motion away from the cued locations slightly more accurately, but the difference was not significant,  $F(1, 6) = 0.95$ , *ns*. This small difference was due to 1 observer, without whom the mean accuracies would be identical (99.2%) for the two directions of motion. Thus, the detectability of the simulated motion was extremely accurate and had no significant directional difference; the small trend found was, if anything, opposite to the prediction of the below-threshold hypothesis and the apparent-motion-masking hypothesis. Therefore, the recovery motion would have had an above-threshold motion signal and the cue-vernier apparent motion would not have masked it. These results indicate that there is no recovery motion; that is, the temporal reduction of the repulsion effect evident in Figure 13a was not processed as motion. This implies that the repulsion effect occurs at the processing level(s) where updating of position representation does not send projections to the motion processing mechanism. At that level of position processing, the labile initial representations might be lost in the temporal summation of position during a longer exposure of the vernier, as the process of forming a veridical representation continued.

If such temporal summation of position occurred over the entire exposure duration of the vernier probe, it could contribute to the long tails seen in Figure 13a. Because the perceived position would then be the temporal average of all positions occupied by the vernier probe over the course of its exposure duration, the perceived repulsion effect would have a tail that would remain even after the repulsion effect had ended, that is, even after the vernier had completely gone back to its veridical location. This is because the initial dislocation that was due to the repulsion effect would always be included in the temporal average or summation; in fact, the tail would diminish as  $1/[\text{time}]$  if the summation was linear.<sup>5</sup> The tail would also be longer if the initial displacement that was due to the repulsion effect was larger, generally consistent with the data shown in Figure 13a.

### General Discussion

The results show that a briefly presented vernier appears offset away, or repelled, from the flashed cue circles (Experiment 1). Neither figural aftereffects nor an apparent-motion-based illusion (representational momentum) can account for this repulsion effect. The effect of transient cues overrides the effect of long adaptation, which indicates that it is transient signals, not adaptation, that cause the repulsion effect (Experiment 2). The repulsion effect is undimin-

ished even when apparent motion goes in the opposite direction, which indicates that perception of apparent motion is unnecessary for the effect (Experiment 3).

Having rejected two obvious hypotheses, we examined whether the repulsion effect is due to focused attention. Voluntary attention in the absence of transient signals was shown to produce the repulsion effect (Experiment 4); a briefly presented vernier appears offset away from the foci of voluntary attention. The results also suggested that at least in our experimental conditions, the repulsion effect gives a more sensitive measure of voluntarily focused attention than does the standard target-detection task in which the facilitation of response time is measured.

In Experiment 5 we evaluated the hypothesis that the cue-induced repulsion effect is due to involuntary attention being momentarily captured by flashed cues. The repulsion effect was measured as a function of the cue-vernier SOA; the effect peaked at  $\sim 200$  ms of SOA and fell thereafter. This result is consistent with the temporal behavior of the acuity enhancement effect at cued locations (Nakayama & Mackeben, 1989) and corroborates that both effects are caused by cue-induced attention. Furthermore, the location of the peak did not shift when the cue-vernier distance was varied ( $2-8^\circ$ ), which indicates that the cue-induced repulsion effect is insensitive to the cue-vernier distance. This provides further evidence against a possible role of cue-vernier apparent motion and also indicates that the capturing of attention by transient cues does not take longer at more peripheral locations.

The effect of voluntary attention was also measured as a function of the cue-vernier SOA; about 120 ms was required for the voluntary-attention-induced repulsion effect to rise substantially above zero, in contrast to the 30 ms required for the cue-induced effect (compare Figure 11 with Figures 9 and 10). The difference of 90 ms provided a rough estimate of the time it takes an observer to recognize the shape to be attended and to engage voluntary attention there.

In Experiment 6 we addressed the question of how briefly the vernier should be exposed in order for the repulsion effect to be seen. The attention hypothesis predicted that the repulsion effect should fall considerably within 200 ms of vernier exposure; the prediction was confirmed. In Experiment 7 we examined why the putative recovery motion of

<sup>5</sup> Let  $r(t)$  be the temporal decay function of the vernier displacement caused by the repulsion effect and  $t_c$  be the time at which the vernier goes back to its veridical location; we have  $r(t) = 0$  for  $t$  equal to or greater than  $t_c$ . Now, let  $R(t)$  be the perceived repulsion effect, that is, the temporal average (summation) of the displacement,  $r(t)$ , over some exposure duration  $t > t_c$ . We then have  $R(t) = [\int_0^{t_c} r(t) dt] / t = \{[\int_0^{t_c} r(t) dt] + [\int_{t_c}^t r(t) dt]\} / t$ . But the second integral in the numerator in the last fraction is zero because  $r(t)$  is zero beyond  $t_c$ , so we have  $R(t) = [\int_0^{t_c} r(t) dt] / t$  for  $t > t_c$ .

Since the numerator is a constant (in time), the perceived repulsion effect,  $R(t)$ , decays as  $1/[\text{time}]$  after  $t_c$ . Note that the integral in the numerator grows monotonically with the magnitude of the repulsion effect; thus, a longer tail is expected for a stronger repulsion effect.

the vernier lines was never observed when long exposures were used. The simulated vernier motion, equivalent to the lowest estimated recovery motion, was accurately seen whether it was toward or away from the cued locations. That indicated that the recovery motion should be above threshold and not completely masked by the salient cue—vernier apparent motion, if it existed. The results thus implied that when a sufficient position signal is available, the distorted initial representations are irrevocably replaced by the stable asymptotic representation (perhaps via temporal summation of position) and that this updating of position representation does not feed into the motion perception mechanism.

The evidence from these experiments indicates that the repulsion effect is produced by involuntary and voluntary attention. Focused attention, either captured momentarily by transient cues or engaged voluntarily, repels briefly presented stimuli away from its focus. We now propose a hypothesis that the attentional repulsion effect represents a necessary cost of a general mechanism that operates to enhance perception at the attended location.

First we assume that positions are represented as the overall response patterns of a population of position-coding neural units. The position-coding units have spatially localized receptive fields (RFs) and collectively span the whole visual field. Cells in any visual area where retinotopy is preserved, such as those in V1, V2, V3, and V4 (e.g., Felleman & Van Essen, 1991), could serve as the position-coding units. It is reasonable to assume that a perceived position is represented by the centroid (first-order moment) of the response distribution of these position-coding units in the retinal space. Presentation of a vernier line at some distance from the focus of attention would activate a set of position-coding units whose RFs overlap the vernier line and fall within a range of distance from the attended location. The attentional repulsion effect requires that the position of the centroid of this response distribution be shifted away from the locus of attention. In other words, the response distribution should be skewed away from, that is, relatively depressed toward, the attended location.

This could be accomplished in at least three different ways. The first possibility is that the activity of the cells surrounding the focus of attention is suppressed perhaps via lateral inhibition—the surround suppression hypothesis. This could increase the spatial selectivity for the attended location by curtailing the interference from the most potent source of noise, the noise that is spatially proximate (e.g., Flom, Heath, & Takahashi, 1963; Toet & Levi, 1992). The second possibility is that focused attention recruits those units that are tuned to nearby locations—the RF recruitment hypothesis. The RFs near the focus of attention shift toward it. These recruited units respond less (than they normally would) to the stimuli distant from the attended location, producing the required skew in the population response (skewed away from the focus of attention). The recruitment of the neighboring units would also increase the sampling density at the attended location. The third possibility is that the position tunings sharpen (shrink) around the attended location—the RF shrinking hypothesis. Similar to the previous case of recruitment, the more sharply tuned RFs

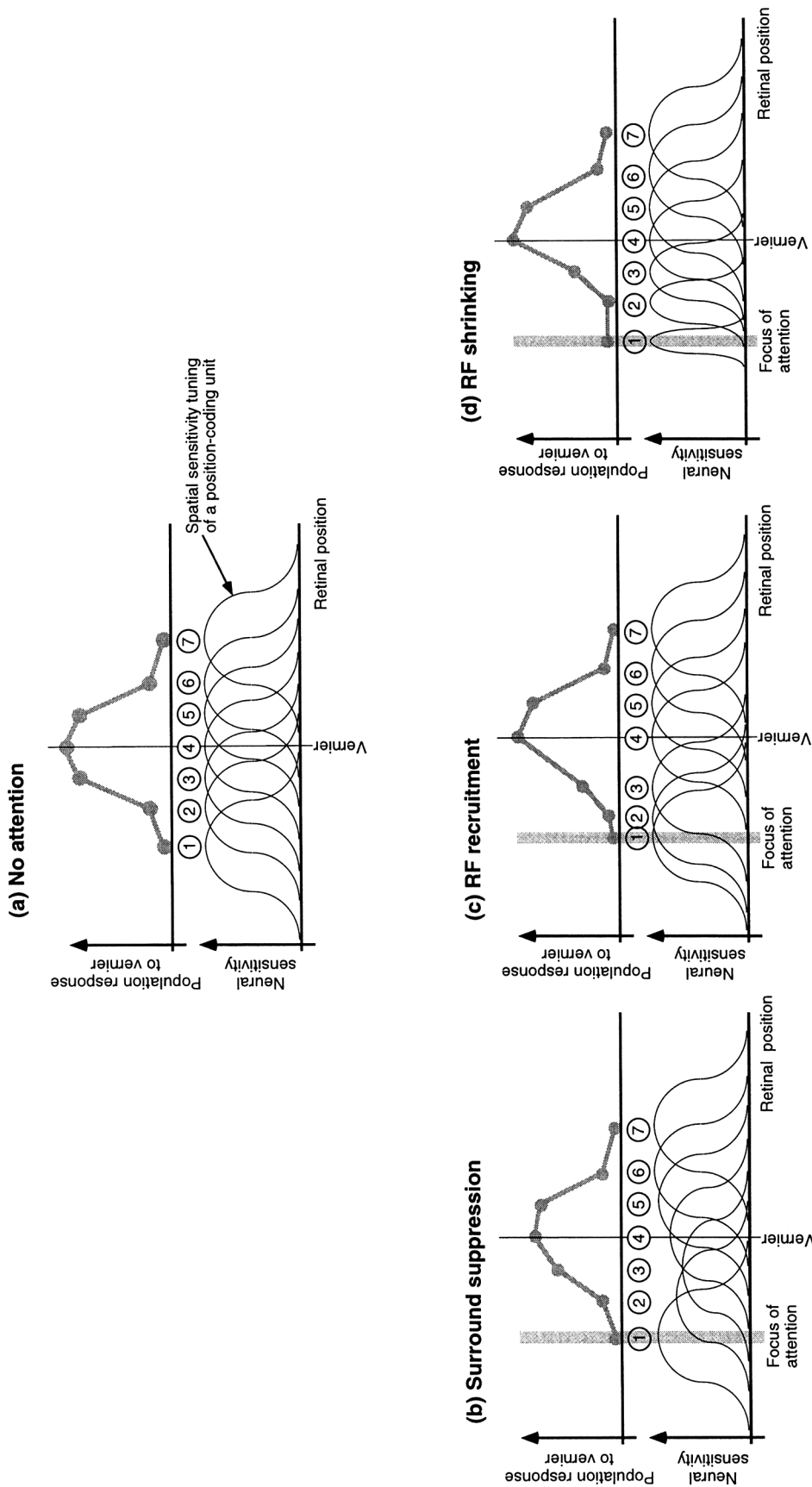
(shrunk RFs) near the focus of attention respond less to stimuli distant from the attended location, again producing the required skew in the population response (skewed away from the focus of attention). The sharper tunings would also enhance spatial selectivity at the attended location.

The last two possibilities, the RF recruitment and shrinking hypotheses, receive some empirical support. Connor et al. (1994) mapped out the RFs of V4 cells 100–200 ms following the flash of a task-relevant cue that presumably captured attention. They found that those RFs near the attended location shifted toward it, consistent with the RF recruitment hypothesis. Moran and Desimone (1985) reported that voluntary attention directed to one stimulus within the receptive field of a V4 neuron made the cell unresponsive to the other stimulus presented simultaneously but elsewhere within the same RF. Similar RF modulation was found in IT cells as well (Desimone et al., 1990). Desimone et al. proposed that RFs shrank around the focus of attention, though these authors never fully mapped out the reduced RFs. There is also evidence that orientation and color tunings of the cells in V4 sharpen when the discrimination tasks are made more difficult (Spitzer, Desimone, & Moran, 1988). The sharpening of orientation tunings of V4 cells is also found when the stimulus is reward contingent, that is, when the monkey receives rewards based on its response to the stimulus (Haenny & Schiller, 1989). These RF sharpening effects might be due to focused attention being induced by the increased task difficulty and reward contingency. These results provide evidence for the RF shrinking hypothesis. Next we briefly sketch how the three mechanisms—surround suppression, RF recruitment, and RF shrinking—might give rise to the observed attentional repulsion effect.

The bottom graph in Figure 14a shows spatial tuning curves of seven hypothetical position-coding units (seven humps), say in V4, tuned to adjacent positions in the retinal space. Each unit responds most strongly when the stimulus is presented at the position of its peak sensitivity, that is, at the position corresponding to the apex of its bell-shaped sensitivity curve. The response decreases as the stimulus is presented away from the apex; no response occurs if the stimulus falls outside the area of the bell-shaped tuning.

Suppose a vernier line is presented, say, centered at the RF of Unit 4 in the middle. The amount of response from each unit is given by the intersection of each tuning curve with the position of the vernier (middle vertical line in Figure 14a). Unit 4 responds most strongly because its tuning curve intersects the vernier at its peak. The tuning curves of the two adjacent units (Units 3 and 5) intersect the vernier at a slightly lower point, and the tuning curves of the next pair of adjacent units (Units 2 and 6) intersect at a much lower point. For the two most distant units (Units 1 and 7), the tuning curves never intersect the vernier position; thus, those units make no response. The top graph in Figure 14a shows the activity of the seven units in response to the vernier line. The position of each numbered circle along the abscissa represents the retinal position encoded by the corresponding unit. The overall pattern of population activity of these units is shown by the gray curve. The





**Figure 14.** An explanation of the attentional repulsion effect based on the modifications of spatial tunings (or receptive fields, RFs) of the position-coding units near the focus of attention. (a) Seven humps represent the position tunings (RFs) of seven hypothetical units tuned to adjacent retinal positions. The position of each numbered circle along the abscissa indicates the retinal position encoded by the corresponding unit. The gray points indicate the activity levels of these units in response to the vernier line presented at the RF center of the middle unit (Unit 4). The activity level of each unit is given by the intersection of its tuning curve and the vernier position (the middle vertical line). The centroid of the population activity corresponds to the perceived position of the vernier. With no focused attention, the centroid coincides with the vernier position of the vernier. (b) Shorter humps near the focus of attention represent the attention-induced suppression of sensitivity near the locus of attention. The centroid of the population activity is now shifted slightly to the right, producing a repulsion effect. (c) The humps near the focus of attention have been shifted toward the attended location, representing the attention-induced recruitment of RFs occurring near the focus of attention. Here we assume that the position-coding units are not labeled lines so that the shifts of individual RFs are completely compensated. This compensation is represented by the numbered circles (positions encoded by the units) being shifted to match the shifts of the RFs. Note that the centroid of the population response would shift even further to the right if this compensation was incomplete. (d) The humps have been crunched near the focus of attention, representing the shrinking of RFs (or sharpening of the spatial tunings) around the focus of attention. The population response is again shifted slightly to the right, indicating a repulsion effect.

position of the centroid (the vertical line that divides the gray curve into two equal areas) indicates the perceived position of the vernier. In Figure 14a, where focused attention is absent, the population activity is symmetric about the vernier position; that is, the centroid coincides with the veridical vernier position. The perceived vernier position is thus veridical in this case.

Figure 14b depicts the surround suppression hypothesis. In this example, attention is focused at the peak location of the leftmost position-coding unit (Unit 1). In response to the focusing of attention, the sensitivity of the units near the focus of attention is depressed (shorter humps near the focus of attention) perhaps through lateral inhibition (e.g., Benvenuto, Creutzfeldt, & Kuhnt, 1972; Hess, Negishi, & Creutzfeldt, 1975). The gray curve again shows the responses of the seven units to the vernier. Note that the responses from the units toward the focus of attention are reduced because of the attention-induced suppression of these units. As a result, the population response (the centroid of the gray curve) has shifted slightly to the right. Thus, the vernier appears displaced slightly off to the right from the veridical position, a repulsion effect.

The RF recruitment hypothesis is depicted in Figure 14c. In this case, the RFs of the units near the focus of attention shift to the left, that is, toward the locus of attention. This shift results in reduced responses to the vernier from the units near the focus of attention. This again shifts the population activity (the centroid of the gray curve) slightly to the right of the veridical position of the vernier, producing a repulsion effect. Here we assume that the position-coding units are not labeled lines (see Watson & Robson, 1981) so that the shifts of individual RFs are completely compensated. This compensation is represented in Figure 14c by the numbered circles' being shifted to match the shifts of the RFs; that is, the recruited RFs encode the new shifted locations. This compensation is necessary to be consistent with the fact that when the same shape is flashed twice in rapid succession, the second flash never appears larger. If the position-coding units were labeled lines, the second flash would appear larger because it would activate the units recruited by the first flash, which would still encode the unshifted positions. Note that the centroid of the population response would shift further away from the focus of attention if this compensation was incomplete.

Figure 14d depicts the RF shrinking (sharpening of tuning) hypothesis. Focusing of attention in this case sharpens the spatial tunings of the units near the focus of attention (narrower bell curves). This again results in the reduced responses to the vernier from the units near the focus of attention, resulting in a slight rightward skew of the population response. A repulsion effect is thus obtained again.

Note that the first two hypotheses, surround suppression and RF recruitment, also predict that the vernier line would be attracted toward the focus of attention if presented sufficiently close to it. In the case of surround suppression, if the line was presented closer to the focus of attention than the position of the most suppressed RF, the population activity would then be depressed away from the focus of attention, causing attraction (see Figure 15b). Similarly, for

RF recruitment, if the line was presented close enough to the focus of attention so as to activate the recruited units, the population activity would be higher toward the focus of attention, again producing an attraction effect (see Figure 15c). On the other hand, the RF shrinking hypothesis always predicts repulsion (see Figure 15d).

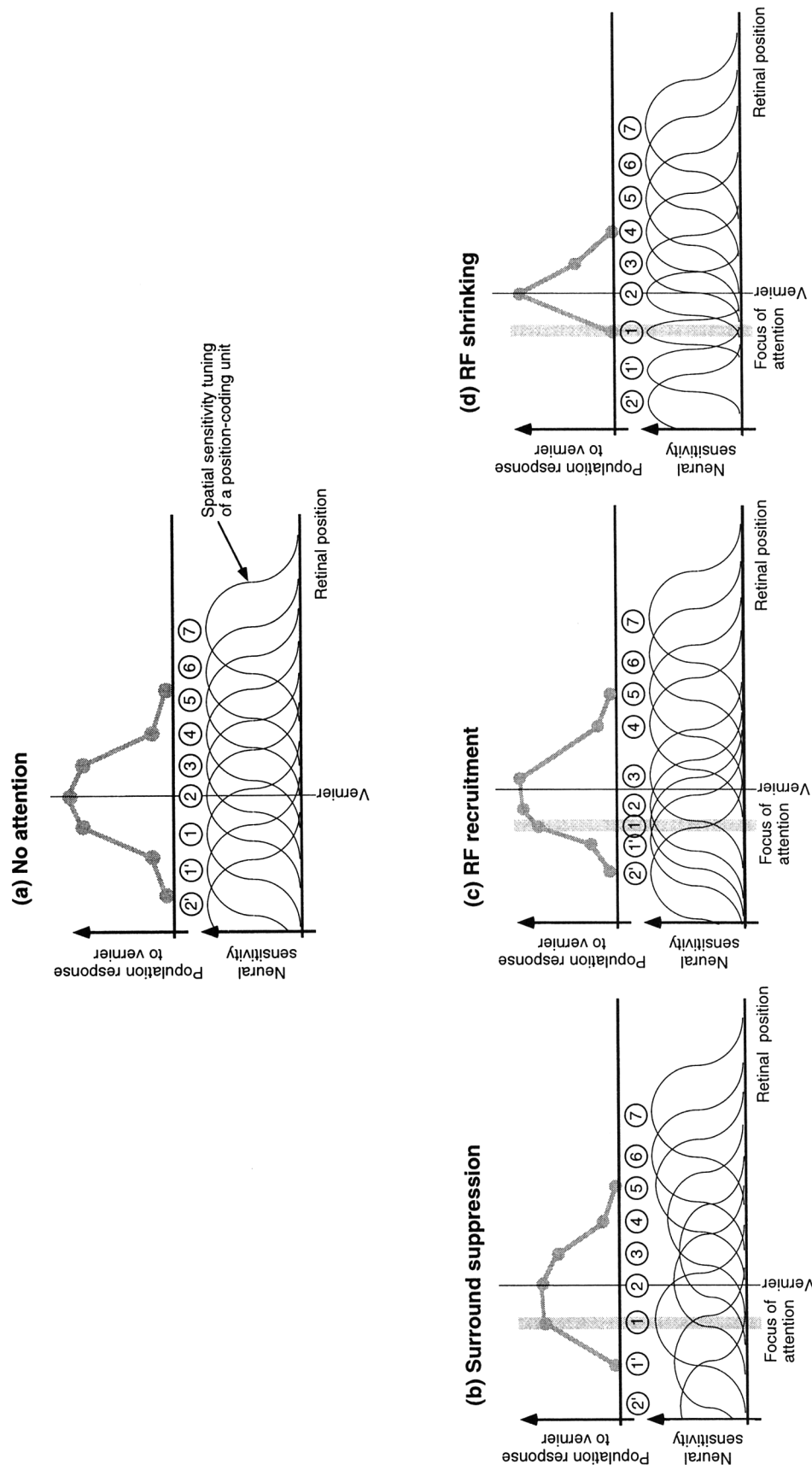
Although we have seen that the repulsion effect depends little on the cue-vernier distance in the range of 2–8° (Experiments 1 and 4), the effect might suddenly turn to attraction with shorter distances. The repulsion effect did turn to attraction when the cue-vernier distance was made less than 20–30' in a pilot study.<sup>6</sup> Although this seems to support the suppression and the RF recruitment hypothesis, the attraction in this range of distance could be due to contour interactions instead of the cue-induced attention. Contour attraction effects have been reported with sustained stimuli (with no possible effects of focused attention) for contour separations less than ~20' (e.g., Rentschler, Hiltz, & Grimm, 1975; Rivest & Cavanagh, 1996). We are currently designing experiments to tease apart the attraction effect that is due to attention from the attraction effects that are due to contour interactions and classic figural aftereffects.

We have seen that the attentional repulsion effect could result from (a) surround suppression, (b) RF recruitment, and (c) RF shrinking, all occurring around the attended location. The same neural mechanisms could also explain the attentional enhancement of visual perception, through (a) curtailing of proximate noise, (b) increasing of sampling density, and (c) sharpening of tunings.

The mechanisms presented here, however, are far from complete. The model's parameter values have been chosen only qualitatively to illustrate the point that a single mechanism motivated by the recent physiological findings could account for both the perceptual enhancement and the repulsion effects at the focus of attention. The model is problematic if Figure 14 is taken literally because many parameters depicted there are actually free parameters. In particular, if all position tunings were of the same size and modulated by attention in the way depicted in Figure 14, the repulsion effect would be a peaked function of the cue-vernier distance instead of a flat function obtained for a broad range (2–8°). We could easily modify the model, however, to explain the data by postulating particular eccentricity dependence<sup>7</sup> of its free parameters such as the scale of position tuning, the amount of attentional modulation, and the weighting of individual position-coding units in computing the activation centroid. As it stands, the model is quantitatively underdetermined and remains neutral as to the particular distance dependence of the repulsion effect except when, as discussed earlier, the distance is so small that the probe stimulus encroaches within the radius of the attentional RF modulation. In that case, the surround sup-

<sup>6</sup> To avoid stimulus overlap at small distances, we used vertical lines (identical to the vernier lines) instead of circles as the attentional cues. Otherwise, the experimental procedure was identical to that in Experiment 1.

<sup>7</sup> Note that in our experimental design, the distance was necessarily confounded with eccentricity.



**Figure 15.** An explanation of the attentional repulsion effect basically identical to that in Figure 14 except that the vernier is presented very close to the focus of attention. Two additional position-coding units (Units 1' and 2') are shown to the left of the focus of attention because the vernier is now within the range of their receptive fields in the cases of (a), (b), and (c). Note that negative repulsion (attraction) effects are predicted by the surround suppression and the receptive field (RF) recruitment hypotheses, whereas the RF shrinking hypothesis (d) still predicts a positive (repulsive) effect.

pression and the RF recruitment predict a qualitative change of the effect, from repulsion to attraction, a prediction seemingly supported by the pilot study.

In order to construct a more specific model, we must know more about how perceived position is represented in the brain. A moment of thought reveals that the way the visual system encodes a feature as simple as position is far more complex than it first appears. For example, position-based population responses occur simultaneously at multiple brain areas, including superior colliculus, V1, V2, V3, V4, and parietal areas (e.g., Andersen & Zipser, 1988; Felleman & Van Essen, 1991; Goldberg & Colby, 1989), where retinotopy (or spatiotopy) is preserved to various degrees. Not only that, but these multiple population responses also occur simultaneously at multiple scaling levels and at different cortical magnification factors across the visual field. No one knows how the final unitary percept of position emerges from these multiple codings. Two extreme possibilities would be (a) that the activity in a single area determines perceived position or (b) that perceived position is represented in the whole activation pattern of all relevant areas. In either case, however, it has yet to be shown how the visual system maps those heterogeneously anisotropic cortical spaces to the unified and isotropic space of the world. It could be that the unitary percept of position is an illusion (McCloskey et al., 1995). Thus, although we postulated V4 as the possible site of the repulsion effect, motivated by the recent physiological findings, the attentional distortion of RFs could be occurring at any level(s) of position representation, possibly excluding areas with strong projections to areas supporting motion analyses (as suggested by Experiment 7).

In conclusion, we have demonstrated that focused attention affects not only the quality of image representation, as reported by many (e.g., Colegate et al., 1973; Eriksen & Collins, 1969; Eriksen & Rohrbaugh, 1970; Hawkins et al., 1990; Nakayama & Mackeben, 1989), but also the form of image representation; both cue-induced attention and voluntarily engaged attention distort the representation of position. We propose that the distortion is integral to the mechanism by which attention enhances visual perception.

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