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Multiple-Location Access in Vision: Evidence From Illusory Line Motion

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Four experiments with undergraduates used illusory line motion (ILM) to contrast Z. W. Pylyshyn's (1989) FINST theory of spatial indexing with predictions made by unitary attention models. Multiple-onset stimuli were able to cause ILM at disparate, noncontiguous spatial locations. Consistent with gradient explanations of ILM and with FINST theory predictions, varying line-drawing speed and the number of stimuli revealed a decrease in ILM and a capacity limitation, respectively. Modeling analyses suggested a limit in the number of locations (5–7) that could elicit the illusion. Requiring participants to report the locations of all stimuli exhibiting illusory motion in a specified direction suggested parallel access to between 2 and 5 display locations simultaneously. The results of all 4 experiments were predicted by FINST theory but not by a broad class of unitary attention hypotheses.

Considerable debate has emerged concerning whether people have simultaneous access to information from multiple visual locations. Traditional "spotlight" theories of visual attention posit a unitary attentional "beam" that facilitates the processing of stimuli within its focus (Eriksen & St. James, 1986; Jonides, 1980; Posner, Snyder, & Davidson, 1980). Zoom lens variants of the spotlight account hypothesize that the area covered by the attentional focus can change according to task demands and the participant's intentions (Eriksen & St. James, 1986; Eriksen & Yeh, 1985). All of these theories agree that attentional facilitation is limited to a single contiguous region of visual space.

A number of findings that report the apparent processing of information from multiple spatially noncontiguous display locations present difficulties for spotlight theories of visual attention. Pylyshyn (1994; Pylyshyn et al., 1994; Pylyshyn & Storm, 1988) reported findings from a number of tasks in which it appears that participants have parallel access to information presented at several noncontiguous spatial locations. Visual tracking experiments show that participants can simultaneously track several randomly moving items among identical distractors and that response time to visual events involving any of the tracked items is faster than to events involving untracked items (Pylyshyn & Storm, 1988).

Using a visual search paradigm, Burkell and Pylyshyn (1997) have shown that several disparate items can be precued from among a larger set of similar elements and that these precued elements can be treated by visual processes as though they are the only items in the scene. Additionally, these studies showed that information from all of the indexed elements (two to five of them) was available for processing and that the time required to access this information was independent of its spatial location.

Additional experimental evidence has suggested that multiple, noncontiguous regions of the visual array may be simultaneously facilitated and accessed by visual attention. Kramer and Hahn (1995) found that an attentional cuing manipulation facilitated participants' ability to provide a match or mismatch response for two spatially separated letters, even when intervening distractor letters were presented. Those authors proposed that attentional selection was spatially confined to the target letter locations. Extending the cuing manipulation to encompass the distractor letter space resulted in poor task performance (the distractor letters now caused interference with the match–mismatch task), lending support to the suggestion that in the earlier experiment, participants were able to simultaneously access two spatially noncontiguous locations. Castiello and Umiltà (1992) reported attentional splitting only when existing objects explicitly marked the location and spatial extent of

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the locations to be attended. Wright (1994) reported similar results in experiments using single and multiple cuing designs. Regardless of whether one or two locations had been cued, a benefit in response time was observed to targets appearing at cued locations but not at uncued or between cued locations. Furthermore, there was no difference in response time in displays with one or two cues. Taken together, these results are inconsistent with the traditional spotlight view.

Data such as these prompted Pylyshyn (1989, 1994; Pylyshyn & Storm, 1988) to develop the FINST theory,[1] which postulates a preattentive mechanism capable of individuating a limited number of visual features. Spatial indexes, or FINSTs, are hypothesized to be drawn to visual locations by salient stimuli (such as onsets) and to make information about the features they index available to visual routines (e.g., Ullman, 1984), or to focused attention, for further processing. Thus, the FINST hypothesis would predict that the appearance of a new object in the visual field will automatically make information about it more readily available as a result of its becoming indexed by a FINST. Because the hypothesis posits the existence of a small number of FINSTs, it predicts the possibility that visual routines or focused-attention can access information at a number of locations in the visual field simultaneously (Pylyshyn, 1989).

We refer to the capability of simultaneously accessing information at several disparate display locations as having potential parallel access to information at those places. Having access to an object or place is different from carrying out an operation on it. The operands that the visual system operates on may be features or objects located at certain places in the visual field. Having access to these objects means that the visual system has a way to interrogate or to carry out some process over some or all of a set of objects in the visual field that have been indexed or, as we say, "FINSTed." Information about these features or objects can be accessed through FINSTs in any order determined by the nature of the process that uses them (be it a visual routine or a focused-attention task) without first scanning or searching. To have potential parallel access does not require that all indexed locations are processed simultaneously: They may or may not be processed in parallel depending on the nature of the task or of the visual routine that is using the index to gain access to scene information. What parallel access does entail is that the access mechanism itself does not need to constrain the processing to occur in any particular order given by the layout of the places. Thus, it is not necessary that object processing in a scene proceeds in a serial fashion.

A concrete way of thinking about FINSTs is to consider the role that the pointer plays in many procedural programming languages. The pointer provides a mechanism whereby information that is pointed to can be accessed by a process regardless of where in memory such information might actually be stored. FINSTs provide visual routines with a means of accessing information in the visual scene regardless of the precise location in the scene that the information originates. Like the pointer, FINSTs are abstract structures that are a part of the processing architecture: They are used by processes to consult information stored within data structures, but they are not themselves a process or a data structure. The main difference between pointers in many computer languages and the FINST proposal for vision is that the latter is accompanied by a mechanism that directs the assignment of FINSTs to scene elements and maintains that assignment despite changes in the location of the indexed elements. A pointer, on the other hand, is inert and has no primitive mechanism that ensures that the pointer remains bound to a particular data structure should the position of that data structure move (i.e., shift position in memory).

If people lacked a mechanism for indexing several places, then they would have to rely on some sort of strictly serial scanning process to locate the places and on some kind of location-encoding process to retain these locations. If they want to avoid positing scanning and coordinate-encoding processes, then there will have to have a primitive way of sending attention, action, or processing information from certain places. This is precisely the role that is filled by the FINST indexing mechanism. The FINST hypothesis is really a series of proposals for a primitive mechanism that operates on early saliency maps and that precedes the allocation of focused attention. Note that the FINST hypothesis has little to say about the nature of those maps or the influence on behavior that they yield; FINSTs are simply a mechanism that mediates information exchange and marks important locations in the visual field. (For a more general discussion of the FINST mechanism and its properties, see Pylyshyn, 1989, 1994.)

FINST theory is well aligned with the results of several investigations suggesting that the visual system has the capacity to prioritize access to a number of locations and that attentional processes gain access to (or select for processing) information from these locations according to their assigned priority level (e.g., Yantis & Johnson, 1990; Yantis & Jones, 1991). This task would seem to require preattentive processes to encode and maintain information about several locations simultaneously. Prioritization may result from other aspects of the overall system, such as a temporal decay of the representations that are individuated (see Yantis & Jones, 1991), or even explicit visual routines that subsequently order the allocation of attention. Important for FINST theory is evidence that several locations are simultaneously marked and that a mechanism is required that provides potential parallel access to information at several display locations.

Besides searching for evidence that many tasks of the

[1] FINST is a historical label that is no longer of any real consequence. This acronym, which is short for "FINger of INSTantiation," was first used in a visual image processing computer program (see Pylyshyn, Elcock, Marmor, & Sander, 1978) that required a spatial indexing mechanism of the sort that we are now hypothesizing that the human visual system uses. The term now performs the role of referring to spatial indexes along with the properties that FINST theory proposes such indexes exhibit.

human visual system require FINST indexes and that there are a limited number of indexes, a large part of our current research program involves investigating the empirical conditions under which index assignment and maintenance takes place. The goal of the current set of experiments was to investigate whether multiple-onset stimuli (i.e., visual objects appearing in space where no object had previously been; see Yantis & Jonides, 1984) at disparate locations could induce an attention-sensitive line-motion illusion to more than a single locus and, if so, to determine whether an upper bound on the number of such loci exists. Additionally, in the third experiment we investigated properties of the stimulus that might be used to draw the assignment of FINSTs. A fourth experiment was included to ensure that participants had parallel access to multiple spatial locations.

In all of the current experiments we used the illusory line-motion (ILM) percept of Hikosaka, Miyauchi, and Shimojo (1991, 1993a, 1993b). Those authors have demonstrated that a motionless line terminating near an exogenously cued spatial location incorrectly appears to be drawn away from the cue. To use this technique, one presents a probe line at any location in a visual display and asks participants about their motion percepts. Even if no real motion is involved in the line's presentation, it appears to be drawn away from the cued end.

Hikosaka et al. (1993b) hypothesized that attentional facilitation radiates outward in all directions from its strongest point, along a gradient that weakens with distance. Hikosaka et al. (1993a, 1993b) are not the first researchers to hypothesize a gradient of facilitation. On the basis of their data, LaBerge and Brown (1989; LaBerge, 1983; McCormick & Klein, 1990) proposed that facilitation accumulates at locations corresponding to features in the visual array. If such accumulations surpass a threshold value, then a channel of focused attention is hypothesized to open up at the facilitated location.

The illusion was explained by Hikosaka et al. (1993a, 1993b) within the attentional gradient framework by postulating that attention locally speeds the transmission of signals arising from locations closest to the facilitative focal point, resulting in information in the vicinity gaining entry for subsequent processing before more distant information (Stelmach & Herdman, 1991; Stelmach, Herdman, & McNeil, 1994). As a result, the end of the line closest to the facilitative center is processed before the line's other end. Motion processing mechanisms are assumed to be sensitive to the order of arrival of incoming signals, and, as a result, motion is detected away from the location of the initial signal in the direction of subsequent arriving signals. This direction is always away from the locally strongest location on the gradient surface.

The role of FINSTs in the illusion is to mediate signal transmission from the location on a saliency map (such as that postulated in models by Koch & Ullman, 1985) to downstream processing centers. Such processing might include visual routines involved in detecting the order of signal arrival and computing the motion direction and strength for various objects in the visual scene. FINST theory predicts that despite the possibility that visual routines involved in ILM operate in a spatially parallel fashion, there should be a limitation in the number of locations in the scene to which FINSTs can provide potential parallel access. The source of this capacity limitation is hypothesized to arise from a limitation on the number of FINSTs characteristic of the cognitive architecture.

In the first two experiments of our research, multiple peripheral cues were presented with sudden onset and then a single probe line appeared. This line always had the fixation as one of its end points, and sometimes it had one of the onset stimuli as its other end point. This enabled us to contrast the FINST hypothesis, which posits access to multiple loci, with the broad class of unitary attention hypotheses that suggest that information access should be limited to a single contiguous spatial location.

According to a simple spotlight view, focal attention should be captured by a single cue, leading to ILM on only a fraction of the trials (i.e., those trials in which the line happens to probe the attended cue). The predicted frequency of ILM would be $1/n$, where n is the number of cued locations in the display. By contrast, FINST theory posits that visual indexes provide potential parallel access to all indexed display items and predicts that the illusion will occur each time the line terminates on an indexed element. This should give rise to a much higher frequency of line motion that will be limited by the number of locations that can be simultaneously indexed.

Some spotlight theorists, notably those supporting a zoom lens account (Eriksen & St. James, 1986; Eriksen & Yeh, 1985), might object to the claim that if any subset of a number of multiple-onset stimuli is capable of evoking ILM, then potential parallel access is implied. According to a zoom lens account, this result could be accommodated by a single zoom lens of attentional facilitation encompassing a number of the cued locations. If this were the case, then facilitation would be distributed throughout the spatially contiguous spotlight area and the illusion would be expected to occur equally often at cued and uncued locations. In addition, the shape of the attended area would have to be limited to the peripheral ring of target positions to maintain a gradient between cued points and the center of the display for the line-motion illusion to occur. For cued points placed on opposite sides of fixation, this would require a level of control of the shape of the attentional field that is not supported by zoom lens theories. A second way of differentiating spotlight models from a potential parallel access model is that the latter predicts that all of the cued locations have the potential to support ILM, whereas uncued locations do not because they do not have indexes assigned to them.

According to the FINST hypothesis, if facilitation occurs at multiple noncontiguous regions, then line motion would be expected when multiple stimuli, but not the locations between those stimuli, are probed. If, on the other hand, facilitation and information access are limited to contiguous regions of space consisting of a single stimulus location, then line motion would be expected to occur for only a small portion of the randomly probed stimuli. If, as in the zoom lens account, the spotlight is assumed to expand to cover a number of stimulus locations, then ILM would be expected to occur when the (unfilled) empty space between stimulus locations is probed.

Experiment 1

In Experiment 1 we examined the frequency of ILM in response to multiple-onset stimuli distributed around the circumference of an imaginary circle. Participants were presented with displays containing two or four abrupt-onset stimuli. Probe lines either connected the center of the circle with a cued location or terminated within the empty space between two cued locations. The participants' task was to report the direction that they perceived the line to be drawn (toward or away from the display's center).

In Experiment 1 we used three different types of trials: those in which the line terminated on a cued location (i.e., on-item trials), those in which the line terminated in the empty space between two cued locations (i.e., between-items trials), and those that probed empty space without the presentation of any onset stimuli beforehand (i.e., catch trials). These different types of trials are illustrated in Figure 1.

Method

Participants. Twelve undergraduates participated in a single 20-min experimental session in exchange for course credit. All students reported normal or corrected-to-normal vision.

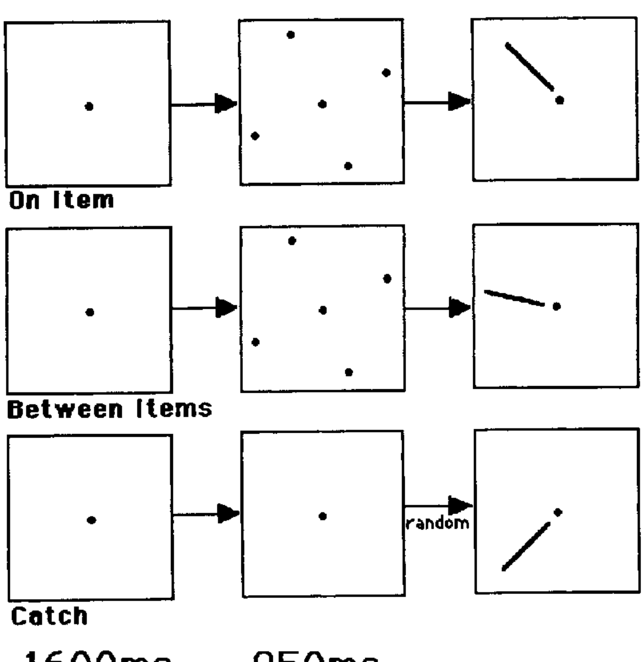


Figure 1. Experiment 1 trial sequence. Cued trials began with the presentation of a fixation point followed by the onset of either two or four stimuli. A line appeared 950 ms later probing a filled location in on-item trials or the empty space between two filled locations in between-items trials. During catch trials, no stimuli were present and the line terminated on a randomly chosen location.

Apparatus and stimuli. The stimuli were presented on a Tektronix 608 oscilloscope equipped with a fast-decay P15 phosphor. The oscilloscope was controlled by a point plotting buffer (Interactive Video Systems, Edmonton, Alberta, Canada; Finley, 1985) driven by an 80386DX microcomputer.

Stimuli were composed of single points (0.2°), and stimulus positions were evenly spaced around an imaginary circle (radius = 3.67°). The exact location of the stimuli varied from trial to trial. A single point in the middle of the display acted as the fixation point. The probe stimulus was composed of 15 evenly spaced points forming a line (2.7°) from the center fixation to the circumference of the circle. The line appeared on the radius 0.8° from the center fixation point and 0.18° from the location of the stimulus.

The oscilloscope's background was a dim green and had a luminance of 0.6 cd/m^2. The luminance of the stimuli and the fixation point was 3.0 cd/m^2, whereas a section of the line was 12.0 cd/m^2. Luminance was measured using a Minolta digital photometer directed at a single presentation of the stimulus. A full-field pattern (7.5° × 7.5°) composed of an array of 55 × 27 evenly spaced dots (0.2°) was used to signal the beginning of each trial.

Procedure. Each participant sat in a dimly lit room 57 cm from the display. His or her head was steadied by a head rest. Each trial was initiated by the participant's previous response or, in the case of the first trial in a block, by a buttonpress.

The sequence of events and their associated durations are shown in Figure 1. All the trials began with the appearance of a full-field pattern for 1,000 ms followed by a fixation point. After 1,600 ms, if the trial was not a catch trial, two or four stimuli appeared evenly spaced and randomly situated on the circumference of an imaginary circle. The stimuli remained for 950 ms, and all existing stimuli were then extinguished and replaced with a line between the fixation and a point on the circle's circumference. The line, which remained visible until the participant responded, terminated on a randomly chosen stimulus in on-item trials and between two randomly chosen stimuli in between-items trials. If the trial was a catch trial, no stimuli were presented, but the fixation point was visible for 2,550 ms before the probe line appeared on the circle's radius at a randomly chosen angle.

At this point in the trial sequence, the participants made a judgment about the line motion by pressing a button on the computer mouse, which initiated the sequence for the next trial. Participants were allowed to take a break at any point in the session by simply withholding their response, and they were explicitly given the opportunity to take a break every 50 trials.

Participants were instructed to maintain fixation throughout each trial (eye position was not monitored) and to use a chin rest to steady their head. They were then told that they would be viewing several trials and that their task was simply to determine whether a line that would appear was drawn from the outside of the circle toward the inside. If they detected the line being drawn toward the center of the display (the illusion), they were to press a button on the mouse marked "in"; otherwise, they were to press the other mouse button, which was marked "out."

Design. Two variables were systematically manipulated in the current experiment: probe line position (on-item or between-items) and display size (two or four stimulus positions). In addition, there was a group of catch trials to determine the frequency of spontaneous reports of the illusion in the absence of stimuli to ensure that participants were not simply guessing.

There was a total of 240 experimental trials composed of 60 on-item trials (20 of Display Size 2 and 40 of Display Size 4), 60 between-items trials (20 of Display Size 2 and 40 of Display Size 4), and 120 catch trials. The experimental session began with a block of 20 randomly selected practice trials. The order of trial delivery was randomly determined and was different for each participant. Data from practice trials were discarded.

Results and Discussion

The frequency of the illusion (percentage of "in" responses) in each condition with display items (on-item or between-items trials) was calculated and the data were analyzed using a 2 (probe line position) × 2 (display size) repeated measures analysis of variance (ANOVA). Cell means are plotted in Figure 2.

The probe position main effect confirmed that there was little facilitation at spatial locations unoccupied by visual objects (34%) compared with filled locations (87%), $F(1, 11) = 63.22$, $p < .0001$. The display size main effect was not significant.

The position of the probe line interacted with the number of stimuli present in the display, $F(1, 11) = 8.97$, $p < .01$. Tests of simple effects revealed that the illusion occurred more frequently, $F(1, 22) = 5.2$, $p < .05$, when the illusion occurred to an item in two-item displays (92%) than four-item displays (82%). When the line probed the empty space between two items, however, there was little difference between displays with different numbers of stimuli (35% in two-item displays vs. 34% in four-item displays).

To assess whether the level of line motion reported in the between-items condition was greater than in the catch condition, we conducted a one-way ANOVA to compare values collapsed across display size for on-item, between-items, and catch trials. The main effect was significant, $F(2, 22) = 60.28$, $p < .0001$, and was investigated using Tukey–Kramer pairwise comparisons among the cell means. Post hoc tests revealed significant differences ($p < .001$) between the frequency of the illusion in the on-item condition (87%) and both the between-items condition (34%) and the catch condition (34%). No difference was observed between the between-items and catch conditions. This observation verifies that probe lines terminating in the space between two filled locations revealed no more facilitation than probe lines appearing in displays that had no stimuli at all, supporting the notion that potential parallel access occurred.

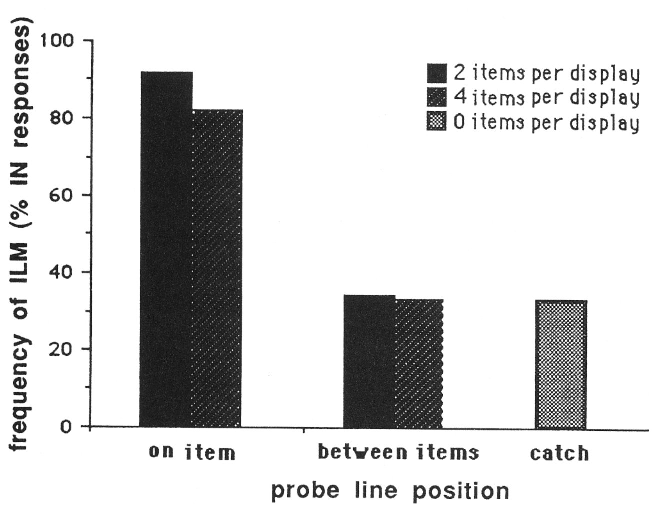


Figure 2. Frequency of illusory line motion (ILM) in Experiment 1.

A unitary spotlight account would predict that either a single display stimulus was being attended to (e.g., Posner et al., 1980) or that processing resources were targeting the entire cued area (e.g., Eriksen & St. James, 1986; Eriksen & Yeh, 1985). The failure to elicit the illusion as frequently when the location between two stimuli was probed compared with the probing of a filled location supports the notion that access is not necessarily limited to a single contiguous spatial area. The illusion occurred frequently when any one of the stimuli was probed, suggesting that it was not the case that a single isolated stimulus was being facilitated by a spotlight. The sites able to be accessed were occupied locations, not locations unoccupied by visual objects. A mechanism that enables multiple location access, with or without attention (such as that proposed by FINST theory), is necessary to account for these data.

Experiment 2

The results of Experiment 1 suggest that focal attention models are insufficient to explain some of the effects of multiple visual onsets because access to a number of display locations had the potential to be carried out in parallel. These results are consistent with either a limited capacity parallel model, such as the FINST theory, or an unlimited capacity parallel hypothesis. Distinguishing between these two possibilities would require us to examine the maximum number of loci that are capable of eliciting a line-motion illusion. According to the FINST hypothesis, under conditions similar to those in Experiment 1, it should be possible to observe an upper limit on the number of simultaneous locations at which the illusion can occur. Accordingly, in Experiment 2 we presented an increased number (one to eight) of abrupt-onset stimuli around the circumference of an imaginary circle. As in Experiment 1, a probe line appeared on the radius of the circle and participants reported the perceived direction of the line's motion. As before, the probe line appeared with either one end near an onset item or terminating in the empty space between two items.

We included another manipulation to examine the validity of the gradient hypothesis (Hikosaka et al., 1993a, 1993b) and to reduce the base frequency of inward judgments. In this experiment, test lines were actually drawn growing out from the fixation point toward the peripheral stimuli. If the illusion is attributable to differential signal transmission across a spatial gradient, it should be possible to decrease the frequency of ILM by counteracting the effects of the gradient with apparent motion in the opposite direction.

As in Experiment 1, contrary to spotlight accounts, a theory supporting potential parallel access would predict that multiple filled locations would be able to elicit ILM as long as a visual object, or facilitation from a nearby object, is present at the probe location. The FINST hypothesis would predict a limit to the number of onset cues able to support the illusion based on limits on the number of available FINSTs (see, e.g., Pylyshyn et al., 1994). Given the current experimental paradigm, such a breakdown would manifest itself as a gently sloped function with increasing numbers of display items, as opposed to a steep step. This function is a result of sampling the distribution of assigned indexes on a number of discrete occasions.

Method

Participants. Nine members of the university community were recruited to participate in a single 90-min session. Four participants were paid $15 to participate, and the remaining 5 donated their time. All participants reported normal or corrected-to-normal vision.

Apparatus and stimuli. The stimuli were identical to those used in Experiment 1. To counteract the hypothesized gradient of facilitation radiating outward from onset stimuli, we drew probe lines with apparent motion at speeds of 2,700°/s, 180°/s, or 90°/s toward the circle's circumference. Respectively, the rendering of the line took approximately 1, 15, or 30 ms at each of these speeds. A single point in the middle of the display acted as the fixation point.

Procedure. A full-field pattern appeared for 1,000 ms, followed by the appearance of the fixation point in the middle of the screen for 1,600 ms, and the onset of a number of stimuli around the circle. After 250 ms,[2] all of the stimuli were extinguished and a line was drawn along the circle's radius between the fixation point and the circle's circumference. The line terminated on a location where a randomly chosen stimulus had previously existed or directly between two adjacent items. No catch trials were included. All other details of the procedure replicated those of Experiment 1.

Design. Three variables were systematically manipulated in this experiment: probe line position (on-item or between-items), display size (one to eight stimulus positions), and drawing speed (2,700°/s, 180°/s, or 90°/s). All conditions had 20 replications, resulting in a total of 960 experimental trials (8 display sizes × 2 stimulus destinations × 3 drawing speeds × 20 replications). The experimental session began with a block of 20 randomly selected practice trials. The order of trial delivery was randomly determined and was different for each participant. Data from practice trials were discarded.

Results and Discussion

The frequency of the illusion (percentage of "in" responses) in each condition was calculated and the data were analyzed using a 2 (probe line position) × 8 (display size) × 3 (drawing speed) repeated measures ANOVA. The cell means are presented in Figure 3.

The probe line position main effect, $F(1, 8) = 193.35, p < .0001$, replicated the finding from Experiment 1 showing that the illusion occurred infrequently (9%) when the line probed the empty space between two stimuli, but frequently when a filled location was probed (66%). An effect of drawing speed, $F(2, 16) = 44.63, p < .0001$, confirmed that apparent motion successfully counteracted illusory motion, resulting in less frequent occurrence of the illusion as the drawing speed decreased. Finally, a display size main effect, $F(7, 56) = 7.04, p < .0001$, resulted from less frequent line motion as the number of items in the display increased.

Although the triple-order interaction failed to reach significance, $F(14, 112) = 1.75, p > .10$, each of the variables interacted with all others. An examination of the Drawing Speed × Display Size interaction, $F(14, 112) = 4.68, p < .0001$, suggested that at small display sizes, the illusion occurred more frequently regardless of the drawing speed. At larger display sizes, the illusion occurred less frequently with slower drawing speeds but maintained a high frequency with the fastest (virtually instantaneous) drawing speed.

The Probe Line Position × Drawing Speed interaction, $F(2, 16) = 12.91, p < .0005$, demonstrated a consistently low frequency of line motion when the probe line terminated between two filled locations (14%, 9%, and 6% for drawing speeds of 2,700°/s, 180°/s, and 90°/s, respectively). However, this trend was only marginally significant, $F(2, 24) = 3.50, p = .05$. As the drawing speed decreased, the time between erasing the display and the completion of line drawing increased. The fast dissipation of facilitation between cued locations during this time period may have resulted in the slightly lower report of the illusion at slower than at faster drawing speeds. There was a highly significant, $F(2, 24) = 12.31, p < .0002$, decrease in the frequency of line motion to filled locations as the drawing speed of the line probe slowed (82%, 67%, and 49%). Again, consistent with the Hikosaka et al. (1993b) gradient model, the dissipation of facilitation with the time afforded by the slower drawing speeds was the source of this effect. The finding of a weak effect when the probe line terminated in empty space versus a strong effect when the line terminated on a filled location supports the notion that facilitation radiated outward along a gradient from each of the filled stimulus locations.

An examination of the Probe Line Position × Display Size interaction, $F(7, 56) = 43.73, p < .0001$, revealed that as the number of stimuli in the display increased, the frequency of ILM increased when the line probed the empty space between two filled locations and that it decreased when the line probed a stimulus item. The presence of a linear trend showed that when filled locations were probed, there was the predicted breakdown in the frequency of the illusion with an increase in display size, $F(1, 208) = 65.15, p < .0001$. The unexpected increasing trend, $F(1, 208) = 70.54, p < .0001$, when the probe line terminated between display items with larger display sizes was likely the result of decreasing the distance between the probe line and stimuli. Because our displays evenly distributed stimuli around the circumference of an imaginary circle, trials with greater numbers of stimuli had a shorter distance between stimuli. Consequently, in such trials the probe line would intersect a stronger point on the hypothesized gradient, resulting in the observed increase of line-motion reports with display size. Even with these trends, tests of simple effects revealed that the illusion occurred significantly more frequently when the line probed a filled location than an empty location in displays of all sizes ($p < .01$).

Predictions based on the number of indexes operating can be made about the frequency of line motion that would be

[2] The duration of the onset stimuli in Experiment 1 (950 ms) was excessive; subsequent experiments consequently reduced this parameter (250 ms).

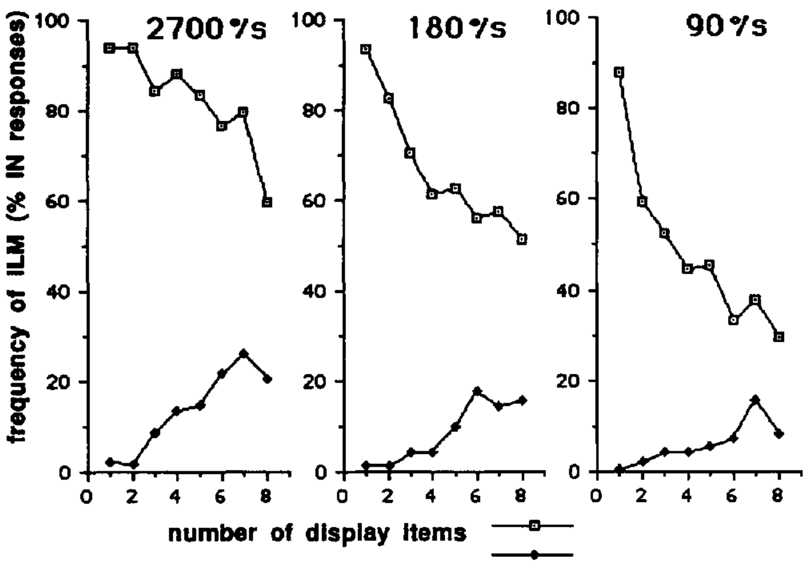


Figure 3. Frequency of illusory line motion (ILM) in Experiment 2 at each of three different probe-line drawing speeds.

expected in the fastest drawing speed, on-item condition. For instance, if there are three indexes and four display tokens, and we assume that if an index is available it will always be deployed to a nonindexed display token, then we would expect that ILM could occur up to 75% of the time when a randomly selected token is probed.[3] Depending on the number of indexes available, different expected frequencies of line motion occur for displays with different numbers of items. Figure 4A shows the frequency of line motion that would be expected in this experiment assuming five to seven indexes. The figure also shows the expected frequency of motion predicted by a spotlight model in which only a single display item can be attended to (one index). Superimposed on these ideal data is the mean frequency of line motion occurring in each of the displays from Experiment 2.

On the basis of the results from Experiment 1, it is reasonable to expect that index assignment or line-motion reports may not be perfect. The data from that experiment indicated that even in displays with only two or four stimuli, approximately 15% of the time that a stimulus item was probed, line motion failed to be reported. Figure 4B illustrates the expected frequency of line motion modified to reflect the possibility that only 85% of the time that an index is assigned and a stimulus item probed will a report of line motion occur. The data in Figure 4A suggest that approximately five indexes were operating in the current experiment, whereas the data in Figure 4B suggest that there were five to seven indexes.

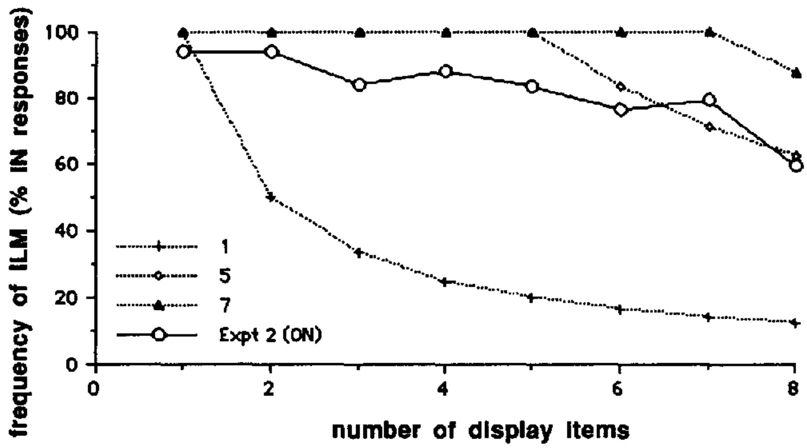
Chi-square statistics contrasting the mean participant data with predictions based on the spotlight account, and between four and eight FINSTs, are shown in Table 1. The second column of the table shows the goodness-of-fit test statistics between the mean data from Experiment 2 and the expected frequencies of the FINST hypothesis. The data do not significantly deviate from the FINST hypothesis assuming that five indexes were operating. The third column of Table 1 shows the goodness-of-fit test statistics between the mean data from Experiment 2 and the expected frequencies derived with the additional assumption that only 85% of the time that an index is available will line-motion reports occur. These data suggest that five or more indexes may be operating.

A similar chi-square goodness-of-fit test was carried out on a subject-by-subject basis, assuming that 100% of the time that an index was available, line-motion reports would occur. Five of the 9 participants conformed to the predicted expectancies (all $ps > .05$), whereas the remaining 4 participants all deviated significantly from the predicted expectancy models (all $ps < .05$). Of the 5 conforming participants, 2 did not deviate significantly from the expected frequencies assuming four or five FINSTs, 1 did not deviate from the five-FINST model, 1 suggested that five to seven FINSTs were operating, and the last one did not deviate significantly from the six to eight FINST expected frequencies. Of the remaining participants whose chi-square scores did not conform to the expected frequencies, 2 had minimum chi-square scores (i.e., a minimal deviation from the expected distribution) for the five FINST goodness-of-fit test, 1 showed a minimum at three FINSTs, and the remaining one at four FINSTs.

Overall, the data from Experiment 2 suggest that there is a breakdown in the number of locations at which ILM can occur. It would appear that the average participant has potential parallel access to at least five and possibly as many as seven display locations.

Hecht (1995) demonstrated that a luminant fixation point

[3] The expected frequency of line motion can be derived by dividing the number of indexes assumed to be operative by the number of display items.



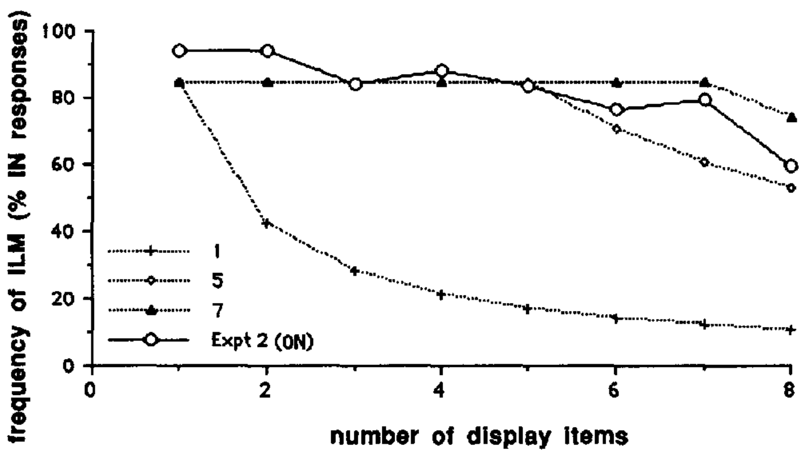


Figure 4. Predicted and observed frequency of illusory line motion (ILM) in Experiment 2 (top) when a display item was indexed and probed and (bottom) assuming that 85% of the time that a display item was indexed and probed, illusory line motion reports would ensue.

Table 1
Chi-Square Goodness-of-Fit Statistics Contrasting the Expected Frequencies Based on a Spotlight Account and Accounts With Four to Eight FINSTs With the Mean Participant Data From Experiment 2

No. of indexes	Fit assuming 100% reports	Fit assuming 85% reports
1	1,166.59*	1,516.54*
4	16.63*	38.81*
5	8.91	9.01
6	16.47*	3.72
7	26.03*	6.23
8	33.49*	10.92

Note. Column 2 shows goodness-of-fit statistics assuming 100% reports of the illusion given an available index, and column 3 shows the fit under the assumption that the illusion will be reported 85% of the time that an index is available. χ^2_{critical} $(7, N = 9) = 14.07$.
$*p < .05$.

can elicit line-motion reports to some degree, in a direction away from its display position. That is, the luminant fixation point also seems to establish a spatial gradient around it that affects the arrival times of subsequently presented signals. Because several researchers (e.g., von Grünau, Dube, & Kwas, 1996; von Grünau & Faubert, 1994) found that there is both a perceptual and an attentional component to ILM, an interesting question concerns the role that fixation played in our experiments.

The luminant fixation point was present throughout each trial and was likely setting up a gradient of arrival times to counteract those of the display items situated around it on the imaginary circle's circumference. Measures were taken in the design of the display to reduce the effects that fixation might have on the results. First, the fixation point appeared well before the onset stimuli, making the exogenous attention that its appearance may have attracted unlikely to be still operative at the time that the probe line appeared.

Second, although the probe line was drawn along the circle's radius, it did not link the entire distance between fixation and the circle's circumference; instead, there was a gap between the probe line and fixation and no corresponding gap between the probe line and the probed item. The motivation for this gap was to prevent motion within the probe line from being influenced by the strongest portion of the fixation point's gradient. Although the fixation point's presence may have produced motion to counteract that of the display items, the latter had the effects of having recently onset (and thus a high probability of having been indexed) plus their gradients, whereas the former presumably had only the effects of its gradient. In addition, only the weakest portion of the fixation point's gradient was allowed to influence the motion within the line.

Experiment 3

The data from Experiment 2 were compatible with the notion that a limited-capacity mechanism affords potential parallel access to five to seven locations. Because displays had a maximum of eight stimuli, it would be desirable to replicate this observation of a capacity limitation using displays with a larger number of items so that the breakdown would be more pronounced. In Experiment 3 we examined whether a similar breakdown in the frequency of ILM could be detected in displays that consistently contained 12 filled locations.

The high frequency of line motion in Experiment 2 when any filled location was probed compared with probing empty locations suggests that the luminance of the stimuli might play a pivotal role in causing the illusion. If pathway priming, rather than attention, were responsible for causing the illusion, then the frequency of line motion would be high in response to any luminant object regardless of the number of stimuli present. However, if a limited-capacity mechanism (such as the FINST model postulates) mediates line-motion processes, then a limit on the number of locations that can support the illusion would be predicted independent of the number of display items present.

Pylyshyn (1989) proposed that salient items in the visual display would be preferentially indexed. Previous work has suggested that new objects and luminance increments attract visual indexes (Pylyshyn et al., 1994; Yantis & Hillstrom, 1994; Yantis & Jonides, 1984). Therefore, it should be possible to demonstrate some control over which items in a display are indexed by manipulating the salience of some display items. Also, if the number of salient items is larger than the presumed number of indexes, then it should be possible to observe a breakdown in the number of stimuli that can be accessed, in parallel, by processes responsible for ILM.

Luminance increments and decrements were used to promote salience in Experiment 3. If either type of change is sufficient to draw indexes, then no difference between luminance increments and decrements should occur. On the other hand, if one of these changes is a stronger attractor of indexes, then a difference should be observed, with the stronger type of change demonstrating a larger capacity than the weaker type of change.

Trials in this experiment began by presenting 12 onset stimuli that were all displayed at the same level of luminance that could be either bright or dim. Next, a randomly chosen subset of the stimuli underwent a brief change in luminance, which was accomplished by presenting them at the other luminance level present in the display (i.e., low-luminance items became high luminance and vice versa). Lines were then used to randomly probe either changed or unchanged stimulus locations. If indexes were assigned to locations undergoing any sort of change, then we would expect changed locations to preferentially elicit ILM over unchanged locations regardless of the nature of the change. If there is a limit on the number of visual indexes available, then we would expect to observe a limit on the number of locations that would support line motion. Because the size of the subset of indexed items outnumbers the availability of indexes, a breakdown in the frequency of ILM would be expected to occur. In Experiment 3 we manipulated the number of stimuli in a display that underwent a change (0–12), the type of change that display elements underwent (luminance increment or decrement), and the type of stimulus that was probed afterward (bright or dim).

Method

Participants. Eight members of the university community were paid $10 to participate in a single 50-min session. All participants reported normal or corrected-to-normal vision.

Apparatus and stimuli. The apparatus and display layout were identical to those used in Experiment 1. Dim stimuli were composed of single points (0.2°), and bright stimuli consisted of five points in a cross-shaped cluster three points high and three points wide (0.3°). The luminance of the dim stimuli and the fixation point was 3.0 cd/m^2, and the bright stimuli had a luminance of 25.0 cd/m^2.

Procedure. On each trial, a full-field pattern appeared for 1,000 ms. This was followed by the appearance of the fixation point in the middle of the screen for 1,200 ms and the onset of 12 dim or 12 bright stimuli around the circumference of an imaginary circle. After 1,000 ms, a randomly chosen subset of these stimuli (from 1 to 12 in number) changed their form to the opposite stimulus type, resulting in the brightening or dimming of randomly located stimuli around the circle. After 250 ms, all of the stimuli were extinguished and a line appeared (in less than 1 ms) between the fixation and the location where a randomly chosen dim or bright item had been. If the entire set of 12 stimuli was identical after the change (i.e., the display was homogeneously filled), then only a single type of stimulus was probed, that of the homogenous display. The participant then made a judgment about the line motion, and this initiated the sequence for the next trial.

On half of the trials, all stimuli in the display were initially dim and the change was to bright (luminance increments), and on the other half the stimuli in the initial display were bright and the change was to dim (luminance decrements). The trial sequence is illustrated in Figure 5.

Design. Three variables were systematically manipulated in this experiment: the type of stimulus item that was probed (bright or dim), the type of change that a subset of the display elements underwent (luminance increment or decrement), and the size of the subset of items that underwent a change (1–11). An equal number

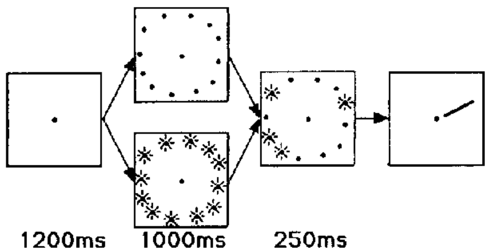


Figure 5. Experiment 3 trial sequence. Each trial began with the appearance of the fixation point followed by 12 items either homogeneously bright or dim. Shortly afterward, a subset of the stimuli underwent a change to the opposite stimulus type, and then all of the stimuli were extinguished and the probe line appeared.

of trials were included in the luminance increment and decrement conditions. In contrast to the previous experiments, only filled locations were probed.

Additional conditions were included in which no stimuli or all stimuli underwent a change. These displays were either homogeneously brightly filled or homogeneously dimly filled at the time that the probe line appeared. In such displays, only one type of stimulus could be probed.

There was a total of 480 experimental trials (48 conditions with 10 replications each). The order of trial delivery was randomized separately for each participant. The session began with a block of 20 practice trials. Data from practice trials were discarded.

Results and Discussion

The frequency of ILM (percentage of "in" responses) was calculated for all of the groups involved and treated as the dependent variable in a repeated measures factorial ANOVA. The independent variables were the size of the subset of elements that underwent a change (1–11), the stimulus type probed (dim or bright), and the type of change that took place in the display (luminance increments or decrements).

Main effects of stimulus type, $F(1, 7) = 43.24, p < .0001$, change type, $F(1, 7) = 15.08, p < .006$, and change subset size, $F(10, 70) = 6.88, p < .0005$, were significant. The stimulus type effect resulted from more frequent line motion in the vicinity of bright than dim stimuli (84% vs. 57%, respectively). The change type effect resulted from an overall higher frequency of the illusion when the subset of stimuli underwent a luminance decrement than a luminance increment (74% vs. 67%, respectively).

The interaction among all three variables was significant, $F(10, 70) = 17.05, p < .0001$, and visual inspection of the cell means (see A and B in Figure 6) suggested that the bright stimuli generally captured the illusion from the dim stimuli regardless of the change that occurred in the display. When a large number of bright items was present, no single bright item was distinctive enough to capture attentional facilitation from the other bright or dim items. As a result, line motion was not greater for either bright or dim items when a large number of bright elements were present in the display. As the number of bright stimuli decreased, the illusion occurred more frequently when a bright item in the display was probed than when a dim item was probed. These data are compatible with the FINST hypothesis assuming that visual indexes are preferentially assigned to bright display items. The capacity limitations observed in terms of the number of bright elements that can simultaneously elicit ILM are compatible with the results obtained in Experiment 2.

Statistical support for the aforementioned interpretation of this triple interaction was found in tests of interaction simple effects at each level of change subset size at each level of change type. In luminance decrement trials, the

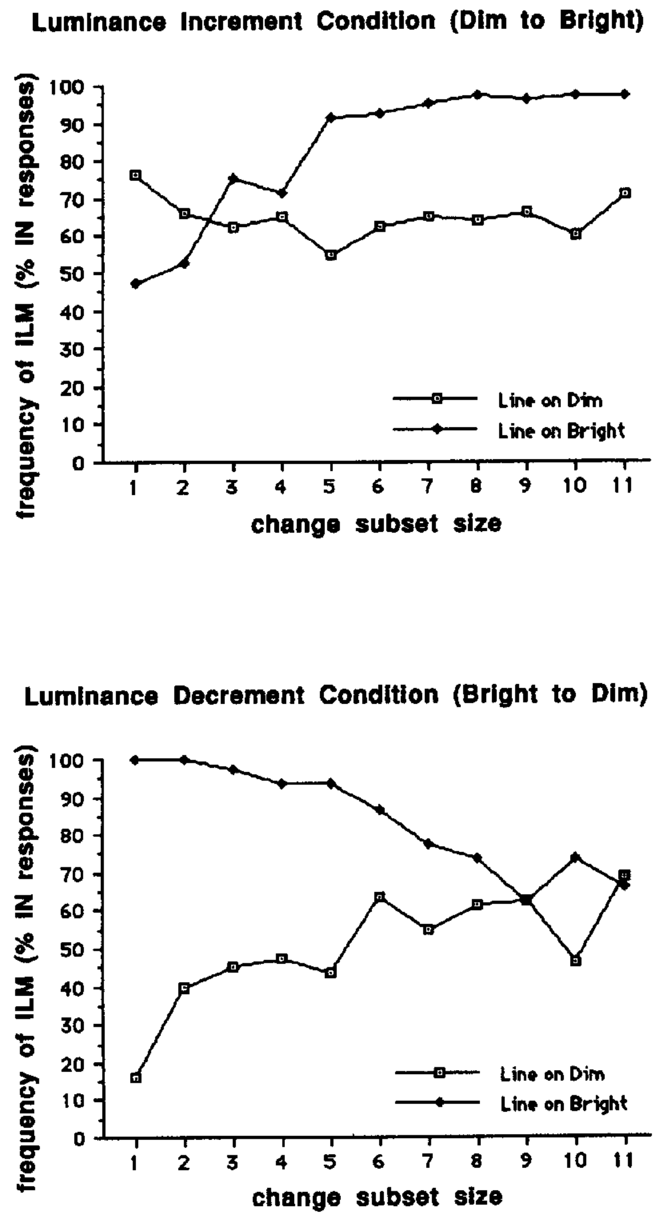


Figure 6. Frequency of illusory line motion (ILM) to dim and bright items when a subset of display elements underwent (top) a luminance increment and (bottom) a luminance decrement. Both graphs show line-motion frequencies as a function of the number of display elements that underwent a change in luminance.

Table 2
Interaction Simple Effect Statistics for the Stimulus Type Probed at Each Level of Change Subset Size When the Change Type Was From Bright to Dim and From Dim to Bright

Change subset size	No. of bright stimuli	% ILM from dim	% ILM from bright	$F(1, 14)$	p
		Bright to dim			
1	11	76	47	5.83	.03*
2	10	66	52	1.16	.30
3	9	63	75	1.80	.20
4	8	65	71	0.02	.65
5	7	55	91	15.70	.002*
6	6	63	93	12.29	.004*
7	5	65	95	15.75	.002*
8	4	64	98	21.70	.0005*
9	3	66	96	11.02	.005*
10	2	60	98	25.00	.0005*
11	1	71	98	14.63	.002*
		Dim to bright			
1	1	16	100	283.10	.0001*
2	2	40	100	91.64	.0001*
3	3	45	98	43.48	.0001*
4	4	48	94	19.52	.0006*
5	5	44	94	25.10	.0002*
6	6	64	86	3.16	.09
7	7	55	78	3.32	.09
8	8	61	74	1.03	.33
9	9	63	63	0.0005	1.0
10	10	74	74	4.33	.06
11	11	66	68	0.04	.84

Note. ILM = illusory line motion.
*$p < .05$.

illusion occurred significantly more often ($p < .05$) to bright stimuli when seven or fewer bright stimuli were present in the display (see Figure 6A and Table 2). Thus, even when the stimulus item probed had not undergone a change in luminance, it showed greater facilitation than items that had changed. In displays with luminance decrements, the illusion also occurred more frequently when bright items were probed ($p < .05$); however, this did not occur when more than five bright items were present in the display (see Figure 6B, Table 2). When six or seven bright elements were in the display, the bright stimuli were facilitated more frequently than the dim stimuli ($p < .10$); however, these effects failed to reach significance at the .05 level. When more than seven items in the display were bright, there was no significant difference between the frequency of ILM elicited by either dim or bright stimuli. It appears that the high level of luminance increase in the display prevented the remaining dim stimuli from attracting indexes. Regardless of the particulars, it is apparent that a breakdown in the number of locations that can simultaneously support ILM was observed in this experiment, adding support to the capacity limitation finding of Experiment 2.

The observed frequencies of line motion when bright stimulus items were probed after luminance decrements and increments are plotted in Figure 7, along with the predicted frequencies of line motion calculated as in Experiment 2. An assumption made in deriving these predictions was that all bright items in the display were equally likely to be indexed and that the presence of other display items would not interfere with the assignment of indexes. As can be seen from Figure 7, there is a close fit between the data and the predictions of the FINST hypothesis if one assumes that at least five, but as many as seven spatial locations can be accessed in parallel by visual line-motion processes.

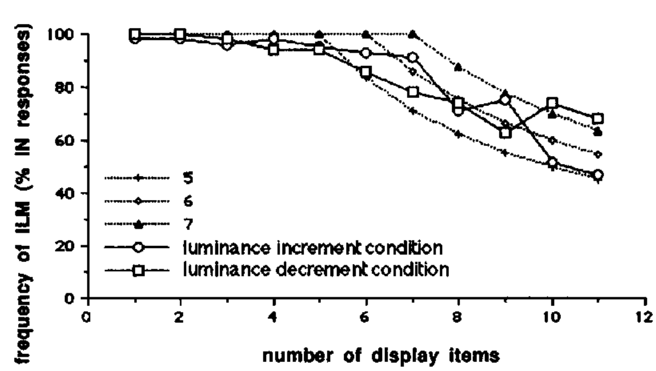


Figure 7. Predicted and observed frequency of illusory line motion (ILM) in Experiment 3 when bright stimulus items were probed after some items in the display underwent either a luminance decrement or a luminance increment.

As in Experiment 2, chi-square goodness-of-fit statistics were calculated to compare the human data with the frequencies predicted by the FINST hypothesis. Frequencies for 4–9 indexes were examined, and the goodness-of-fit tests that appear in Table 3 revealed that the human data did not significantly deviate from the FINST predictions assuming 5–7 indexes in the luminance increment condition and 6 or 7 indexes in the luminance decrement condition. These data fit well with the results from Experiment 2, which suggested that at least five and as many as seven spatial locations were capable of simultaneously supporting ILM.

An additional effect from the interaction simple effects warrants mention. When all of the display items started out bright, and a single stimulus underwent a luminance decrement (a change subset size of 1), the luminance singleton (the single item that differed from all others only on the dimension of luminance) elicited the illusion more frequently than any of the bright stimuli ($p < .05$; see Table 2). This is highly suggestive of stimulus-driven attentional capture. The illusion occurred frequently to a single bright item among dim items, and it occurred frequently to a single dim item among bright items. Hence, it would appear that these singleton stimuli captured processing from nonsingleton stimuli. This capture effect probably reflects the assignment of indexes to the most distinctive display items. When there are few distinctive items, these are more likely to be indexed than when there are many. This finding is compatible with Pylyshyn's (1989) hypothesis that visual indexes are attracted to locally distinct features in the visual display.

The analysis so far suggests that the occurrence of the illusion to bright items is principally a result of the items' intensities and not primarily the result of local changes occurring in the display. The ability of luminance change to induce the illusion was directly investigated through tests of interaction simple effects at each level of change subset size at each level of the stimulus type probed. The line was used to probe either bright or dim items that had undergone either a luminance increment or decrement. Table 4 shows the effects of probing changed versus unchanged items at each level of luminance.

From Table 4 it can be seen that when fewer than four items underwent a change in luminance and a bright item was probed, the changed, bright token elicited the illusion significantly more often than unchanged bright items ($p < .05$). When five or fewer bright items remained unchanged, they elicited line motion more frequently than bright changed items in the display ($p < .05$). This interaction revealed that luminance change was less important than luminance level for bright items. When dim items were probed, the only time that changes in the display had an effect occurred when one or two items had undergone a luminance decrement; otherwise, the bright stimuli in the display were evoking ILM.

The Stimulus Type × Change Type interaction, $F(1, 7) = 32.85$, $p < .0007$, resulted from a similar frequency of line motion to bright stimuli regardless of the type of change (83% with luminance decrements and 84% with luminance increments), whereas the frequency of the illusion to dim stimuli varied with the type of change, as discussed earlier. The Stimulus Type × Change Subset Size interaction, $F(10, 70) = 2.90$, $p < .05$, reflected the greater frequency of illusory motion to bright than to dim stimuli at all levels of change subset size. Finally, the significant Change Type × Change Subset Size interaction, $F(10, 70) = 3.43$, $p < .05$, reflected the overall greater frequency of line motion at larger change subset sizes for luminance decrements than increments.

A second repeated measures ANOVA was carried out on the remaining data, which concerned the effects of probing displays of homogenous display elements. The role of change versus brightness was directly assessed by contrasting the frequency of line motion in displays in which all of the items underwent a change versus displays in which no items underwent a change. This change variable was crossed with the type of stimulus probed to produce a 2 (change type [all or none]) × 2 (probe type [dim or bright stimulus]) analysis. If brightness plays a more important role than change, then we would expect a significant interaction to occur. Otherwise, displays containing change, regardless of its form, should elicit ILM more frequently.

The interaction effect failed to reach significance ($p > .10$), as did the probe type main effect ($p > .10$). However, if the display underwent a change before the line appeared, regardless of the form of that change, line motion occurred more frequently (69%) than if no change had taken place (51%), $F(1, 7) = 10.16$, $p < .02$. Therefore, it appears that for homogenous displays, intensity played a less important role in causing the illusion than a change in intensity. The interaction cell means are presented in Table 5.

Although in nonhomogenous displays intensity appears to play an important role in index assignment and the generation of a spatial gradient, as well as in the elicitation of ILM, and although changes in intensity do not appear to be the dominant factor in attracting indexing, the data require more than a simple explanation based on intensity levels. First, a breakdown in the number of locations was observed. If the line-motion illusion were driven solely by intensity, an increase in line-motion frequency, not a breakdown, would be predicted with displays containing more bright items.

Table 3
Chi-Square Goodness-of-Fit Statistics Contrasting Expected Frequencies Based on FINST Accounts With Four to Nine Indexes With the Mean Participant Data From Experiment 3

No. of indexes	Bright-to-dim change	Dim-to-bright change
4	91.77*	70.10*
5	27.27*	15.11
6	10.21	4.71
7	12.98	14.02
8	22.62*	31.31*
9	33.19*	47.35*

Note. FINST = spatial index. $\chi^2_{\text{critical}}(10, N = 8) = 18.31$.
*$p < .05$.

Table 4
Interaction Simple Effect Statistics for the Type of Change at Each Level of Change Subset Size When Bright and Dim Items Were Probed

Change subset size	% ILM from changed items	% ILM from unchanged items	$F(1, 14)$	p
		Bright items		
1	100	47	41.16	.0001*
2	100	52	17.67	.0009*
3	98	75	13.19	.003*
4	94	71	4.25	.06
5	94	91	0.4	.54
6	86	93	1.42	.25
7	78	95	4.83	.04*
8	74	98	10.07	.007*
9	63	96	8.94	.01*
10	74	98	6.96	.02*
11	68	98	10.65	.006*
		Dim items		
1	76	16	36.16	.0001*
2	66	40	9.22	.009*
3	63	45	2.79	.12
4	65	48	1.80	.20
5	55	44	0.76	.40
6	63	64	0.01	.93
7	65	55	0.68	.44
8	64	61	0.4	.84
9	66	63	0.08	.78
10	60	74	1.26	.28
11	71	66	0.06	.81

Note. Bright items underwent a change for dim-to-bright displays, whereas dim items underwent a change for bright-to-dim displays. ILM = illusory line motion.
$^*p < .05$.

Second, the least intense item (an intensity singleton that had undergone a luminance decrement) in a display full of bright items captured the illusion even in the presence of brighter display elements. These data support the notion that locally distinctive features (which may, coincidentally, be bright) can be considered the important aspect of the current displays that acted to draw indexes and to elicit ILM. Such locally distinctive features provided us with a heuristic notion of salience.

In summary, in Experiment 3 we found support for the notion that visually distinctive items attract visual indexes and afford multiple-location access to support ILM. Evidence also was found for the notion that the number of locations that can simultaneously support ILM is five to seven. The breakdown in the number of locations that can support ILM demonstrates that there are limits within the visual system in the number of locations that can be accessed in parallel. This finding is incompatible with a low-level, pathway-priming explanation of ILM in this and in previous studies. Pathway-priming interpretations of our results require local mechanisms that should not be subject to capacity limitations such as those observed in Experiment 3. These limitations, together with the observed increase in effect for dim versus bright stimuli in some situations, support a higher level explanation of these results.

Table 5
Percentage of Illusory Line Motion in Homogenous Displays in Experiment 3

Change condition	Homogeneously dim	Homogeneously bright
All	65	74
None	55	46

Experiment 4

The results of Experiments 1–3 demonstrate that ILM can occur away from multiple locations and that the number of such locations may be limited. We have interpreted these findings as support for FINST theory, which proposes that people have potential parallel access to information at a limited number of locations. The tasks used in previous demonstrations of parallel access have required that the participant do something with the location or content of information accessed in order to demonstrate that parallel information access is possible. For instance, in target-tracking experiments, participants are required to indicate the final locations of multiple tracked items (Pylyshyn & Storm, 1988), and, with subitizing experiments, participants are required to report the total number of target items present in a display (Trick & Pylyshyn, 1993). The ILM experiments presented so far have not demonstrated that information at indexed locations can be accessed in parallel because a single stimulus location was probed on each trial. Experiment 4 was designed to address this issue by requiring participants to report motion direction judgments for several locations on each trial.

To demonstrate that participants can access multiple locations, Experiment 4 moved from a partial report study in which participants were simply required to detect ILM at a single location (such as that used in Experiments 1–3) to a partial report study in which participants were required to indicate all of the locations in a display that simultaneously yielded ILM in a given direction. In this experiment, a computer display was divided into 20 cells, and a number of simultaneous dots (two, four, six, or eight) appeared randomly dispersed within these cells. Shortly afterward, horizontal lines associated with each dot were simultaneously presented, and the participant's task was to indicate the locations of each display element that yielded motion in a predetermined direction (either leftward or rightward).

The FINST hypothesis suggests that a subset of the initial dots will be indexed, presumably as many as there are FINSTs. Accordingly, any ILM experienced will be FINST mediated and location information about such an experience should be accessible to the participant. Therefore, we should be able to demonstrate that participants will experience ILM at multiple locations in parallel and that they can assess their experience at multiple locations. Also, a limitation in the number of locations that participants have access to would be expected on the basis of Experiments 2 and 3.

This task was obviously not easy, and there are numerous limitations in its ability to yield a precise estimate of the number of locations that the visual system can simultaneously access. In particular, it would be expected that the task might result in an underestimate of participants' abilities because of the difficulty inherent in reporting multiple simultaneously occurring brief events after their occurrence. Nonetheless, unlike in Experiments 1, 2, and 3, the principal goal of this experiment was to demonstrate that parallel access (i.e., access to information about motion direction at more than a single location) is possible.

To assist participants in their task of recounting precise information about multiple aspects of a brief perceptual event, we presented half of the display items so that they would produce leftward motion (if FINSTed), and half so that they would produce rightward motion (if FINSTed), and required that participants report only the display items exhibiting motion in a specific direction. This manipulation not only minimized the number of events that participants had to report but it also eliminated the possibility of overestimating the number of locations of parallel access attributable to participants strategically examining displays for motion only in a display's minority direction. For instance, had participants been required to report leftward motion when seven out of eight items were in that direction, then they might rely on a strategy of detecting rightward motion at one location and reporting leftward motion at all others. Clearly, under such circumstances, participants would not have had access to seven locations.

Method

Participants. Six adults (William C. Schmidt and 5 undergraduates) participated in a single 35-min experimental session. Two participants had previous experience with the illusion. All participants reported normal or corrected-to-normal vision.

Apparatus and stimuli. The stimuli were presented on an Apple Color Plus display controlled by a Macintosh Performa 630 computer using custom-written computer software. The display was partitioned into an imaginary grid of 20 (5 horizontal × 4 vertical) cells (measuring 3.5° × 3.5° each) arranged around a white fixation cross (1.0° high and 1.0° wide) in the display's center. The display background was black. The white cue stimuli were 0.75° squares randomly distributed among the cells on each trial. Each cue appeared 0.63° from its cell's closest vertical edge and was centered vertically within the cell. If illusory motion for the cell was to be leftward, then the cue stimulus was drawn closest to the cell's right edge, and if the motion direction was to be rightward, then the cue stimulus was drawn closest to the cell's left edge. Line stimuli were 0.75° thick and 2.25° long and completely overlapped the cue locations. Centered at the bottom of the screen on each trial was the word *leftward* or *rightward* printed in yellow Geneva 14-point font, indicating the direction of motion that participants were to report during the trial.

Cells that participants selected were filled using a pattern of sparsely distributed white dots, and feedback was presented with a pattern containing densely packed white dots. The dense feedback pattern oscillated within the cell five times with the black display background in 500-ms steps accompanied by simple beeping sounds.

Procedure. Each participant sat in a dimly lit room at a distance of 57 cm from the display with his or her head steadied by a head rest. Each trial was initiated by a buttonpress. Optional breaks were given every 50 trials.

On each trial a fixation cross appeared in the display's center, and the word *leftward* or *rightward* was displayed at the bottom of the display. These initial items remained present for the duration of the trial. One second after the fixation's appearance, two-, four-, six-, or eight-dot stimuli appeared randomly distributed throughout the display. After a cue lead time of 250 ms, a line associated with each of the dot stimuli appeared and remained present until the end of the trial. Participants were instructed to maintain fixation in the display center during the presentation of the stimuli and to then use the computer mouse to select the lines in the display that were drawn in the direction indicated at the bottom of the screen. Participants were informed that up to half of the items in the display could be presented in the targeted direction.

The computer's mouse was used to highlight display locations judged to have contained motion in the targeted direction by clicking the mouse in the vicinity of the lines that they had selected. If the click was in a cell occupied by a line, the entire cell was marked as selected using a pattern of sparsely distributed white dots. Clicking on a previously selected item toggled the item's selection status. After participants finished reporting target motion locations, they pressed the space bar to receive feedback. Cell locations that would have produced illusory motion in the targeted direction were highlighted using a pattern of densely packed white dots. Incorrect cells that participants had selected remained visible and, because of their sparsely distributed dot pattern, were easily discernible from the feedback. A numerical report on the trial performance also was displayed in terms of the number of hits (correct selections), false alarms (the selection of items that should not yield the illusion in the targeted direction), and misses (items not selected that should have yielded motion in the targeted direction). When participants were finished examining the feedback screen, they were allowed to continue by pressing the mouse button.

Experimental trials were divided into two blocks of 48 trials each and were preceded by 40 practice trials. The motion direction to be selected (leftward vs. rightward) was run in separate blocks and counterbalanced for order. Each block contained 12 trials of four different levels of display size: two, four, six, or eight. Data from practice trials were discarded.

Results and Discussion

The frequency of correct selections (hits) for each participant in each condition was tabulated and examined using a 2 (motion direction) × 4 (display size) repeated measures ANOVA. Only the main effect of display size was significant, $F(3, 15) = 51.55$, $p < .0001$, demonstrating that the direction of motion selected had no discernible effect on observers' performance. An examination of the means revealed that observers were quite accurate for displays with 2 (99%) or 4 (84%) items but that performance dropped in 6 (63%) and 8 (58%) item displays. Participants averaged selecting fewer than half of the display items for all but the smallest display size (50.0%, 49.5%, 47.0%, and 42.5% for display sizes of two-, four-, six-, and eight-element displays, respectively), even though they were informed that half of the items in each display would exhibit motion in the targeted direction.

The simple model. The mean frequencies collapsed across motion direction and participant were submitted to chi-square goodness-of-fit tests. We first tested the frequencies against a simple model assuming that location access would be randomly distributed across the cue elements (the initial dots) and that the probability of the participant experiencing ILM for a subsequently presented line (a leftward or rightward motion percept) would be a function of the probability that the line was indexed (the number of hypothesized indexes/number of elements in the display). Considering the distributions derived from models postulating that between one and six display locations could be accessed in parallel revealed that the combined participant distribution differed significantly ($p < .05$) from all but the distribution expected if participants had access to four locations.

The frequency distributions generated by our simple model, along with the chi-square error and probability values, are reported in Table 6. An inspection of the chi-square statistics shows that error deviation scores were lowest for the four- and five-location models, suggesting that both provided a good fit to the averaged data. A subject-by-subject chi-square goodness-of-fit analysis revealed that the models of parallel access to three, four, and five locations each provided the best fit to the performance of 2 participants. For all but 1 participant (a three-location participant), the observed distribution did not differ significantly from the model. The eccentric participant's data deviated least from the three ($p = .03$)- and four ($p = .02$)-location parallel access models.

For each display size, the observed hit frequencies were contrasted with the frequencies predicted by the spotlight model (one location access) using one-tailed single sample t tests. The statistics, which are reported in columns 2 and 3 of Table 6, revealed that the observed frequencies differed significantly ($p < .05$) from the spotlight model for each display size.

An analysis of the incorrect selection (false-alarm) frequency using a 2 (motion direction) × 4 (display size) repeated measures ANOVA revealed only a significant main effect of display size, $F(3, 15) = 51.45$, $p < .0001$. Unsurprisingly, false alarms (the selection of a display location incorrectly claiming motion in the targeted direction) occurred more frequently in displays with larger numbers of elements. The mean frequency of false alarms was 1.4%, 14.9%, 30.3%, and 26.7% for displays with two,

Table 6
The Simple Model: The Observed Frequency of Illusory Motion Accurately Identified in Experiment 4 (Mean %) Contrasted With Models of Expected Frequencies if Parallel Access Occurred for One to Six Locations

Display size	Mean %	$t(5)$ one location	p	No. of locations: 1	2	3	4	5	6
Hits									
2	98.61	35.00	<.0001*	50.00	100.00	100.00	100.00	100.00	100.00
4	83.68	19.16	<.0001*	25.00	50.00	75.00	100.00	100.00	100.00
6	63.19	12.34	<.0001*	16.66	33.33	50.00	66.66	83.33	100.00
8	58.33	10.41	<.0001*	12.50	25.00	37.50	50.00	62.50	75.00
χ^2				482.94	93.90	16.08	4.25	7.83	19.93
p for χ^2				<.001*	<.0001*	<.002*	=.24	=.05	<.0002*

Note. Chi-square goodness-of-fit statistics show that the best fitting models hypothesize parallel access to four or five locations. Columns 3 and 4 show the one-tailed t statistics and associated probability values contrasting the observed data with the expected mean on the spotlight (1 location access) account. Performance differed significantly from the spotlight account for all display sizes. For the chi-squares, the degrees of freedom were 3 and the sample size was 6. $\chi^2_{\text{critical}}(3, N = 6) = 7.80$.
*$p < .05$.

Table 7

The Complex Model: The Observed Frequency of Illusory Motion Accurately Identified in Experiment 4 (Mean %) Contrasted With Models of Expected Frequencies if Parallel Access Occurred for One to Six Locations, With Participants Randomly Guessing the Motion Direction for the Remainder of the Display Items

Display size	Mean %	$t(5)$ one location	p	No. of locations 1	2	3	4	5	6
Hits									
2	98.61	17.00	<.0001*	51.40	100.00	100.00	100.00	100.00	100.00
4	83.68	6.92	<.0005*	47.35	64.90	82.45	100.00	100.00	100.00
6	63.19	1.27	=.13	67.50	74.00	80.50	87.00	93.50	100.00
8	58.33	0.47	=.33	49.25	56.50	63.75	71.00	78.25	85.50
χ^2				73.19	7.90	4.22	11.46	17.58	24.86
p for χ^2				<.001*	=.07*	=.24	<.01*	<.0005*	<.0001*
False alarms									
2	1.39	−17.00	<.0001*	1.40	0.00	0.00	0.00	0.00	0.00
4	14.93	−6.68	<.0006*	22.35	14.90	7.45	0.00	0.00	0.00
6	30.32	−5.73	<.0011*	50.83	40.66	30.50	20.33	10.16	0.00
8	26.74	−3.66	<.0073*	36.75	31.50	26.25	21.00	15.75	10.50
χ^2				13.47	3.50	7.67	200.67	241.82	1,079.20
p for χ^2				<.004*	=.32	=.05	<.0001*	<.0001*	<.0001*

Note. Chi-square goodness-of-fit statistics show that the best fitting models hypothesize parallel access to two or three locations for both hit and false-alarm data. Columns 3 and 4 show the one-tailed t statistics and associated probability values contrasting the observed data with the expected mean on the spotlight (1 location access) account. Performance differed significantly from the spotlight false-alarm account for all display sizes and from the spotlight hit account only for the smallest two display sizes. For the chi-squares, the degrees of freedom were 3 and the sample size was 6. χ^2_{critical} (3, N = 6) = 7.80.
*$p < .05$.

four, six, and eight elements, respectively. For displays containing more items, participants were making more guesses about the direction of motion.

The complex model. Although a nice fit to the hit data was found, our simple model did not take into account that some participants might guess that some proportion of non-FINSTed display elements had exhibited motion in the targeted direction. Hence, the simple model was unable to account for false alarms and overestimated the number of locations that participants were able to access in parallel. Consequently, we tested the observed frequencies against a more complex model in which participants were assumed to have guessed that 50% of non-FINSTed display items exhibited motion in the targeted direction, thus predicting that false alarms would occur for 50% of the non-FINSTed items. The complex model hypothesized that, in addition to getting FINSTed items correct, participants would guess the correct direction (50% correct by chance) arbitrarily for half of the display items that they were unsure about (non-FINSTed items). The other half of the time, non-FINSTed items were predicted to generate false alarms. The results of chi-square goodness-of-fit tests separately contrasting the observed frequencies of hits and false alarms with those predicted by the model appear in Table 7.

The results of the simple model augmented with a guessing strategy revealed that the simple model did overestimate the number of locations that afforded parallel access. An examination of the chi-square statistics in Table 7 reveals that error deviation scores for the hit data were lowest for, and did not differ significantly from, the two- and three-location parallel access models. The false-alarm data most closely matched a three-location parallel model augmented with random guessing on half of the remaining display items.[4]

A subject-by-subject chi-square goodness-of-fit analysis revealed good fits ($p > .05$) to at least one of the models. Two of the participants' hit rates did not differ from the distribution expected if parallel access to two or three locations was occurring, and their false-alarm data did not differ significantly from that predicted by the three-location parallel access model. Two other participants' hit rates did not differ significantly from the four-location model, whereas their false-alarm rates did not deviate from the three-location model. One participant's hit and false-alarm rates did not differ significantly from the three-location hit and false-alarm models. The remaining participant's hit data fit a two-location model, whereas their false-alarm data deviated significantly from all of the models, with the closest match being to the one- and two-location distributions.

The results of contrasting the observed hit and false-alarm frequencies with the frequencies predicted by the spotlight complex model data (1 location access) for each display size, using one-tailed single sample t tests, are shown in columns 2 and 3 of Table 7. Although the observed false alarms differed significantly ($p < .05$) from the predictions of the single-location access model, performance on only the

[4] Note that in computing the chi-square statistics for the false-alarm models, the expected frequencies in some cells are zero, which results in a zero denominator in the chi-square formula. Consequently, a value of one was substituted for zeros in the expected distributions generated by the false-alarm models throughout this article, resulting in the ability to compute the chi-square statistic.

smallest two display sizes differed significantly for the hit data.

The informed complex model. Recall that the complex model assumed that participants would guess a direction for half of the items in the display that they were unsure about (non-FINSTed items). We examined the fit of the complex model informed with an estimate of the frequency of guessing that actually occurred in the experiment. The false alarms made by participants represented half of the frequency of guessing because there was a 50% chance that participants would guess either correctly or incorrectly. Hence, substituting the probability of guessing for the complex model's assumed 50% guessing of non-FINSTed items should yield a more accurate set of models. The results of informing the complex model with the mean rate of guessing appear in Table 8.

An examination of the chi-square statistics for each of the models in Table 8 reveals that the hit data did not differ significantly from a model assuming parallel access to three-display locations, whereas the false-alarm data did not differ significantly from the two- and three-location access models.

Subject-by-subject chi-square goodness-of-fit analyses contrasted against the distributions generated by the informed complex model used each participant's own false-alarm data as an estimate of their particular frequency of guessing. Although the fit of these distributions to the participant's own data were not as accurate as those of the complex model (i.e., only 2 participants' data failed to deviate significantly, $p > .05$, from the expected distributions for hit data and 3 participants for false-alarm data), the results are similar. One participant's hit rates did not differ from the three-, four-, and five-location access models, whereas their false-alarm rates did not differ from the three-location model. A second participant's hit data most closely matched three- and four-location access models, whereas their false-alarm data matched two- and three-location models. Two participants' hit and false-alarm rates matched two- and three-location models, and the remaining 2 participants' hit and false-alarm data most closely matched the two-location access distributions.

Finally, the results of contrasting the observed hit and false-alarm frequencies with the frequencies predicted by the spotlight informed complex model data (one-location access) for each display size, using one-tailed single sample t tests, are present in columns 2 and 3 of Table 8. The hit data differed significantly ($p < .05$) from the single-location access model at each display size, and the false-alarm data differed significantly at all but the smallest display size.

Summary. Experiment 4 provides evidence that individuals can access more than a single location in parallel. Participants demonstrated performance consistent with the ability to access between two and five locations in parallel, with a mode of three-location access. Importantly, at all display sizes of the informed complex model, the hit performance data differed significantly from what would be expected if access were limited to a single-display location. Similarly, the false-alarm performance also deviated signifi-

Table 8
The Informed Complex Model: The Observed Frequency of Illusory Motion Accurately Identified in Experiment 4 (Mean %) Contrasted With Models of Expected Frequencies if Parallel Access Occurred for One to Six Locations, With Participants Making Random Guesses for the Remainder of Their Responses

Display size	Mean %	$t(5)$ one location	p	No. of locations: 1	2	3	4	5	6
Hits									
2	98.61	70.00	<.0001*	75.00	100.00	100.00	100.00	100.00	100.00
4	83.68	20.03	<.0001*	62.50	75.00	87.50	100.00	100.00	100.00
6	63.19	3.23	<.0116*	58.33	66.66	75.00	83.33	91.66	100.00
8	58.33	4.90	<.0022*	56.25	62.50	68.75	75.00	81.25	87.50
χ^2				15.09	1.48	3.62	11.25	17.99	25.95
p for χ^2				<.002*	=.69	=.31	=0.02*	<.0004*	<.0001*
False alarms									
2	1.39	−0.08	=.50	25.00	0.00	0.00	0.00	0.00	0.00
4	14.93	−2.20	<.0397*	37.50	25.00	12.50	0.00	0.00	0.00
6	30.32	−10.37	<.0001*	41.66	33.33	25.00	16.66	8.33	0.00
8	26.74	−2.15	<.0419*	43.75	37.50	31.25	25.00	18.75	12.50
χ^2				45.59	7.57	2.41	205.51	255.63	1,070.31
p for χ^2				<.001*	=.05	=.49	<.0001*	<.0001*	<.0001*

Note. Chi-square goodness-of-fit statistics show that the best fitting models hypothesize parallel access to two or three locations for both hit and false-alarm data. Columns 3 and 4 show the one-tailed t statistics and associated probability values contrasting the observed data with the expected mean on the spotlight (1 location access) account. Performance differed significantly from the spotlight hit account for all display sizes and from the spotlight false-alarm account for all but the smallest display size. For the chi-squares, the degrees of freedom were 3 and the sample size was 6. $\chi^2_{\text{critical}}\,(3, N = 6) = 7.80$.
$^*p < .05$.

cantly from expected spotlight performance. Participants clearly were able to access information at multiple locations simultaneously.

The difficulty of the task used in Experiment 4 (i.e., memory and response demands) was likely to have contributed to a conservative estimate of participants' abilities, as was the use of primarily nonpracticed, inexperienced participants. Nonetheless, support for parallel access to approximately three locations was still found, and a capacity limitation in the number of locations at which ILM was experienced was reproduced using a much different methodology.

General Discussion

The results of Experiments 1 and 2 demonstrate that multiple simultaneous onset stimuli have the potential to produce ILM and that the locations between such stimuli do not. This effectively excludes a broad class of unitary attention models as providing a plausible mechanism for the mediation of ILM. An attempt to salvage a unitary attention explanation by positing a rapid shift of attention between positions would require the beam to move at speeds much greater than has been previously suggested (instantaneously) without passing through (and hence facilitating) locations where no onset stimuli occurred. Pylyshyn and Storm (1988) considered a spotlight movement interpretation in some depth and rejected it as a feasible explanation of multiple target-tracking results, and their argument applies here. Also, the sensitivity of the illusion to a number of salient locations and to singleton stimuli (Experiment 3) would seem to require a unitary spotlight account to posit preattentive mechanisms (like FINSTs) whose task it is to direct a unitary attentional beam. Furthermore, such a mechanism would have to be capable of providing spatially parallel access to information at noncontiguous locations such as was found in Experiment 4.

Our findings require us to consider models that permit the possibility of multiple independent foci of attention. The FINST hypothesis (Pylyshyn, 1989, 1994) posits a limited number of visual indexes that enable higher order processes to access informational elements within preprocessed representations of the visual array. The indexes, or FINSTs, are hypothesized to independently individuate salient features irrespective of spatial location and to afford visual processes parallel access to information at a limited number of locations. The results of our studies are consistent with such a limited-capacity parallel mechanism.

Approximately five to seven locations had the potential to support ILM in Experiments 2 and 3. An average of three locations (with a range of two to five) were shown to afford parallel information access in Experiment 4. The source of the capacity limitation observed here and in other experimental paradigms (see Pylyshyn, 1994, for an overview) can be attributed to either a fixed number of indexes or to limitations in the number of indexes that can be processed by higher order visual routines (Ullman, 1984) or attention.

On the basis of the results from Experiments 2 and 3, we inferred that a number of FINST indexes were operating and proposed that the FINST mechanism supplied participants with the ability to access any of the FINSTed locations in parallel. In both of these tasks, participants were required to submit information about their motion percept at a single, unpredictable display location. Experiment 4 forced an analysis of participants' ability to access information at multiple display locations in parallel. If FINSTs were indeed operating, then some evidence of their ability to afford parallel access, rather than just the potential for parallel access, should have been possible. Experiment 4 demonstrated that participants could access motion direction information from multiple locations simultaneously. However, the number of locations from which information actually could be accessed in parallel was fewer than the number of locations that Experiments 2 and 3 suggested had the potential for such access. This difference suggests that although an indexing mechanism may exist, the mechanism's eventual throughput in any task is likely to be lower than the indexing mechanism's capacity would suggest. This observation may be an important one regarding studies that purport to find attentional processing at multiple locations (Castiello & Umiltà, 1992; Kramer & Hahn, 1995; Wright, 1994). Visual processes required to execute a task may enforce whether information can be accessed in parallel. A mechanism such as FINST indexing, however, suggests that the bottleneck is not necessarily at an early stage of processing.

Because the FINST hypothesis claims that indexing is an essential first step in processing higher order stimulus characteristics, any limitation in the number of FINSTs would be expected to limit performance in a wide variety of tasks. Visual search and tracking experiments (Pylyshyn et al., 1994; Pylyshyn & Storm, 1988; Yantis & Jones, 1991) have shown that approximately three to five items could be accessed, whereas subitizing experiments (Trick & Pylyshyn, 1993) show a shift in performance when more than four items are present in the display. The results of our Experiments 2 and 3 document performance shifts that occurred when more than three to seven visual onset items appeared simultaneously. Results of Experiment 4 demonstrate that parallel access to information about perceptual events (direction of experienced motion) at two to five simultaneous onset locations (with an overall average of approximately three locations) was possible. Considering the diversity of tasks, targets, and display characteristics used across all of these studies, the consensus was remarkable.

The possibility exists that in Experiments 2 and 3 we might have overestimated the number of locations that can afford potential parallel access. Recall that in Experiment 2, the frequency of ILM decreased with an increase in the number of display items when the probe line was presented nearby a display item, as would be predicted by a limited-capacity model. However, there was a corresponding increase in the frequency of ILM when the probe line was presented between two display items. We explained this increase by positing that the gradient surrounding display items spilled into the area between items, thereby boosting the frequency of ILM report at those locations. An anonymous reviewer pointed out that there also might be a corresponding increase in the frequency of ILM when display locations were probed. Such an effect would result in an artificial inflation in our estimate of the number of indexes available to visual routines, but the fact that we nevertheless observed a capacity limitation in the number of locations that provided the potential for parallel access supports the FINST hypothesis.

While on the topic of the number of locations at which ILM may occur, we note that there are stimulus displays that may not allow individuals to experience a capacity breakdown. For instance, our experimentation started out by drawing radii probes to each of a varying number of cued locations in displays like Experiment 2. We hoped that the resulting "imploding asterisk" effect would cease to exist once a participant's capacity limit was reached. Instead, however, motion entrainment, or grouping effects, took over such that regardless of the number of cued locations in the display, inward motion always seemed to occur. It seems as though motion within some of the lines induced an overall motion experience within the entire group. Similar effects with ILM have been reported elsewhere (Kawahara, Yokosawa, Nishida, & Sato, 1995), in which it was observed that individuals have great difficulty in searching for ILM in a minority direction when the majority of ILM is in the opposite direction. Schmidt and Klein (1996) examined this issue and reported that consistent with a motion entrainment hypothesis, the majority motion signal dominates the participant's perception of motion in the display. Hence, if displays allow motion entrainment to occur (i.e., do not equate the overall proportion of motion signals in a given direction with signals in the opposite direction), a capacity limit may not be observed.

ILM: Gradients or Apparent Motion Impletion?

Downing and Treisman (1995, 1997) have proposed that ILM is not caused by a spatial or temporal gradient of signals arriving at motion detectors but from apparent motion impletion mechanisms that can be biased by attentional manipulations. An impletion process is hypothesized to generate a motion trajectory between object locations that is consistent with real-world movement and transformations of a single object. According to this account, the line in ILM is taken to be the same object as the priming dot: The dot is interpreted by the impletion system as jumping to the location of the line and then growing outward (Downing & Treisman, 1997).

Regardless of the underlying mechanism, our use of the illusion remains focused on demonstrating potential parallel access in vision. FINST theory speaks to issues of access by the illusion's mechanism, but it is agnostic about the nature of this mechanism. Whether FINSTs provide impletion processes with access to representations of the visual scene, or whether they supply other sorts of visual routines with access to an underlying gradient representation, the important point for FINST theory is that multiple locations in the display are simultaneously individuated and that information from those locations can be accessed before such processes can operate. The sort of visual routines that operate to produce ILM remain the domain of future research.

Despite the agnosticism of FINST theory about the mechanism producing ILM, empirical findings from Experiment 2 lend support to a gradient interpretation of the illusion. Consistent with the gradient of arrival times hypothesis, the results of Experiment 2 reveal that the use of apparent motion to draw the line in a direction opposite to that of ILM counteracts, but does not prevent, the illusion. According to the gradient account, one would expect that this method of directly manipulating signal arrival times would weaken but would not necessarily change the direction of the resulting motion percept because a gradient around the original priming dot would still modulate incoming signals. Experiment 2 also revealed that slower counteracting apparent motion defeated the illusion more strongly than faster motion. Again, this is consistent with the idea that signal arrival time is an important factor in causing ILM.

Without postulating further mechanisms, an apparent motion impletion account is hard-pressed to explain why apparent motion toward Experiment 2's priming dot was not experienced. In this situation, there is an object that is drawn to be growing over time toward the priming dot, so presumably impletion processes would conclude that the line object was expanding toward the dot. The dominant percept however, as predicted by the gradient account, is motion within the line away from the priming dot.

Some researchers have interpreted Downing and Treisman's (1997) work as challenging the notion that ILM is sensitive to attention. Although Downing and Treisman reported difficulty evoking the illusion endogenously, their work (Experiment 2A in Downing & Treisman, 1995) confirmed that ILM is attention sensitive in that an endogenously tracked target reliably elicited ILM. They hypothesized that rather than attention modulating the speed of signal transmission (see Hikosaka et al., 1993a, 1993b; Stelmach & Herdman, 1991; Stelmach et al., 1994), attention instead acts to bias certain scene interpretations over others. Regardless of the theory one adopts, there is a role for attention in ILM; however, future researchers will determine just what this role is.

An Organizational Framework

Given that there is support for attentional involvement in the line-motion illusion and for multiple loci of this effect, our results lead us to reexamine old arguments about the nature of attentional phenomena. The arguments presented here are not intended to refute the concept of a serially driven, spatially confined (i.e., "spotlight") form of attention; rather, we take them as demonstrating that such an account is not comprehensive. Our findings support the proposal for a second, spatially parallel, low-level form of attention that operates in conjunction with attentional mechanisms as they are traditionally viewed.

Recent work using the inattention paradigm (Mack, Tang, Tuma, Kahn, & Rock, 1992; Rock, Linnett, Grant, & Mack, 1992) suggests that multiple levels of attentional processing may exist. Mack et al. (1992) showed that in the absence of the allocation of attention, processes traditionally classified as preattentive (texture segregation as well as grouping by similarity of lightness or proximity) failed to affect participants' behavior. They concluded that even gestalt organizational processes are at least somewhat attention demanding. Rock et al. (1992) have discovered that access to information about color, location, and number (for up to four items) can be obtained in a truly preattentive fashion. The last of these attributes is clearly a finding that fits nicely with FINST theory.

We view the ILM data as suggesting the following taxonomic framework, which builds on that of Mack et al. (1992). Primitive visual indexing processes operate without attention and are prerequisite for any sort of visual processing involving information from discriminable display objects. Such indexing operates as outlined by Pylyshyn's (1989, 1994) FINST hypothesis. Next, a spatially parallel distributed visual attention system capable of subserving processes of primitive scene organization operates in an automatic fashion. The output of this system is linked to, and may invoke processing in, a serial, controlled attentional system. This latter system may (or may not) operate in parallel with and take inputs from the primitive nonattentive stage of processing. Also, there may be some mechanism for the serial attention system to influence processing at the primitive indexing stage. Needless to say, the elucidation of such a framework is an ambitious program for future research.

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