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Does attention follow the motion in the "shooting line" illusion?

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When a line is presented in the vicinity of a recent luminance change (peripheral cue), it is perceived to be drawn over time away from its "cued" end even though the line is actually presented all at once. This study was designed to determine whether attention, exogenously attracted to the cue, would come under the exogenous control of this illusory motion and follow the drawing motion from the cued end to its terminus. Each trial began with the display of four small squares at the corners of an imaginary square centered about fixation. On the critical trials, one of the four squares brightened briefly, after which a horizontal line was presented joining either the two upper or the two lower squares. Shortly thereafter, the distribution of attention was determined by asking the observer to indicate the nature of a change that was equally likely to occur to one of the squares. Responses to targets presented at a noncued location that was at the end of an illusorily drawn line were as fast as those to targets at the cued location and were much faster than those to targets at the remaining noncued locations. This pattern was not shown when the line preceded the cue, strongly suggesting that attention follows the motion in this illusion.

When a luminance increase is presented in the periphery and, subsequently, a line is presented in its entirety such that one end of the line is adjacent to the luminance increase, the line appears to be drawn away from the previously "cued" location. Although this illusion was initially reported by Kanizsa (1951, 1979), investigations of it were minimal until it was rediscovered by Hikosaka, Miyauchi, and Shimojo (1991, 1993a). Recently, there has been much interest in the degree to which *illusory line motion* (ILM; also referred to as the *shooting line illusion*, *induced motion*, and *morphing motion*) is mediated by, and therefore can be used as a measure of, the locus of visual attention (Hikosaka, Miyauchi, & Shimojo, 1993b; Klein & Christie, 1996; Schmidt, 2000). Several explanations (which are not mutually exclusive) have been proposed for this illusory motion experience (see Schmidt, 1998, for a review).

One explanation for ILM is the *attentional gradient account* (Schmidt & Klein, 1997). Surrounding a peripheral cue, and declining with distance from the cue, there is a reduction in transmission time through the visual system (Hikosaka et al., 1993a, 1993b; Laberge, 1983; Stelmach & Herdman, 1991) to mechanisms subserving awareness. Hence, when a line, presented instantaneously, falls along this gradient, points along the line are subject to a monotonic increase in arrival time with increasing distance from the cued end of the line. This situation creates precisely the signal that is interpreted as motion (see Reichardt, 1959), and that signal will be presented to all systems subsequent to where the gradient is implemented.

A second explanation is suggested by Downing and Treisman (1997), who posit that ILM is not a direct result of an attentional gradient simulating the low-level signal of a moving object but rather is a direct result of the high-level impletion process responsible for apparent motion. Downing and Treisman argue that the display conditions that produce ILM are ambiguous. The display may represent two separate nonmoving objects or a single object that moves and stretches. When presented with an ambiguous display, the visual system applies assumptions about the real world. A single object in motion is the simplest real-world interpretation of the ambiguous display, because it is less improbable than an object (the line) suddenly appearing. Although Downing and Treisman do not attribute a causal role to visual attention for ILM, they do include a role for the locus of attention. Downing and Treisman state that the interpretation of motion will be biased away from the locus of attention.

Carefully designed experiments have shown either that endogenously allocated attention does not elicit the illusion (Downing & Triesman, 1997; Klein & Christie, 1996) or that, when it does (see Schmidt, 2000, for such evidence and a review), the effect is very much less than what is observed following a peripherally presented cue. Attentional gradient accounts argue that ILM is associated with asymmetries in the distribution of visual signals reaching as

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yet undetermined brain systems and that, when ILM is observed following endogenous shifts of attention, this is due to attentionally mediated amplification of exogenous signals.

Thus, it is reasonable to assert that ILM is elicited by conditions that also attract attention exogenously. Furthermore, it is reasonable to assert that exogenous attention mediates the perception of ILM, either causally via an attentional gradient or indirectly by producing a bias in the interpretation of an ambiguous display. In the present study, we sought to determine whether a reverse relationship exists: When ILM is elicited by a peripheral luminance increment (or cue), does attention, which will have been attracted to the cue, follow the motion in the illusorily drawn line to its terminus? Before describing our method for answering this question, we must first briefly introduce attention as we explored it in this study.

When a brief luminance change is presented in peripheral vision, responses to targets presented shortly thereafter in the vicinity of the peripheral cue tend to be faster and more accurate than those to targets in other locations. Such a nonuniform distribution of performance across potential target locations is typically attributed to a shift of attention that is elicited by, and toward, the cue (Posner, 1980). Such performance asymmetries occur whether or not the luminance change is informative concerning the location of the upcoming target, though they tend to be bigger when the cues are informative (Jonides, 1980). For this and other reasons, it has been inferred that visual attention is automatically attracted by the luminance change. In the experiments to be described below, we inferred the locus of attention from performance differences among four possible target locations. It is methodologically pertinent that the performance improvement following a peripheral cue is transient and is followed by a performance decrement, which begins at about 200–300 msec after cue onset for simple detection tasks (Posner & Cohen, 1984; see Klein, 2000, for a review). This decrement has been referred to as *inhibition of return* (IOR). IOR may, or may not (Klein & Taylor, 1994), be evoked during discrimination tasks similar to those used in the present experiments, and when it has been observed, its onset has been significantly delayed relative to simple detection (Lupiáñez, Milán, Tornay, Madrid, & Tudela, 1997).

The central question of interest for this paper is, "What is the distribution of attention after ILM?" Since we may assume that the peripheral cue that produces ILM will also automatically attract attention, then at the beginning of the ILM, attention is focused at the end of the line from which the motion is generated. Both the gradient model and the impletion account can explain ILM without requiring that attention move from the cued location along the line to its destination. Nevertheless, such a movement of attention might be expected if the perceived onset of each point of the illusorily drawn line functions as a cue. Additionally, Ro and Rafal (1999) have shown that exogenous attention tracks a real moving stimulus. Although there have been no direct tests of the possibility that attention will track illusory motion, there is one study we are aware of that serendipitously reports pertinent data.

In a study of the role of attention in the object superiority effect, Cai and Chen (1993) reported higher target identification accuracy at a noncued location than at a peripherally cued location when these two locations were connected by a line that accompanied a target that was touching one end of the line. Without the connecting line, accuracy was higher at the cued location. For further discussion of this inadvertent evidence suggesting that attention follows the illusory motion, see the General Discussion section. The experiments presented here were specifically designed to determine the distribution of attention after ILM and measured both reaction time (RT) and response accuracy while controlling for any potential cuing or masking effects of the line itself.

EXPERIMENT 1

To determine the locus of attention, we measured performance on a two-alternative forced-choice task using the sequence of displays illustrated in Figure 1. Peripheral cues, when presented, consisted of a brief brightening of one of the boxes. Immediately after the cue, one of two horizontal lines (connecting boxes at the same height) might be presented, and then one of the four boxes changed in height. Only horizontal lines were used because there is a slight tendency for vertically oriented lines to be perceived to be drawn downward even in the absence of a cue. Cues had no predictive validity concerning the location of the line, and neither cues nor lines were predictive of the target's location. Therefore, any asymmetries in performance on the size discrimination task could be attributed to the exogenous (nonstrategic) allocation of attention in response to the display events.

In the absence of a line, we expected attention to be allocated toward the peripheral cue and, hence, expected performance to be faster and/or more accurate at the cued location than at a noncued location. On trials with cues, lines presented adjacent to a cued location will appear to be drawn away from that location. To the extent that attention is attracted by the illusory motion, performance at the noncued end of the line will be improved in relation to one or both of the following, critical, comparison conditions: (1) the other noncued locations in such a display (this comparison equates for cue presentation and illusory motion but distinguishes whether targets are located adjacent to a line, and (2) the end of a line that is not adjacent to the cue, and, hence, "nonmoving," but of equal distance from the cue (this comparison equates for adjacency to a line and distance from the cue but distinguishes whether the display includes the occurrence of ILM). In contrast, if attention is unaffected by the illusion, then performance at the noncued end of a cued line will not differ from either of these comparison conditions, presuming a line per se does not influence performance. Influence of the line

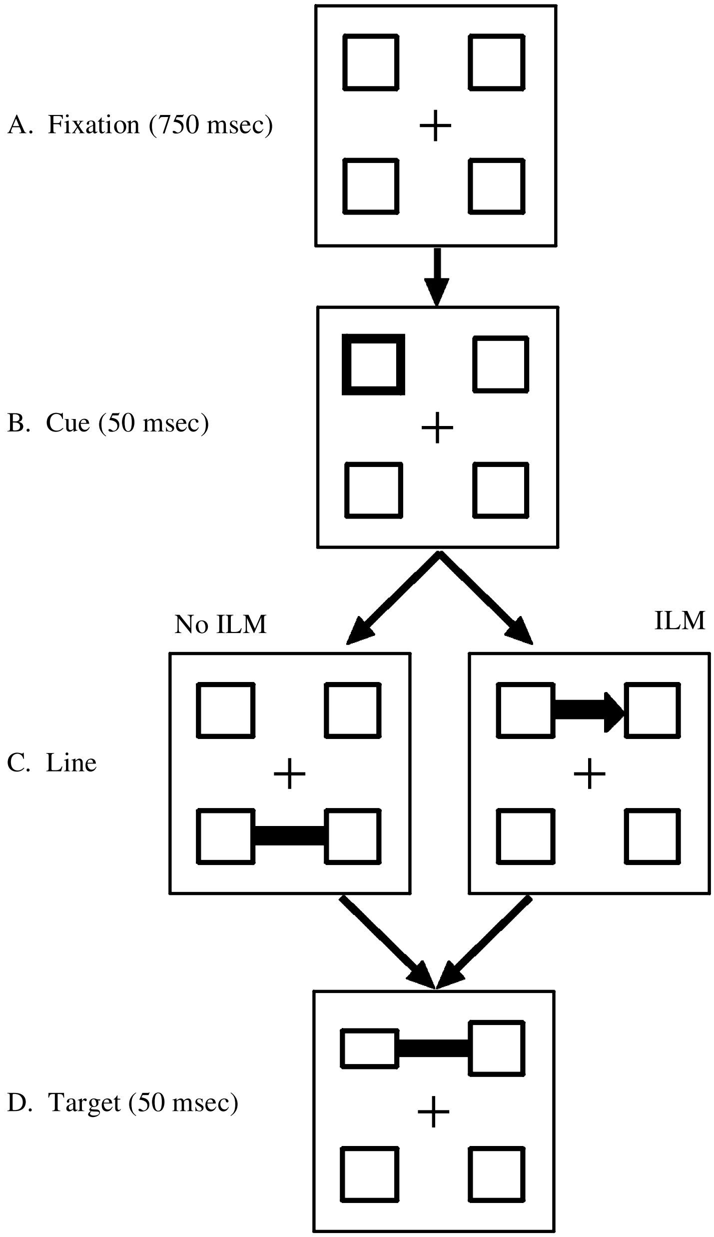

Figure 1: Sequence of events in a trial with a cue. A fixation cross and four boxes (A) were displayed for 750 msec. One of the four boxes brightened for 50 msec (B). At the termination of this cue, a line was displayed (C). When the line was not adjacent to the cue, there was no illusion of line motion (C, left); when the line was adjacent to the cue, illusory line motion was experienced away from the cue (C, right; the direction of ILM is indicated by the arrowhead). After 100 msec (in Experiment 1) or 150 msec (in Experiment 2), a target (one of the four boxes changed size) was presented (D) for 50 msec, after which all display elements terminated except the fixation plus, which was removed when the response was made. Note that, in the actual experiment, the background was dark gray and the displayed items were lighter (see text).

on performance was assessed using a control condition that included a line but no cue where targets might be "on" or "off" the line.

If, prior to the appearance of the target, attention consistently disengages from the cued location, follows the motion indicated by ILM, and reengages at the location indicated by the terminus of ILM, then performance at this terminal location will be faster/more accurate than at the initially cued end of the line. Additionally, performance at the previously cued end of the line will resemble that at noncued locations. However, such a complete reversal of cuing performance is not the only possible influence of ILM on the location/distribution of attention. For example, attentional stretching or mixture of trials where attention has moved and not moved would both indicate that attention "follows the line" to a degree. The present experiments were designed to determine whether—and if so, how—the distribution of attention is influenced by ILM.

Methods

Subjects. Twenty subjects (9 males, 11 females), between the ages of 18 and 36 years, participated voluntarily or received one credit toward an introductory psychology course.

Apparatus. The experiment was controlled by an IBM-compatible 486 computer with a SVGA monitor with 640 × 480 pixel resolution. Responses were made using the "1" and "2" keys of the number pad on a standard computer keyboard. In order to obtain ±1-msec accuracy in the timing of the responses, the keyboard was monitored as recommended by Brysbaert (1990). Millisecond timing routines were adapted from Crosbie (1989), with stimulus onset synchronized with the screen refresh as recommended by Heathcote (1988).

Display. The display background was a dark gray. Four lighter, square, unfilled boxes were presented at the corners of an imaginary square around a white fixation cross. Each of the boxes subtended 1.2° of visual angle. The target was a symmetric, 33% increase or decrease in the height of one of the four boxes. Because widths remained the same, one of the squares became a tall or squat rectangle. The distance from the center of a box and the center of the fixation cross was 3.9° of visual angle. A cue constituted the brightening of one of the four squares for 50 msec and then returning to its initial luminance. At cue offset, a line connected the two upper or lower squares. The line thickness was 0.4°, and it was just long enough to touch the edges of the two boxes it connected.

Stimuli and Procedure. The subjects' task was to respond as quickly and as accurately as possible, indicating whether one of the four target boxes changed to a horizontally (small) or vertically (tall) elongated rectangle. The subjects were to depress the "1" key to indicate a "small" response or the "2" key to indicate a "tall" response. The subjects were allowed to use the preferred hand to make this decision. In all experiments presented here, the subjects initially performed 16 trials on which only the targets (two "small" and two "tall" at each of the four locations) were presented, to familiarize themselves with the task. They were then given 96 practice trials that employed a noninformative luminance increase of one of the four boxes on 80% of the trials, to familiarize them with the temporal sequence of events. Since neither of these conditions addressed the influence of ILM on the locus of attention, they are not discussed further.

Prototypical trial. A trial began with the presentation of a white fixation cross located in the center of a dark gray computer screen (see Figure 1 for a diagram of a trial sequence). After a delay of 750 msec (see Figure 1A), one of the four target boxes brightened (Figure 1B) for 50 msec. At the termination of the cue, if present, the line was added to the display connecting either the lower or the upper two locations (Figures 1C, showing no ILM trials and ILM trials, on the left and right, respectively). After a 100-msec delay, one of the four boxes changed height (see Figure 1D). Fifty milliseconds after the target was presented, the screen returned to a dark gray field, except for the central fixation cross. A trial terminated when a response was made or when 4,000 msec from target presentation had elapsed, at which time all display elements were removed simultaneously.

The subjects were informed that although any one of the four locations might brighten and that lines would appear, these events did not predict which of the four locations was likely to contain the target. As such, they were told to ignore the flashes and lines and to maintain fixation and attention on the central cross. There were equal numbers of small and tall targets at each of the four locations for all trial conditions.

After completing the practice blocks, the subjects performed the experimental trials. The subjects performed 192 trials, with a break at the halfway point. There were 16 cued trials (cue and target in the same location), 32 neutral trials (no cue presented), and 48 noncued trials (cue and target in different location) for targets appearing adjacent to the line, and there were 16 cued trials, 32 neutral trials, and 48 noncued trials for targets appearing in a location not adjacent to the line. Again, target location, cue location (if any), line location, and target change (response) were completely counterbalance d, meaning that, regardless of cue location and/or line location, each of the four locations remained equally likely to be the target.

Results

Data from the experimental block were subjected to one-way, within subjects analyses of variance (ANOVAs). In order to address the questions of interest, planned contrasts were used to evaluate predictions. In order to more easily describe the contrasts that composed the analysis, the following section will first describe how the experimental data were organized.

Experimental trials fell into one of three display types, represented in Figure 2 as sections i, ii, and iii. Each trial contained a line connecting either the two upper or the two lower display locations. The layout of the figure represents prototypical trials of each type.

Section i represents neutral trials that did not contain a luminance flash. Cell A represents the 32 trials in which the target was presented next to the line. Cell B represents the 32 trials in which the target was presented away from the line. These are referred to as the *on the line* and *off the line* neutrals. Cells A and B are presented twice to fill the four locations of the display, but each cell median is entered into the analysis only once. Note, as with all the displays, there are an equal number (in this case, eight) of target presentations in each of the four display conditions making up Cells A and B.

Section ii represents trials in which the line was not presented next to the location of the luminance flash and, hence, was not expected to produce ILM. The thicker box at C represents the location of the luminance flash. For example, Cell C represents the 16 cued trials in which the line was not adjacent to the cued location. Cell D represents the 16 noncued trials in which the target was near the cue but not on the line.

Section iii represents trials in which the line was presented next to the location of the luminance flash. This line–luminance flash correspondence produced ILM away from the location of the luminance flash, represented by the arrow. Cell G contains data from the 16 trials in which the target appeared in the location of the luminance flash and in which the line was thought to show ILM away from the cued location. Similarly, Cell H represents the 16 trials in which the target location was not cued by the luminance flash but corresponded to the terminal location of the ILM.

Median RTs for each of these conditions were calculated as recommended by Jolicœur and Van Selst (1993)[1] to avoid the median sample size bias reported by Miller

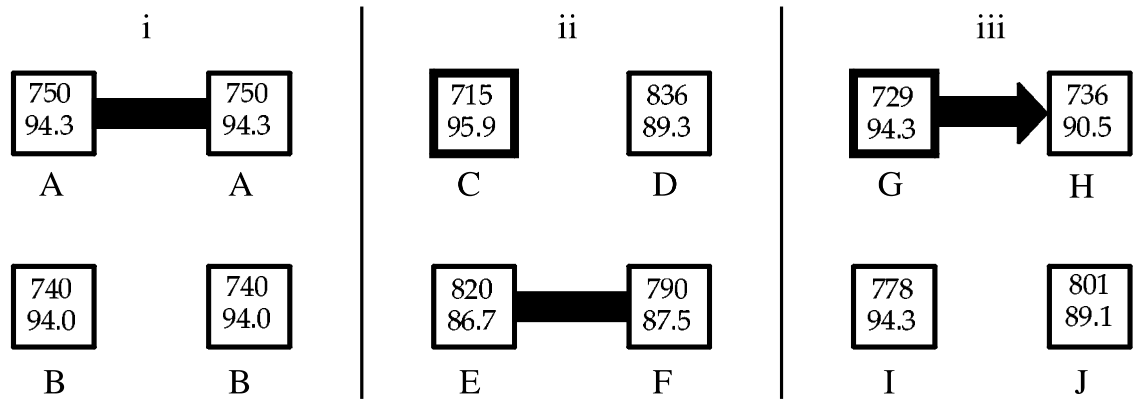

Figure 2: Diagram showing the three display types (i, no cue displays; ii, cued displays with no ILM; iii, cued displays with ILM). Median reaction time (in milliseconds) accuracy (% correct) for each condition of Experiment 1 are shown inside the box corresponding to the location of the target (note that reaction time is presented above accuracy in each box). Letters are used to label conditions for which performance data have been calculated. The cue and line locations shown are illustrative. In the experiment, these and the target location were random and uncorrelated. Contrasts used to explore these data are shown in Table 1 (see text for explanation).

(1988). The median RTs [$F(9,171) = 9.55$, $MS_e = 3{,}590$, $p < .001$] and accuracies [$F(9,171) = 4.41$, $MS_e = 50.38$, $p < .001$] are shown in Figure 2.

Contrast analysis. The following set of planned contrasts was employed to address questions of theoretical interest (see Table 1). Although the contrast set is nonorthogonal, orthogonality is not a requirement of a theoretically useful set of contrasts (Keppel, 1982), provided that caution is taken to avoid paradoxical explanations. Note that, because of the square display, the means for Cells F and J were not tested in the contrasts because of their increased physical distance from the cue relative to the terminal location of ILM, but the data are included in the tables and in the calculation of the MS_e term.

Line control tests. Contrasts 1 and 2 were used to determine whether merely being adjacent to the line influenced performance.

Tests for attentional cuing. Contrasts 3–5 compared the cued location with noncued locations on cued trials, to determine whether, as expected, the cue was attracting attention. Given the difficulty of providing truly neutral conditions, attentional resources were measured as the combined costs plus benefits by comparing the cued trials with the noncued trials. Contrast 3 compared the cued location when the cue was not next to the line with noncued locations from the same trials. Contrasts 4 and 5 compared the cued location when the cue was next to the line (producing ILM away from the cue) with noncued locations, to determine whether, in the presence of ILM, attention continued to be oriented toward the cued location. The far noncued trials were not included in these tests, in order to enhance the comparison with the critical contrast, which involved a near location.

Tests of ILM's terminal location. Contrasts 6–8 compared performance at ILM's terminus with performance at ILM's beginning location (Contrast 6) and with performance at other noncued locations (Contrasts 7 and 8). These contrasts determined whether performance at the terminus of ILM was similar to performance at a cued location (Contrast 6) or with performance at other noncued locations (Contrast 7 and 8).

Test to determine if attention was drawn away by ILM. Contrast 9 compared performance at the cued location under ILM and non-ILM conditions to determine whether

Table 1
Contrasts Used to Explore the Data

	Cell									
Contrast	A	B	C	D	E	F	G	H	I	J
1	1	−1	0	0	0	0	0	0	0	0
2	0	0	0	1	−1	0	0	0	0	0
3	0	0	2	−1	−1	0	0	0	0	0
4	0	0	0	0	0	0	1	0	−1	0
5	0	0	0	0	1	0	−1	0	0	0
6	0	0	0	0	0	0	1	−1	0	0
7	0	0	0	0	0	0	0	1	−1	0
8	0	0	0	0	1	0	0	−1	0	0
9	0	0	1	0	0	0	−1	0	0	0

Note—Letters correspond to conditions illustrated in Figures 2–4.

ILM had influenced the attention allocated to the cued location.

The statistical results of the contrast analysis are laid out in the columns under "Experiment 1" in Table 2, along with the statistics resulting from the contrast analysis of Experiments 2 and 3. Verbal description of the results and the corresponding data will be presented in the corresponding Results sections.

Summary of results. The following summary of the contrast analysis reflects the analysis of the RT data. Unless otherwise indicated, the analysis of the accuracy data supports the given interpretation rather than suggesting speed–accuracy tradeoffs. The contrast analysis revealed that being next to the line per se did not influence performance (Contrasts 1 and 2), therefore, any change in the distribution of attention toward the ILM terminus cannot be attributed simply to the presence of the line. Contrasts 3 and 4 revealed that RTs to targets in the cued location when not adjacent to the line were faster than RTs to targets at the near noncued locations. These findings demonstrate that attention was attracted to the location of the noninformative luminance cue. Contrast 5 showed that RTs were faster at the cued location from which ILM originated than were RTs at nearby noncued locations that were also on a noncued line. Contrast 6, however, revealed that when this noncued location was where ILM terminated, RTs did not differ from those at the cued location. Contrasts 7 and 8 supported the finding of Contrast 6, revealing that RTs at ILM's terminus were faster than those at other near, noncued locations. Finally, Contrast 9 showed that RTs at the cued location were not affected by the presence of ILM.

Discussion

In the absence of ILM, there were significant cuing effects, which is consistent with the proposal that attention was attracted toward to the cued location. Several comparisons revealed that the allocation of attention was strongly influenced by ILM. First, on trials in which ILM was elicited, the noncued location that was the terminus of ILM showed performance that did not differ from the cued location. This finding cannot be due to a general facilitatory effect when a target is adjacent to a line, because no such effect was obtained on the trials with no ILM (neutral trials or trials with cues when the line was not adjacent to the cue). Second, performance at the ILM terminus was better than that at the other noncued locations in a display in which ILM was elicited. Third, performance at the terminus of the ILM line was better than that at the equally distant end of a line in a display with no ILM. This pattern of results allows the conclusion that the distribution of attention is influenced by display conditions that result in ILM.

Although we might tentatively conclude that attention was regularly transported along the line away from the cued location, there are two findings that might argue

Table 2
Summary of Contrast Statistics for Reaction Time (RT) and Percent Correct From Experiments 1 and 2

		Experiment 1				Experiment 2			
		RT		% Correct		RT		% Correct	
Contrast	Purpose	$F(1,171)$	$p < .05$	$F(1,171)$	$p < .05$	$F(1,171)$	$p < .05$	$F(1,171)$	$p < .05$
1 (A vs. B)	Does the line influence performance in the absence of a cue?	<1.0	No	<1.0	No	<1.0	No	<1.0	No
2 (D vs. E)	Does the line influence performance when the line is not cued?	<1.0	No	1.35	No	<1.0	No	8.72	Yes; interferes
3 (C vs. D+E)	Are there more attentional resources at cued locations that are not on the line relative to noncued near locations?	142.02	Yes	49.10	Yes	68.10	Yes	8.60	Yes
4 (G vs. I)	Are there more attentional resources at the cued end of the line than at near noncued locations not connected to the line?	6.62	Yes	<1.0	No	5.88	Yes	<1.0	No
5 (E vs. G)	Are there more attentional resources at the cued end of the line than at noncued near locations at the end of a noncued line?	22.66	Yes	11.35	Yes	5.31	Yes	16.09	Yes
6 (G vs. H)	Are there more attentional resources at the cued end of the line than at the noncued end of the cued line?	<1.0	No	2.89	No	<1.0	No	2.29	No
7 (H vs. I)	Are there more attentional resources at the noncued end of a cued line than at noncued locations not on the line?	4.99	Yes	2.92	No	11.03	Yes	2.67	No
8 (E vs. H)	Are there more attentional resources at the noncued end of the cued line than at equidistant noncued locations on a noncued line?	19.53	Yes	2.79	No	10.25	Yes	6.25	Yes
9 (C vs. G)	Are attentional resources at the cued location reduced when the line is cued?	<1.0	No	<1.0	No	2.68	No	1.14	No

against this particular form of influence. First, performance at the cued location in the presence of ILM was not worse than that at the noncued location at ILM's terminus. Indeed, though neither effect was significant, performance at the cued end of a line tended to be more rapid and more accurate than performance at the motion terminus. Second, performance at the cued location in the presence of ILM did not differ significantly from performance at the cued location in the absence of ILM.

If attention is transported along the moving line, away from the cued location and toward the terminus of the motion, then one might reasonably expect the originally cued location to show some deterioration in performance when compared with performance when there is no ILM. Although not significant, there were slight trends in this direction with both RT and accuracy (9 msec and 1.6%). One possible interpretation is that attention does follow the motion in the "shooting line" illusion, but the timing of events in our experiment may not have been optimally aimed at obtaining evidence of this behavior. For example, according to one view of attention shifts (Posner, Cohen, & Rafal, 1982), if attention were drawn along the moving line, it would first have to disengage from the cued location, then move with the ILM, and, finally, reengage at the new location. Perhaps the 150-msec cue–target stimulus onset asynchrony (SOA) is insufficient to perform all of these stages.

EXPERIMENT 2

Experiment 2 was designed to replicate Experiment 1, with an additional 50 msec added to the cue–target SOA, in order to allow more time for the hypothetical shift of attention in response to the ILM to take place. Considering the resultant cue–target SOA of 200 msec, some reduction in the overall cuing effect was expected due to decay of purely exogenous orienting and the possible onset of IOR (Posner & Cohen, 1984). However, in Experiment 2, because the ILM–target SOA was 150 msec due to the presentation of the line at cue offset, if attention was carried toward the ILM terminus, it was not expected to reflect as much decay.

Method

Subjects. Twenty subjects (7 males, 13 females), between the ages of 18 and 42 years, participated voluntarily or received one credit toward an introductory psychology course.

Apparatus and Stimuli. The apparatus and stimuli were the same as those employed in Experiment 1.

Procedure. The procedure was the same as that employed in Experiment 1 with only the following change: The time between cue offset and target onset was increased to 150 msec.

Results

The analysis of the results employed the same contrast sets used in Experiment 1.

The median RTs (see Figure 3) were analyzed as in Experiment 1 and produced a significant omnibus F [$F(9,171) = 5.45, MS_e = 2{,}223, p < .001$], as did the analysis of the percent correct [$F(9,171) = 4.76, MS_e = 43, p < .001$].

The same contrasts were performed as for Experiment 1, and the results appear in the columns under "Experiment 2" in Table 2. As in Experiment 1, RT was unaffected by targets being adjacent to a line in the absence of ILM (Contrasts 1 and 2). However, following a cue, accuracy of performance suffered for targets adjacent to an uncued line (Contrast 2). All other contrasts revealed the same differences as in Experiment 1.

Discussion

The pattern of results from Experiment 1 was replicated in Experiment 2, which permits the same interpretation. As expected, due to the longer cue–target SOA, the cuing effect was reduced overall (Contrast 3, 113 vs. 61.5 msec), possibly reflecting the influence of IOR (Posner & Cohen, 1984). However, each finding from Experiment 1 relevant to the hypothesis that attention might follow illusory line motion was statistically replicated. RTs at the end of a

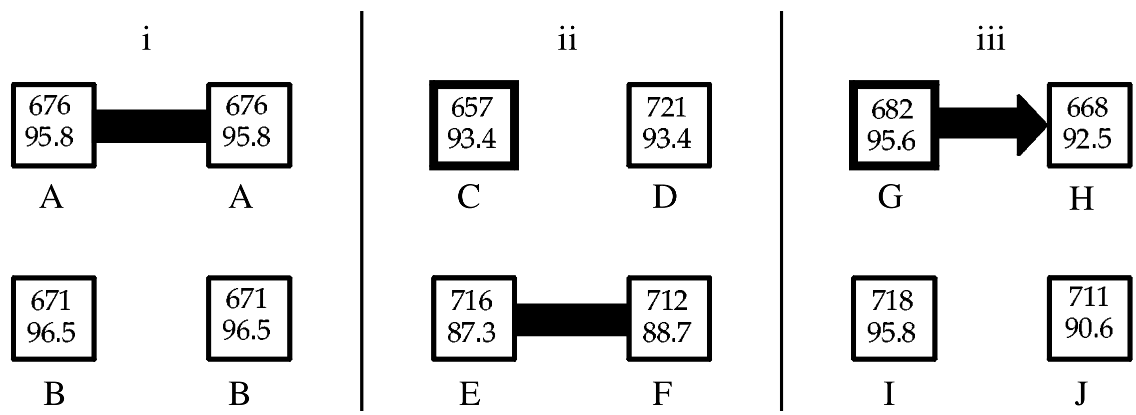

Figure 3. Design and data from Experiment 2. See text and Figure 2 caption for details.

moving line were not different from RTs at the cued location and were faster than RTs at the end of nonmoving lines in the presence of a cue.

However, if attention is leaving the cued location, then, as mentioned in the Discussion section of Experiment 1, performance at the cued location should suffer. Although RTs tended to be longer to cued targets at a location adjacent to a line than were RTs to cued targets that were not adjacent to a line, the accuracy data tend toward the opposite conclusion. This suggests that attention may not shift from the cued location, although it is allocated to the terminal location of the illusory motion.

The pattern of findings from the two experiments unambiguously demonstrates that the distribution of attention is influenced by the line only when the line connects the cued location to another. It is this situation that produces illusory line motion. We will consider two possible explanations for our finding that performance is roughly equivalent at the cued location and at the terminus of ILM, both of which are consistent with the conclusion that attention is influenced by the presentation of the line at the cued location. For this part of the discussion, we will assume that the influence on attention is a result of ILM. We will subsequently consider an alternate explanation, which we tested in Experiment 3.

One possibility is that attention disengages and shifts to the terminal location only on some proportion of trials. This explanation is based on the notion that performance in both conditions is due to a mixture of attended and unattended trials. Suppose we tentatively assume that attention is drawn away from the cue by ILM on most trials. In the discussion that follows, the letters in parentheses indicate the cells from which the data in Figures 2 and 3 have been combined to yield the numbers in parentheses. In this case, RT at the terminus of ILM (H = 702) would be more similar to that at a cued location with no ILM (C = 686) than it would be to a noncued location (E = 768, and I = 748), which is what we observed. However, under this assumption, it would also be expected that the cued location with ILM would be most frequently unattended, and, therefore, RT in this condition (G = 705.5) should be more similar to noncued performance (E = 768, and I = 748) than to performance at a cued location without ILM (C = 686), which is clearly not the case. If we assume instead that attention is rarely drawn away from the cued location, the expectations are reversed and disconfirmed by the fact that RT to targets at the terminal location of ILM does not resemble that at the other noncued locations. The best match one can achieve with a mixture explanation is to assume that attention is split 50% between the cued end of the line and the motion terminus. In this case, the predicted RT for both ends of the cued line (either 717 or 727 msec, depending on whether a noncued location from a display with ILM or a noncued location adjacent to an uncued line is assumed to mix with the cued condition with no ILM) is greater than that of the RTs being predicted (702 and 705.5 msec) but might be regarded as close enough for the mixture view to be viable. Because such an even mixture of RTs from distributions with different means will necessarily have a variance that is larger than the variance of the component distributions, the mixture hypothesis can be tested by examining the within-subjects variance of the RTs in the component and hypothesized composite distributions. The average variance in the conditions with targets at the two ends of a cued line (by hypothesis, both of these might be a mixture) was 63,842. The average variance of the cued condition without ILM was 89,640, and the average variance of the two noncued conditions was 71,350.5. Clearly, 63,842 is not greater than the variance of either of its hypothesized component distributions; therefore, we can reject the mixture hypothesis.

An alternative explanation, and one that we feel does a good job of accounting for our pattern of results, is based on a zoom lens model of attention (e.g., Eriksen, Pan, & Botella, 1993). Within this framework, we would suggest that the motion perceived in ILM stretches the boundaries of the attentional zoom lens to encompass the "moving" line without disengaging from the originally cued location. Eriksen and colleagues have typically assumed that when attention is allocated to a larger area, the overall cuing effect will be reduced because hypothetical resources are more thinly spread. If ILM from the cued location causes an expansion of the attended region, then we should expect to find that performance will not be as efficient as when a single location is cued and there is no ILM. To test this prediction of the zoom lens interpretation of our findings, we combined the data from the two experiments to increase our power, and we performed a contrast testing whether the cued location with no ILM (C = 686) was faster than the average of the cued location with ILM (G = 705.5) and the terminal location of the ILM (H = 702). This contrast was significant [$F(1,39) = 5.38, p < .05$], providing converging evidence in support of the spread of attention interpretation of our findings.

The results from Experiments 1 and 2 indicate that the distribution of attention following an exogenous cue will change if a line is subsequently presented adjacent to the cued location. Under these display conditions, the line will be perceived to be in motion away from the original focus of attention. The change in the spatial distribution of attention is consistent with the interpretation that attention is attracted by the perception of the illusory motion and, as a result, expands in a zoom lens fashion. However, before we could conclude that ILM was the critical factor that influenced the distribution of attention in Experiments 1 and 2, we had to rule out an alternative based on the spread of attention to noncued regions of a cued object (Egly, Driver, & Rafal, 1994).

EXPERIMENT 3

Egly et al. (1994) were the first to show that when attention is directed to one end of an already-present object by an informative peripheral cue, performance is better at the other end of the cued object than at an equivalent location (equieccentric and equidistant from the cue) on an uncued object. This "object-based" attentional cuing effect (which has been replicated and extended in other laboratories, e.g. Abrams & Law, 2000; Maquistan, 1997) might explain the present findings as follows. Attention is attracted to the cue, and the subsequent presentation of the line joins the cued square and one uncued square into a barbell-like object. As in the object-based cuing literature, attention spreads along the object that was formed by the line after the cue. There is one aspect of the pattern from Experiments 1 and 2 that is somewhat challenging to an object-based spread of attention as an alternative to the proposal that attention "follows," or is stretched by, the illusory line motion. In Egly et al. and subsequent studies demonstrating that attention spreads along a cued object, RTs to targets at the cued location are significantly faster than to targets at the uncued location on the cued object, and object-based cuing is demonstrated by reduced costs at the invalid-cued-object location relative to the near end of the invalid-noncued-object(Abrams & Law, 2000; Egly et al., 1994; Macquistan, 1997). In our experiments, performance in these two locations did not differ. Similarly, in Abrams and Law (2000, Experiment 4), performance was equal between the cued end and the noncued end of an object only under display conditions in which ILM type effects may have occurred. We will return to this point in the General Discussion section. Experiment 3 was conducted to directly compare the object-then-cue procedure that has been used in the object experiments with the cue-then-line (object) procedure used here, while reducing the "objectness" of the barbell-like stimulus created once the line is presented.

If the line appears at the beginning of the trial, then no ILM will occur when one end of the line is cued. On the other hand, object-based cuing would still be expected. Therefore, in Experiment 3, we compared the condition that we used in Experiments 1 and 2 (cue-then-line) with the display sequence that has been used in experiments of object-based spread of attention in which the object is instantiated before the cue. If the effects of attentional spread in Experiments 1 and 2 were due to object-based influences, then similar findings should be shown regardless of when the line is presented in the display sequence.

Because the alternative explanation for the present findings involves the spreading of attention along a cued object, we included a small gap between the line and the adjacent squares. If attention is spreading from the cued end of the line to the other end because the two squares and the connecting line form an object, then reducing the objectness of the display by placing the line between, but not touching, the location markers should reduce the attentional effects at the ILM terminus. On the other hand, if attention is tracking the ILM, then, because ILM is still obtained under these conditions (Downing & Treisman, 1997),[2] attention should spread so long as the line is presented after the cue. In contrast, object-based cuing effects should be reduced, or eliminated, because the gap between the boxes and the line prevent the formation of a single object. However, if object-based cuing is still present, it can be measured by the trials in which the line precedes the presentation of the cue. Therefore, if the pattern of results found in Experiments 1 and 2 were replicated in Experiment 3 for the ILM trials but not for the object trials, we may assert that the attentional benefits shown at the terminous of ILM are a result of the ILM rather than a result of object-based cuing effects.

Method

Subjects. Twenty subjects (5 males, 15 females), between the ages of 18 and 48 years, participated voluntarily or received one credit toward an introductory psychology course.

Apparatus and Stimuli. The apparatus and stimuli were the same as in Experiments 1 and 2, with one exception: The horizontal line did not touch the two boxes between which it was placed; instead, there was a 0.2° gap between each end of the line and the adjacent box.

Procedure. The same basic procedure was employed as in Experiment 2, with the number of trials doubled. The additional trials, referred to as the *object* trials, differed from the ILM trials only in that the line appeared at the start of the trial when the boxes were presented rather than at cue offset. Object and ILM trials were mixed together and run in one block, with three breaks. This block was preceded by a practice block with a representative sample of 96 practice trials.

Results

In order to keep the analysis as similar as possible to that of Experiments 1 and 2, the data for the object trials and ILM trials were analyzed in separate one-way ANOVAs. The analysis of the results employed the same contrast sets as used in Experiments 1 and 2.

ILM trials. The median RT and percent correct for the ILM trials are shown in the upper panels of Figure 4. Both omnibus Fs reached significance [RT, $F(9,171) = 7.46$, $MS_e = 2,368$, $p < .001$; percent correct, $F(9,171) = 4.15$, $MS_e = 79$, $p < .001$].

The contrasts described previously were performed and are reported in the columns under "Line After Cue" in Table 3. All of the key findings from Experiment 2 were replicated: (1) There was no effect of the line per se (Contrasts 1 and 2); (2) the cue was effective in attracting attention (Contrasts 3–5); and, critically, (3) RT to targets at the noncued end of the cued line (H = 664) was much more like RT to cued targets from the same trials (G = 668) (Contrast 6 was not significant) than to near noncued targets (E = 721; I = 696) (Contrasts 7 and 8 were significant). Two differences should be noted: (1) Apparently strongly supporting the proposition that attention "follows" ILM, Contrast 9 revealed that, for RT, there was a significant reduction in the degree to which the cued location was attended when ILM might draw attention away (G = 668 > C = 630) from the cue. Because the same contrast with accuracy was marginally significant in the opposite direction, the RT difference should be interpreted cautiously, since it might have been due to a speed–accuracy

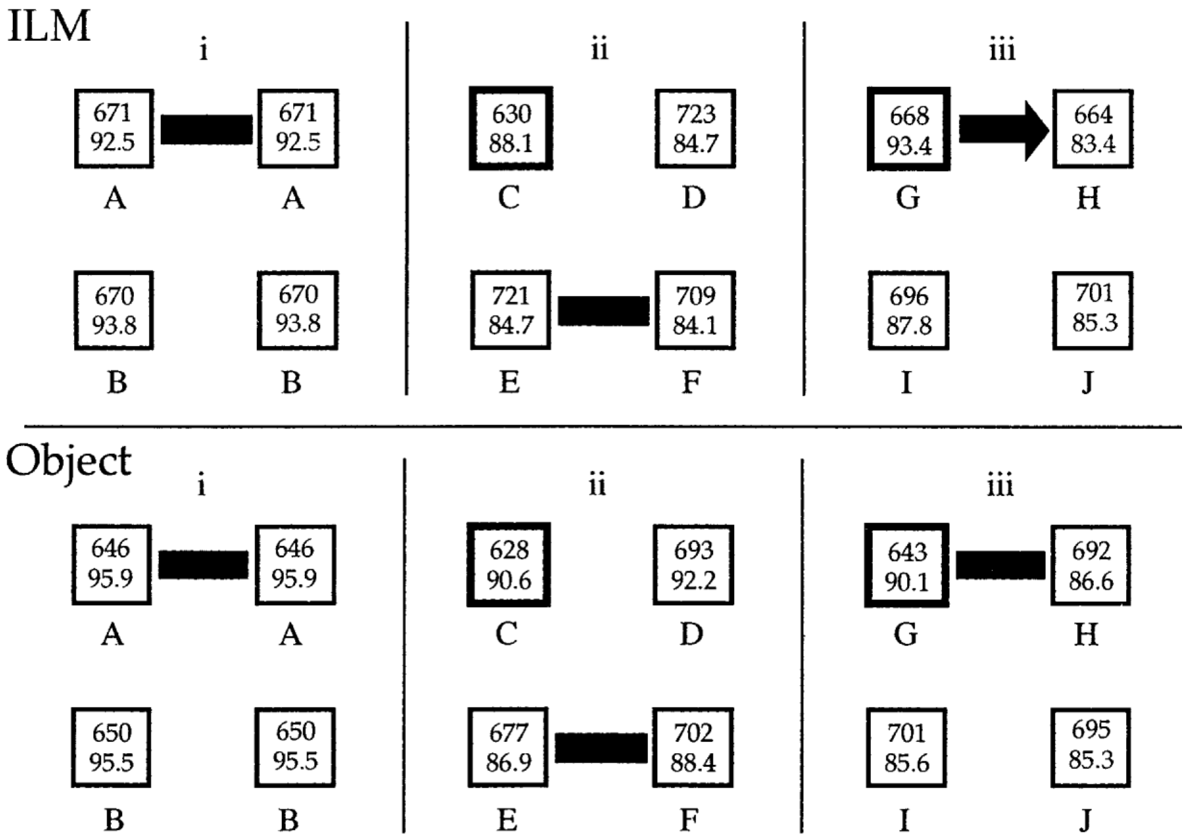

Figure 4. Design and data from Experiment 3. Upper panel shows the data from trials for which the cue preceded the lines and ILM would have been experienced when the line was adjacent to the cue (iii). Lower panel shows the data from trials for which the lines were presented in the fixation array at the beginning of the trial and no ILM would have been experienced. See text and Figure 2 caption for details.

tradeoff. (2) Performance was significantly more accurate at the cued location than at the noncued end of the cued line. Although this suggests that the spread of attention was not as great in this experiment as was found in the previous two experiments, accuracy at the ILM terminous was not different from that of the cued location that was not adjacent to the line [$t(19) = 1.56, p > .1$]. Therefore, the initial difference is probably reflective of a speed–accuracy tradeoff at the ILM starting location, as suggested by Contrast 9. Note, however, any speed–accuracy tradeoff interpretation only serves to equalize performance at the cued locations and does not explain the performance benefits at the terminal location of ILM (Contrasts 7 and 8).

Object trials. The median RT [$F(1,171) = 7.44, MS_e = 2{,}123, p < .001$], and the percent correct [$F(1,171) = 5, MS_e = 5{,}464, p < .001$] for the object trials are shown in the lower panels of Figure 4. The results of the contrast analysis for this condition may be found in the columns under "Line Before Cue" in Table 3.

Unlike the ILM trials, no evidence was obtained for attention being directed to the noncued end of a cued line (Contrast 6 was significant, showing performance was better at the cued location; Contrasts 7 and 8 were nonsignificant, showing that performance at the end of the cued line was not different from that at other near noncued locations). Similarly, a line being adjacent to the cue did not affect performance at the cued location. Apart from the lack of evidence for attention being directed to the noncued end of the line, all other effects were similar to those of the previous experiments: The presence of a line had little effect on performance,[3] and the cue was effective in attracting attention (Contrasts 3–5).

Discussion

With the ILM trials, the pattern of results found in Experiments 1 and 2 was replicated. Again, evidence that attention has been distributed to the ILM terminus location was obtained. Although, on the basis of RT, attentional resources appeared to have been equal at the cued and noncued end of the line, the accuracy data suggest that there may have been more resources at the cued end. This may have been a result of the weaker ILM produced under the gap condition or as a result of the removal of object-based spreading of attention. In either case, performance at the terminal location of ILM was better than that at the

Table 3
Summary of Contrast Statistics for Reaction Time (RT) and Percent Correct From Experiment 3 for the ILM and Object Trials

		Line After Cue				Line Before Cue			
		RT		% Correct		RT		% Correct	
Contrast	Purpose	$F(1,171)$	$p < .05$	$F(1,171)$	$p < .05$	$F(1,171)$	$p < .05$	$F(1,171)$	$p < .05$
1 (A vs. B)	Does the line influence performance in the absence of a cue?	<1.0	No	<1.0	No	<1.0	No	<1.0	No
2 (D vs. E)	Does the line influence performance when the line is not cued?	<1.0	No	<1.0	No	1.20	No	5.26	Yes
3 (C vs. D+E)	Are there more attentional resources at cued locations that are not on the line relative to noncued near locations?	48.11	Yes	1.99	No	20.40	Yes	<1.0	No
4 (G vs. I)	Are there more attentional resources at the cued end of the line than at near noncued locations not connected to the line?	3.22	$p = .07$	4.00	Yes	16.09	Yes	5.26	Yes
5 (E vs. G)	Are there more attentional resources at the cued end of the line than at noncued near locations at the end of a noncued line?	11.91	Yes	9.67	Yes	5.54	Yes	3.08	$p = .08$
6 (G vs. H)	Are there more attentional resources at the cued end of the line than at the noncued end of the cued line?	<1.0	No	12.62	Yes	11.11	Yes	3.57	$p = .06$
7 (H vs. I)	Are there more attentional resources at the noncued end of a cued line than at noncued locations not on the line?	4.24	Yes	2.42	No	<1.0	No	<1.0	No
8 (E vs. H)	Are there more attentional resources at the noncued end of the cued line than at equidistant noncued locations on a noncued line?	13.08	Yes	<1.0	No	<1.0	No	<1.0	No
9 (C vs. G)	Are attentional resources at the cued location reduced when the line is cued?	6.13	Yes	3.56	$p = .06$	1.02	No	<1.0	No

other noncued locations of equidistance from the cue. In contrast to the ILM trials, when the line appeared at the beginning of the trial, there was no evidence that attention, which had clearly been attracted to the cue, had shifted to the other end of the cued object ($H = I \geq E$).

On the basis of the results of Experiments 1, 2, and 3, the simplest explanation for the present findings is that, under conditions of ILM, attention will spread to the terminal location. Furthermore, this spreading of attention cannot be explained using the object-directed attention principles suggested by Egly et al. (1994), because it was not observed at all when the line was presented before the cue. The present findings of Experiment 3, however, are not presented as conflicting with Egly et al.'s interpretation. ILM cannot explain the object-based attentional findings because Egly et al. did not present the object postcue, which is required for ILM to occur. Moreover, Experiment 3 introduced a gap between the cued location and the line stimuli to disrupt the possibility that they would form a single object. To the extent that one wishes to accept the null hypothesis, we can only suggest that the lack of evidence of object-based cuing demonstrates the success to which this manipulation achieved that goal.

GENERAL DISCUSSION

The results of the present experiments suggest that the distribution of attention will be influenced by the presence of ILM even when subjects are not told to expect motion in the display. When subjects are asked to determine the direction of motion or to rate the "strength" of the motion experience, perception of ILM could in part be due to the expectation of motion. However, the present subjects were not informed of the possibility that the lines might appear to move, nor were they asked to make any judgments about line motion. Because conditions under which ILM is assumed to occur show a different pattern of performance than those under which ILM is not thought to occur, we can infer that this difference in performance is a result of the automatic perception of ILM. Because of the automatic nature of ILM and its influence on the locus of attention, when examining studies of object-based attention, some consideration must be given to the possibility that the conditions used may elicit ILM (Cai & Chen, 1993). If a luminance cue is employed to attract attentional resources to a location where an object is subsequently presented, our findings suggest that ILM will manifest itself, causing the object to appear to emerge outward from the cued location. This illusory expansion will then attract attention so that it is distributed over the presented object. When this happens, the results would suggest that attention was directed to the object, which in fact it is, but in this situation the spreading of attention may not be mediated only by "objectness" per se, but it will also be attracted by ILM. Because the present findings demonstrate that attentional resources will be distributed in a pattern similar to that expected by object-based predictions in the presence of ILM, but not when the same display is presented in the absence of ILM, studies designed to test object-directed attention should avoid conditions in which the object is presented postcue. Abrams and Law (2000) explored object-based cuing; in their experiments in which the object preceded the cue, the noncued end of the objects showed reduced costs relative to other noncued locations. However, the noncued end of the object continued to show costs relative to the cued end of the object, similar to other findings (Egly et al., 1994; Macquistan, 1997) . However, in the one experiment in which the noncued end of the object showed equal attentional benefits as the cued end of the object, the exogenous cue was presented before the object display, as described above. We suggest that the additional cuing, beyond what can be explained by object-based attention, is due to cuing via ILM.

Additionally, Cai and Chen (1993) employed peripheral cues that were followed by connecting lines and a target task from which the locus of attention could be inferred. The purpose of Cai and Chen's experiments was to explore the effect of connectedness and attention on the object superiority effect. About 150 msec after the onset of a peripheral cue, a target appeared about 5.5° to the left or right of fixation. The target was accompanied by a horizontal line connecting the two possible target locations on half the trials. Cai and Chen found higher accuracy at the noncued location (relative to the cued location) but only when the line accompanied the target. Unaware of ILM, which would have undoubtedly been elicited in this situation, Cai and Chen's explanation focused on an interaction between the effect of peripheral cuing and connectivity. However, we believe that the findings reflect the influence of ILM automatically attracting attention to the noncued location. Indeed, the pattern of results in Cai and Chen's study is quite consistent with the possibility that attention is literally drawn away from the originally cued location, in contrast to our experiments, which suggest that resources are equal at both the cued location and the terminal location of a cued line. Whereas one can emphasize the difference in our findings, it is important to recognize that both studies imply that the allocation of attention is influenced by ILM and, in particular, that attention is allocated toward the terminus of ILM. The differences in results may be due to the use of a larger number of possible target locations in the present study. Because of the greater target location uncertainty in the present study (four possible locations rather than two), when attention has been allocated to an "uncertain" location, it may be more difficult to disengage. On the other hand, in Cai and Chen's study, the cues were informative (80% valid), whereas in the present study, they were not. Even though central cues that are informative elicit little (Schmidt, 2000) or no (Klein & Christie, 1996) ILM, it may be that the attentional control settings that subjects adopt to deal with cue–target contingencies and the target task strongly influence the degree to which exogenous signals affect the allocation of attention. In our study, the subjects should ignore the cues, which to a degree they cannot do. Nevertheless, their attentional control setting would be "Try to resist attending the brightening box and line onsets because these mean nothing and the task is a size discrimination." In contrast, in Cai and Chen's study, the attentional control setting should be to direct attention toward the exogenous cue, which indicates with 80% validity where the target will be presented. Perhaps in the presence of such a strong control setting in favor of attending to the exogenous signal, when illusory line motion emanates from the cued location, there is less resistance to its pull. Of course, the subjects realize that this motion is not informative, but there is insufficient time between the onset of the cue and the onset of the lines to permit the subjects to change their control settings. Note also that the gap introduced in Experiment 3 prevents the interpretation of the present results as arising merely from connectivity between the locations.

Whatever the underlying cause for the slightly different patterns of results in our study and Cai and Chen's (1993), it is important to consider that ILM appears to be an automatic process, which may arise because of an attentional gradient or a binding bias produced by attention. ILM attracts attentional resources to the terminal location of the ILM. The conditions under which resources will be reduced at the originally cued locations require further investigation to determine when, if ever, attention leaves the initial location and focuses only at the terminus. Researchers wishing to address issues such as connectivity and object-oriented attention must be careful to ensure that their results are not due to a form of ILM elicited by the temporal properties of the stimulus display.

Finally, if ILM is a result of an attentional gradient emulating the real onset asynchronies produced by a moving stimulus (Schmidt & Klein, 1997), then this suggests that attention would follow a real movement as well. In contrast to an attentional gradient explanation for ILM, Downing and Triesman (1997) suggest that ILM is a result of interpolation of events after the cue and line have been linked as a single object in motion, which likewise suggests that attention will track a real moving stimulus. Ro and Rafal (1999) have recently shown that exogenous attention will track a stimulus in motion. However, because these explanations of ILM posit a role for attention in the percept of illusory motion, the present results suggest that attention may be playing a part in creating its own cue.

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NOTES

1. Calculating the corrected median of an equal number of samples requires locating the middle two scores, x and y. The corrected median equals $0.760x + 0.238y$. With an odd number of samples, the previous to middle score (x) and the middle score (y) are combined as $0.258x + 0.742y$. Use of these calculations by Jolicœur and Van Selst (1993) removed the bias reported by Miller (1988), and their results have been replicated in this lab.

2. In a pilot study using the experimental display, 4 naive subjects rated the direction (left, right) and intensity (on a scale from 1 to 10) of illusory motion with and without gaps between the lines and cues. In the no-gap condition, when the cue was adjacent to the line, the intensity of the illusion was rated at 7.19 away from the cue. In the gap condition, the intensity was rated at 5.78 away from the cue. For lines not adjacent to the cue, the strength of the illusion was 1.41 away and 0.03 toward the cue for the nogap and gap conditions, respectively. Therefore, although the introduction of the gap may have slightly reduced the intensity of illusory motion, it was still present and robust.

3. Although Contrast 1 was not significant, Contrast 2 was significant with accuracy: On trials in which a box was cued that was not adjacent to the line, there was a significant disadvantage in accuracy at the near noncued location adjacent to the line (E = 86.9%) relative to the other near noncued location (D = 92.2%). Because RT was faster in the less accurate condition (though not significantly so), it is difficult to draw any firm conclusions about the effect of the line per se.

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