Preattentive perception of multiple illusory line-motion: a formal model of parallel independent-detection in visual search - Abstract

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ABSTRACT. The phenomenon referred to as illusory line-motion (ILM; O. Hikosaka, S. Miyauchi, & S. Shimojo, 1993a) has been described as a measure of the local facilitation of attention gradient. However, J. Kawahara, K. Yokosawa, S. Nishida, and T. Sato (1996) have demonstrated a spatially parallel search for an "odd man out" in the ILM direction. Apart from showing preattentive ILM perception in terms of an analogy between line-motion and apparent motion, the authors examined whether ILM perception is possible without attention from another point of view. Four experiments revealed that the ILM target can be detected in parallel without invoking attentional facilitation and invalidated the possible contribution of attentional set in parallel ILM search. Participants were able to correctly detect the ILM target among multiple nontargets, even when the line orientation was changed from trial to trial. The authors' independent-detection model predicted ILM search performance well on several occasions. These find ings strongly support a preattentive and stimulus-driven explanation of ILM perception.

Key words: illusory line motion, visual attention, visual search

ILLUSORY LINE-MOTION (ILM) is typically produced by the sequential presentation of a small dot and a line--for example, a line presented all at once and perceived successively after a flashed dot is perceived as being drawn from the end at which the dot was presented to the other end. That phenomenon has been attributed to accelerated processing at the locus of attention. According to Hikosaka, Miyauchi, and Shimojo (1993a), attention is captured by the onset of a cue dot, which facilitates the "prior entry" of the visual stimulus nearest around the cued location. That facilitated processing creates virtual time lags across neighboring locations, causing motion detectors to respond to and generate motion sensations. A similar sensation of illusory motion can be observed for various arrangements of stimulus attributes and environments. For example, object-bound ILM (Hikosaka, Miyauchi, & Shimojo, 1993b) and ILM due to voluntary orientation (Hikosaka et al., 1993b) and nonvisual cues, such as auditory and somat osensory cues (Shimojo, Miyauchi, & Hikosaka, 1997), are considered to be favorable evidence for the attentional explanation of ILM.

A typical stimulus eliciting ILM, such as a single pair consisting of a dot and a line, is very similar to that producing apparent motion. Both typical ILM stimuli and classical apparent motion stimuli consist of at least two successive frames containing items that are spatially displaced. Even though there is a difference in appearance between the illusory line and apparent motion-such that the former motion appears to be within the line and the latter between the first and the second item-it is imperative to draw an analogy between these phenomena. Kawahara, Yokosawa, Nishida, and Sato (1995, 1996) have been motivated to examine whether stimulus--driven motion mechanisms, that is, apparent motion mechanisms, subserve illusory line-motion. They devised an ILM search task and found that apparent motion mechanisms directly respond to dot-line pairs to produce illusory motion in the line. In the present study, we obtained additional results to extend this notion and have thus modified a formal model predicting the performance of an ILM search.

ILM Search

To determine whether ILM is perceptible without attention, Kawahara et al. (1996) devised a visual search task in which participants search for a target line that shoots in a direction opposite to the nontargets. The stimulus presented to the participants consists of two sequentially presented frames: The first contains multiple dots presented at random locations for 120 ins, and the second contains the same number of lines. All the lines are presented on the same (e.g., right) side as the dots, except for the odd target line, which is presented on the opposite (e.g., left) side. Their rationale was that if attention is responsible for this illusion, a participant should not be able to perceive ILM with multiple dot-line pairs and, thus, would fail to detect the odd target because it is difficult to direct attention simultaneously to many locations (e.g., Eriksen & Yeh, 1985; Posner, Snyder, & Davidson, 1980; but there are conditions under which attention can be distributed to noncontiguous locations, cf. Kra mer & Hahn, 1995). However, if the ILM of a typical dot-line pair is simply first--order apparent motion-that is, it is perceptible without attention--a participant would be able to detect the odd target among multiple nontargets because the direction of motion is known to be a preattentively detectable feature in the visual search, unless the displacement is very large (e.g., Dick, Ullman, & Sagi, 1987; Ivry & Cohen 1990; Nakayama & Silverman, 1986). The results of the ILM search (Kawahara et al., 1996; see also von Grunau, Dube, & Kwas, 1996) support the notion of the parallel perception of ILM: Participants have been able to detect the target with few errors, even when the set-size (the number of dot-line pairs on the stimulus display) is as many as 8.

To verify the contribution of apparent motion mechanisms to ILM perception, Kawahara et al. (1996) changed the interstimulus interval (ISI) and the contrast polarity between the dots and lines (with either both the dots and lines being brighter than the background or the dots being darker and the lines being brighter). Those factors are critical determinants of apparent motion perception (Edwards & Badcock, 1994). Detecting an ILM target has been observed to be nearly impossible with larger set-sizes when an ISI of a few hundred milliseconds is inserted. Changing the contrast polarity significantly impairs detection, even with no ISI. Those results are ostensive evidence implying the contribution of apparent motion mechanisms to ILM perception. However, there has never been any doubt that ILM perception is susceptible to factors that are known to affect motion perception, because ILM is a phenomenon of perceiving motion. As Hikosaka et al. (1993a, 1993b) have suggested, if attention works at quite an early le vel of perception, it is not sufficient to simply show the involvement of apparent motion mechanisms in ILM perception for us to conclude that the simple ILM of a dot-line pair can be perceptible without attention. However, we have at least two ways to preclude that argument.

Verifying the Preattentive Perception of ILM

Kawahara et al. (1996) have provided one of the ways to corroborate the argument that simple ILM can be perceptible without attention. It is to show that apparent motion mechanisms that directly respond to dot-line pairs produce an illusory sensation of motion. As already mentioned, Kawahara et al. (1996) have shown that the factors that affect ILM target detection have similar effects on the detection of an odd target among typical two-dot apparent-motion stimuli.

The second way to corroborate the preattentive perception of ILM, which has been hinted at by Kawahara et al. (1996), is to show that the search for multiple ILM stimuli can be conducted in parallel. In other words, evidence revealing that an ILM target can be detected without any capacity limit will strongly support the preattentive account of ILM. Kawahara et al. (1996) have capitalized on a preliminary probability model of independent parallel processing in a letter-detection task (e.g., Eriksen & Spencer, 1969) to test whether the search for multiple ILM stimuli can be conducted in parallel. If ILMs are perceived at multiple locations in parallel, the target-detection performance can be predicted from the performance of the direction judgment of ILM. That is because the correct rate for detecting a target item among multiple items can be statistically predicted from the simple production of the correct detection rate for one item on the basis of the independent-detection of each item.

Their predicted performance based on a probability model described the general tends in the data obtained, in that the ILM search performance is gradually impaired as set-size (number of items in the search display) increases. However, the prediction errors tend to be lower in comparison with the measured search results. That incompleteness of the model motivated us to modify it in the present study.

The Aim of the Present Study

The goal of our present study was to provide a better mathematical model of independent-detection of ILM than that suggested by Kawahara et al. (1996). We assumed that a consistent prediction using the independent-detection model with the observed search performance would support the idea that ILM is perceptible in parallel, namely, capacity- (attention-) free perception of ILM. In addition, we tested the model predictability with a larger set-size than that used by Kawahara et al. (1996). This test is important in evaluating the advantages of the independent-detection model in comparison with an alternative model such as the FINST explanation (FINger of INSTantiation; Schmidt, Fisher, & Pylyshyn, 1998), which suggests that a few noncontiguous locations are accessible at the same time, enabling observers to simultaneously perceive multiple ILM. Schmidt et al. (1998) presented multiple pairs of ILM consisting of simple dot-lines and found that participants had parallel access to between two and five locations. That finding itself is consistent with their FINST model. FINST is hypothesized as a spatial index that points to a location where an object exists or has existed. As long as the dot-line pairs are restricted to three to four locations, both the FINST explanation and independent-detection model predict relatively unimpaired performance for an ILM search. However, for a set-size larger than 4, which exceeds the upper limit of FINST indexing, the FINST model simply predicts that performance will be worse than that for set-size 4, whereas the independent-detection model predicts performance quantitatively. If the predicted and measured performances are comparable, then it is highly likely that ILM is perceived independently without attention.

In the present study, we conducted a set of experiments that bolster and expand the idea of independent-detection model of ILM. First, we directly examined some of the unsettled questions from our previous study (Kawahara et al., 1996; see below), which convinced us that ILM can be perceived in a stimulus-driven way without invoking focused attentional facilitation. Second, we excluded the possibility that attentional set might play a major role in an independent ILM search. Finally, we tested whether the independent-detection model predicts search JIM perfor mance with a larger set-size (14 items). We will begin with a brief sketch of the independet-detection model of ILM before describing the experiments in detail.

The Independent-Detection Model of ILM

This model predicts ILM search performance based on the simple product of the error rates in discriminating the motion direction of a dot-line pair, according to the following calculation. The error rate, which, for simplicity we refer to hereafter as ε_1 is considered to be the probability of perceiving the motion of a line from the no-dot side. The subscript indicates the number of dots, which was limited to one in the discrimination task in Kawahara et al. (1996). The probability of line-motion perception from the dot side (the normal direction of ILM perception) is $1 - \varepsilon_1$. Errors in the ILM search will be a miss a target-present trial or a false alarm in a target-absent trial. A miss occurs either when participants incorrectly judge the target direction and correctly judge the directions of all the distractors, or when they correctly judge the target direction and incorrectly judge the directions of all the distractors. Thus, the miss rate (M) for set-size N is given by $M(N) = \varepsilon_1(1 - \varepsilon_1)^{N-1} + (1 - \varepsilon_1)\varepsilon_1^{N-1}$.

This and the following equations are valid when N is larger than 1 because these predictions assume a case in which the target is detected among multiple nontargets. A false alarm occurs when participants do not correctly reject the target-present hypothesis in a target-absent trial. A correct rejection occurs when all the items are judged to be in either the correct direction or the incorrect direction, respectively. The false alarm rate (F) therefore is given by $F(N) = 1 - [(1 - \varepsilon_1)^N + \varepsilon_1^N]$.

Since the same number of target-present and target-absent trials were included, the final error rate is given by

$$\mathrm{Error}(N) = 1/2[M(N) + F(N)]$$

$$= 1/2 \{\varepsilon_1(1 - \varepsilon_1)^{N-1} + (1 - \varepsilon_1)\varepsilon_1^{N-1} + 1 - [(1 -$$

[[epsilon].sub.1]).sup.N] + [[epsilon].sub.1.sup.N]}. (1)

As noted earlier, this model is incomplete in that it tends to underestimate the ILM search performance, although it does describe general trends. The following experiments show evidence to support the notion of an independent-detection model of ILM by examining (a) unsettled questions from our previous study (Kawahara et al., 1996; see below), (b) the possibility that the attentional set might contribute to the independent ILM search, and (c) whether the model predicts ILM search performance with a larger set-size.

General Method

This section contains an outline of the methods that were common across the experiments. The method was a specified here unless a specific difference is noted in the section describing a particular experiment.

Apparatus and Stimuli

The stimuli were generated by a microcomputer (NEC PC9821 Ap2) and displayed on a monitor (SONY GDM-20SE). The participants observed the stimuli in a darkroom from a distance of 120 cm with a chin rest.

The stimuli consisted of a sequence of images 16.7[degrees] horizontally x 12.80 vertically with a small central fixation cross. Either 2,4, or 8 dots appeared for 120 ms in the first frame; the same number of lines appeared in the next frame. Each dot was a 0.1[degrees] X 0.1[degrees] square, and each line was a short horizontal segment of 1.7[degrees] x 0.1[degrees]. The dots were presented at random locations with the following constraints. The location of each dot-and-line pair was determined so that a minimum separation (1.4[degrees] vertically and horizontally) was kept between the dots. One end point of a line completely occluded the preceding dot. The dots did not appear within an area 1.9[degrees] vertically X 3.4[degrees] horizontally around the fixation cross. The dots and lines appeared white on a gray background.

Procedure

The participants performed both an ILM search task containing a variable number of dot-line pairs and a direction-discrimination task containing a variable number of dots and a single line.

In the ILM search task, prior to the beginning of each trial, the fixation cross appeared at the center of the screen. Maintaining fixation throughout each trial was highly stressed in instructions to the participants. The participants pressed the space bar on the keyboard to begin each trial. After 1500 ins, a certain number of dots were presented for 120 ins, followed by the same number of short line segments. The set-size was randomly chosen as 2, 4, or 8. The lines were presented until the participant reported the presence or absence of a target by pressing one of the two assigned keys (the "4" or "6" number key). The target, which was defined as a line, was presented on the side opposite the nontarget lines. The target line could be on either the right or left side of a dot. A target was presented in half of the trials. In the target-absent trials, all the lines were presented on the same side as the dots. Feedback was given for each trial by a tone after each incorrect response. After a participant resp onded, a circle appeared at the target's position, regardless of the participant's response. The set-size was varied within each block. Each participant performed two sessions, each containing three blocks. A block consisted of 60 trials: three set-sizes (2,4, or 8) for two trial types (target present or absent) for 10 repetitions each. The data from the first block were regarded as practice and were discarded.

In the direction-discrimination task, the procedure was identical to that for the visual search task, except for the following points. After a variable number of dots (1, 2, 4, or 8, chosen randomly across trials) were presented for 120 ins, a single line was presented. When the number of dots was 1, the line was presented so that one of its endpoints occluded the dot. When multiple dots were presented, their locations were determined based on the same spatial constraints as in the visual search task, and one of the dots (chosen randomly) was followed by the line. For convenience, we refer to the number of preceding dots in the direction-discrimination task as the set-size. When the line was presented, all the dots were extinguished while the line was present. The participants reported the perceived direction of the motion in the line by using the two-alternative forced-choice method. (1)

Each participant performed a block of trials after approximately 10 practice trials. Each block consisted of 64 trials (4 set-sizes x 2 directions x 8 repetitions). The order of the visual search task and of the direction-discrimination task was counterbalanced across participants.

The Effect of Motion Noise on ILM Search

To begin with, we will consider in this section two possible explanations for the errors predicted using the independent-detection model being lower than those obtained in the experiments of Kawahara et al. (1996); that is, the idea of motion noise and attentional diffusion. We will then present an experiment that corroborates the independent-detection model, which is modified based on the idea of motion noise in the ILM search and then another experiment that argues against attentional diffusion.

One possible explanation for the deviation between the predicted and obtained search performance in ILM search is that the model disregards the noise in the motion signals in the motion-detection stage. Even though the apparent motion phenomenon confirms the visual system's ability to perceive motion by matching features over a wide range of spatiotemporal distances, the correspondence among sequentially presented items will weaken as the number of items increases because of the combinatorial explosion in the number of possible frame-to-frame item matches to be considered (Ullman, 1979). For example, given that a dot-line pair is presented in a direction-discrimination task, the correspondence between the dot and the line can be determined uniquely. However, in the ILM search task, the possibility of a dot appearing at a location adjacent to another dot increases. This possibility leads to an increasing number of incorrect combinations of dot-line correspondences as the set-size increases due to the fact that the relative proximities of the elements are critical in determining the correspondences, especially for apparent motion across homogeneous items (Shechter, Hochstein, & Hillman, 1988). Thus the error rate predicted for visual search based on the judged direction of a single dot-line pair might be lower than the actual search performance. Therefore, the independent-detection model can be modified to incorporate the increasing motion ambiguity as the increment in set-size increases.

EXPERIMENT 1

The first experiment was designed to determine the effect of motion ambiguity caused by presenting multiple items on determining the direction of an ILM. If the presence of multiple preceding noise dots is a critical determinant for line-motion perception, ILM perception will deteriorate as the number of dots is increased. We thus varied the number of preceding noise dots in the direction-discrimination task: Only one dot-line pair was presented, but the dot was presented along with a variable number of dots that had no corresponding lines. In addition, we conducted a visual search task for an odd ILM target to replicate the data of Kawahara et al. (1996). In this task, we varied the number of dot-line pairs (i.e., set-size). (2) That manipulation was done to confirm the parallel detection of ILM. If focal attention is critical to perceiving ILM, the visual search performance will decrease sharply as the set-size increases; this phenomenon, as mentioned earlier, can be explained by the impossibility of the fo cus of attention being simultaneously directed toward many locations (e.g., Posner et al., 1980).

Contrary to the notion that focal attention is critical to perceiving ILM, if the ILM is perceived in parallel but its detection is affected by ambiguity in the motion signals, the search performance will deteriorate as the set-size increases. If that happens, the search performance can be more accurately predicted by using an independent-detection model that incorporates the ambiguity of motion signals. That can be done by using an error rate with multiple preceding-noise dots--in contrast to our original independent-detection model of ILM, which used an error rate but with no preceding-noise dots.

Method

Sixteen undergraduate and graduate students at the University of Tokyo participated for pay. All had normal or corrected-to-normal visual acuity. The participants performed both an ILM search task containing a variable number of dot-line pairs and a direction-discrimination task containing a variable number of dots and a single line. The set-size and the number of preceding dots were 2, 4, or 8. The order of running these tasks was counterbalanced across participants.

Results and Discussion

The means of the accuracy data of the 16 participants for visual search are presented in Figure 1, and those for the direction-discrimination task are in Figure 2, as a function of set-size. In the direction-discrimination task, a response reporting the direction opposite the normal line-motion--that is, the participants perceiving the line-motion direction from the opposite side of the dot toward the dot side--was regarded as an error.

In the visual search task, the participants were able to detect the target with a very low error rate, even when the display contained eight lines. Although the error rate increased with set-size, it was still around, at most, 10%. In the direction-discrimination task, the participants judged the TIM directions with a very low error rate, even when multiple distracting dots were presented simultaneously with the dot, followed by the line. In their self-reports after both tasks, all participants commented that they observed clear motion sensation in the line(s).

We submitted the arcsine-transformed error rates for the visual search task to one-way analysis of variance (ANOVA) with set-size (2,4, or 8) as the primary factor. Set-size yielded a significant effect, $F(2,30) = 7.33$, $p<.005$. A multiple comparison test of this main effect revealed that the error rates at a set-size of 8 were larger than at the other set-size, $ts(30)>2.4$, $p<.05$.

The error rates estimated using the independent-detection hypothesis of Kawahara et al. (1996) are shown in Figure 1 as a thick dotted line. These estimated values tend to be lower than the measured data. As the set-size increased, the difference between the measured and estimated error rates became larger.

These results indicate that participants can perceive ILM at multiple locations in the visual field, and they essentially duplicate previous data (Kawahara et al., 1996), suggesting a preattentive account of the ILM observed in simple stimuli such as dots and lines. The error rate in the ILM search task tended to increase with larger set-sizes. As expected, the error rate in the direction-discrimination task increased with the number of dots in the first frame.

A Revised Model

The predicted error rate in the ILM search task from the original independent-detection model deviated somewhat from the measured value. The original model assumed that the error rate in the visual search simply depends on the set- size: The model always used the error rate for a dot-line pair in the direction-discrimination task. That disregards the effect of motion ambiguity, which occurs when multiple dots are presented in the first frame of the ILM display. The more dots that are presented in the first frame, the stronger the noise in the motion correspondence.

Recall that in the present experiment, the error rate in the direction-discrimination task increased with the number of dots in the first display. Taking this relationship into account should provide a better prediction of the performance of the ILM search. We thus expanded our model to include the error rate obtained in the direction-discrimination task for each set-size.

The predicted error rate for the ILM search task for set-size N is given by

Error(N) 1/2 ([[epsilon].sub.N](1 - [[epsilon].sub.N).sup.N-1] + (1-[epsilon].sub.N])[[epsilon].sub.N].sup.N-1 + 1-[(1-[epsilon].sub.N].sup.N] + [[epsilon].sup.N.sub.N]}, (2)

where with subscript N indicates the error rate in the direction-discrimination task with N dot(s). For example, to predict the error rate for an ILM search with a set-size of 4, the revised model uses the error rate for a direction-discrimination task with a set-size of 4.

The estimate derived from the revised model is shown in Figure I as a thin dotted line. This estimated value is higher than that in the original model. The search functions measured from the present experiment and the value estimated from the revised model show very similar profiles.

To determine which model produces a better prediction for the present results, we calculated the deviation index, which is the sum of the squared error (i.e., the squares of the difference between the predicted and measured values) divided by the predicted value for each set-size for each participant. The deviation indices for both models are shown in Figure 3. If the predicted error rates of both models deviated equally from the observed error rates for the visual search task, the indices would be arrayed on the diagonal. Figure 3 clearly shows that the predictive ability of the revised model, which takes motion noise into account, is better than that of the original model. This improved prediction of search performance strongly implies that multiple ILMs are perceived simultaneously and independently. The result is that the increase in error that occurs with increase in the number of items in the stimulus display "is inherent in any system in which targets are sometimes confused with distractors" (Pashler, 1998, p. 112). An important point is that such increments in error can be predicted well by our revised independent-detection model. As noted earlier, the preattentive account of ILM will be fortified by at least two forms of corroboration: (a) showing the similar effects of variables that are critical to motion perception in an ILM search and an apparent-motion target search and (b) showing the independent-detection of the ILM target. Kawahara et al. (1996) made the former clear, and the present results do the same for the latter. These data argue in favor of preattentive ILM perception.

EXPERIMENT 2

The Effect of Attentional Diffusion

The first experiment provided evidence that bolsters the notion of preattentive ILM perception. Contrarily, one might argue that presenting multiple dots should result in a poor search performance because it is difficult to simultaneously direct attention to multiple locations. The second experiment, however, makes that alternative unlikely. We asked participants to search for a target line moving in the direction opposite that of the other seven lines, as in a typical ILM search. One exception was that half the trials had an additional dot, which was presented at the same or opposite side of the upcoming line (see Figure 4). The distance between the additional and ordinary dot was slightly (1.25 times) larger than the length of the line. Given that the additional dot appeared at both sides of the upcoming line (both-sides condition), observers would see the growing lines collide at the midpoint of the line (e.g., von Grunau, Racette, & Kwas, 1996). Both apparent motion and attention accounts predict this col lision. In contrast, when the additional dot appears at one side of the line (one-side condition), the apparent motion account predicts that the perception of line-motion will be facilitated. Because a batch of two dots and a line are similar in a very low spatial frequency component, line-motion can be easily picked up by motion detector(s) tuned to a low spatial frequency. For the attention account, however, it is difficult to predict enhancement in motion perception unless the attentional facilitation of the additional dot is larger than 2.125[degrees] (dot-to-dot distance) in radius. This seems too large in terms of the following two pieces of evidence: Eriksen and Eriksen (1974) have estimated the size of the attentionally facilitated area to be 10 in radius, and Miyauchi, Hikosaka, and Shimojo (1991) have reported that the effects of attention, as measured by the motion-cancellation task, almost disappear at 2.50 from the cue when the cue-lead-time is 150 ins. In addition to that assumption for the atte ntion account, one must presume that the attentional effect is pooled in the overlapping facilitated areas. We are not aware of any study that has explicitly investigated these assumptions.

Method

Ten undergraduate and graduate students at the University of Tokyo participated for pay. The participants conducted both an odd line-motion search (i.e., with an additional dot) and a normal ILM search (i.e., without an additional dot). The set-size was 8 in both conditions. The order of the running conditions was counterbalanced across participants.

Results and Discussion

The average error rate in the odd line-motion search for all participants was 8.36% under normal ILM search conditions (i.e., without an additional dot), 39.1% under the both-sides condition, and 5.63% under the one-side condition. An important feature of these results is that the error rate of the one-side condition is significantly smaller than that of the normal ILM search condition, $t(9) = 3.49$, $p < .01$.

This result suggests that not a diffusion of attention but a correspondence in the motion signal is critical to the deviation between the predicted and obtained search performance when multiple dots are presented.

One might argue that varying the number of dots in the display might have affected the stimulus load. Indeed, there may be a differential effect between high- and low-load displays on performance in an attention-related task. Some evidence suggests that the extent of processing of irrelevant distractors depends on the load in a task. Lavie (1995) has manipulated the load by set-size or by different processing requirements for identical displays, finding that interference by distractors to the targets is observed only under low-load conditions. Thus, if the same explanation can be applied to the present study, varying the number of dots might have produced some effect on the ILM perception. However, we believe that this hypothesis requires further study, as the definition of load is not yet specified, and it is therefore premature to draw conclusions between studies using different stimulus settings.

EXPERIMENT 3

The Effect of Top-Down Attentional Modulation

The first experiment showed that an ILM target could be independently detected among distractors. Our model fitting supports the idea of a preattentive perception of ILM without the need to propose any attentional processes. The model also assumes that each ILM can be independently detected and that the total correct rate in visual search can be predicted based on the product of the correct rate in the direction-discrimination of a single ILM. It seems to be widely accepted that not only stimulus-driven components but also top-down components (i.e., attentional set) modulate perception (Pashler, 1998; Yantis, 1996). Thus in this experiment, we looked for further evidence indicating a parallel detection of ILM without contributions from top-down components. It is known that there are at least two types of top-down modulations: One directs attention voluntarily to specific stimulus attributes (e.g., Egeth, Virzi, & Garbart, 1984), and the other directs to a specific location (e.g., Posner, Nissen, & Ogden, 1978). We examined whether the top-down modulation plays any role in simultaneous ILM perception from those two points of view.

First, to test the availability of top-down attentional modulation in a specific motion direction, we observed the effects of the predictability of line-motion direction. Suppose that the results of the first experiment indicate the possibility of performing an effortless ILM search by using top-down modulation to detect a specific difference in the motion direction. In other words, an apparently effortless search might be achieved by attempting to detect a horizontal difference in the motion signal (i.e., using the feature search mode of a visual search target; Bacon & Egeth, 1994). That may be possible, because the stimulus lines were kept horizontal in the first experiment and in all the search experiments of Kawahara et al. (1996). Based on this assumption, the participants might perceive only one specific direction of an ILM at a time (e.g., horizontal motion). If top-down modulation is indispensable to ILM perception, the effortless ILM search cannot be taken as unequivocal evidence for the stimulus-dri ven occurrence of ILM.

To determine the contribution of top-down modulation in an ILM search, we attempted to eliminate the effectiveness of the specific-feature (i.e., horizontal opposing motion) detection strategy by randomly changing the orientation of the ILM stimuli from trial to trial. Those changes enabled us to test whether participants were indeed able to search in a stimulus-driven way as in singleton detection mode (Bacon & Egeth, 1994). We thus predicted that if top-down modulation is a necessary condition for ILM perception, the search for an ILM target will be sharply impaired by randomly changing the line orientation from trial to trial. In contrast, if ILM perception occurs in a stimulus-driven fashion without incorporating attention, search performance similar to that in the first experiment will be obtained. That correspondence can be explained by participants being able to simultaneously monitor multiple moving targets, even when the motion directions of the targets and distractors are unknown to the participants (McLeod, Driver, Dienes, & Crisp, 1991).

Note that in a separate trial, all the lines had the same orientation, so that the target was defined as a line shooting to the side opposite that of the other non-target items. The participants searched for the ILM target with an odd motion direction irrespective of the line orientation, which was determined randomly for each trial. The direction-discrimination task was also conducted in this random orientation setting.

We also examined whether participants searched only a limited area of the visual field for a target. If the participants concentrated on target detection around the fixation cross at the expense of detecting targets near the periphery to focus attention in a top-down way, then the target detection error would be as low as when participants searched across the whole visual field. If such a strategy were used, we would expect errors to occur more frequently in peripheral locations than near the center of the visual field. To test this possibility, we analyzed the locations where targets were missed.

Method

The same 16 participants tested in the first experiment also participated in this experiment. The stimuli and procedure were the same as for the first experiment, except that the orientation of the lines was determined randomly between -90[degrees] and +900 50 that not only some cardinal directions (e.g., 45[degrees]: right diagonal, 90[degrees]: horizontal) but also any random direction of line-motion could be presented (e.g., -7[degrees]: almost vertical but slightly tilted to the left). The participants performed an ILM search task with a variable number of dot-line pairs and a direction-discrimination task with a variable number of dots and a single line. In the search task, the participants reported the presence or absence of a target, which appeared in half the trials. In the direction-discrimination task, they reported the perceived direction of the motion in the line by using the two-alternative-forced-choice method. When the line was a right diagonal, the "1," "2," and "4" keys on the keyboard were u sed to report downward motion, and the "6," "8," and "9" keys were used to report upward motion. When the line was a left diagonal, "2," "3" and "6" keys for were for downward and "4," "7," and "8" for upward. Both tasks had the same number of trials as in the first experiment. The order in which the experiments (Experiments 1 and 3) and the tasks (search or direction discrimination) were performed was counterbalanced.

Results and Discussion

The results for the 16 participants in the search task are shown in Figure 5, and the results for the direction-discrimination task are shown in Figure 6. The mean error rates for both tasks were quite low but increased slightly with set-size. Those same trends were also observed in the previous experiment. Comparing the results of Experiment 1 (Figure 1) and those of the present experiment (Figure 5) reveals that the participants were able to detect the target even when the line orientation changed randomly across trials. Most participants (15 of 16) commented in their self-reports that there was no difference in difficulty due to the changing line orientation.

To clarify these results statistically, we submitted the arcsine-transformed error rates for the visual search task to two-way ANOVA with line predictability (constant in the first experiment and variable in the second) and set-size (2, 4, or 8 pairs of dot-line) as the main factors. Set-size yielded the only significant effect, $F(2, 30) = 14.00$, $p < .005$. A multiple-comparison test of this main effect revealed that the error rates at a set-size of 8 were larger than at the other set-size, $ts(30) > 4.00$, $p < .001$. The main effect of line predictability and the interaction of predictability multiplied by set-size were not significant, $F(1, 15) = 0.22$, $p = .64$; $F(2, 30) = 1.38$, $p = .29$, respectively.

We also submitted the arcsine-transformed error rates for the direction-discrimination task to a similar ANOVA with line predictability (constant in the first experiment and variable in the second) and set-size (1, 2,4, or 8 pairs of dot-line) as the main factors. Again the main effect of set-size was significant, $F(3, 45) = 2.85$, $p < .05$. The main effect of line predictability and the interaction of predictability multiplied by set-size did not reach significance, $F(1, 15) = 1.34$, $p = .26$; $F(3, 45) = .02$, $p = .99$, respectively.

To summarize, the results of this experiment showed that changing the line orientation randomly from trial to trial has little effect on the search for and direction discrimination of ILM. These results eliminate the possibility that the participants used a specific-feature (e.g., horizontal motion difference) search mode. Although it is known that prior knowledge of the direction of a moving target enhances its detectability (Chaudhuri, 1990; Raymond, O'Donnell, & Tipper, 1997; Sekuler & Ball, 1977), the present results suggest that such top-down modulation for specific motion direction is insufficient to fully explain the effortless ILM search. Strictly speaking, this comparison of orientation predictability might be possible confounding, because only horizontal lines were used when the orientation was consistent (Experiment 1), whereas the lines tilted at any orientation were used when the orientation was unpredictable (Experiment 3). For a more precise comparison, the line should have been tilted randomly across but consistent within participants. In the present study, we did not utilize these conditions in the first experiment because we intended to compare results between a standard (horizontal) ILM search and that of a previous study using the same stimuli.

To examine the possibility of top-down modulation for directing attention to a limited location, we analyzed the location where targets were missed (see Figure 7). As noted earlier, if participants directed attention in detecting the target to only a limited area around the fixation cross, at the expense of targets at the periphery, then the error should have occurred more frequently at peripheral locations. Contrary to this prediction, there is no obvious bias of location concerning where the targets were missed. Consequently, the participants were unlikely to have used top-down modulation for directing their attention to a specific location.

Our present results exclude the feasible contribution of stimulus-driven modulation (i.e., focused attention in Experiment 1) and top-down modulation (two types of attentional set--that is, directing attention to specific features and locations in Experiment 3), whereas our previous research (Kawahara et al., 1996) tested only the former type of attentional contribution. Thus we can conclude that the ILM search is conducted in a stimulus-driven fashion.

The results suggesting the nonsignificant effects of orientation predictability were essentially based on acceptance of the null hypothesis. However, the error rates under the variable orientation condition (Experiment 3) were quite low, and most of the participants reported that their ILM search performance gained little from a knowledge of the line orientation. Therefore, it seems that the effortless visual search of the ILM target is not due to the contribution of a higher-order process, but that a stimulus-driven motion mechanism plays a major role.

Again, the independent-detection hypothesis produced a good fit to the search results. Figure 5 shows the fit of the original independent-detection model to the error rates for the visual search task (thick dotted line) and that of the revised model (thin dotted line) as a function of set-size. The fit of the revised model was very close for all set-sizes, and the deviations in predictions from the measured error rate were smaller than with the original model, even when line orientation was unpredictable across trials. The deviation indices were obtained using the same calculation as that for the first experiment and are plotted in Figure 8. These indices show that the revised model provided a better prediction of the visual search performance than does the original model.

EXPERIMENT 4

A Test of the Independent-Detection Model With a Larger Set-Size

The present results have thus far provided evidence supporting the independent-detection model. This model predicts a better ILM search performance in comparison with the original independent-detection model (Kawahara et al., 1996). Actually, the error rates for ILM search increase slightly with set-size. Thus it might be possible to explain this impairment by a limited-capacity model of attention. For example, Schmidt et al. (1998) have shown that the perception of multiple ILMs is relatively low as long as the dot-line pairs are restricted to three or four locations. They argued that this is because multiple (up to four) locations can be attended simultaneously by FINST indexing, which provides a hypothesized spatial pointer to indicate a location where an object exists or has existed. The FINST model predicts that the performance for perceiving simultaneous ILM will be worse than that for set-size 4. However the independent-detection model has an advantage in that this model provides quantitative predictio n. Thus in this experiment, we tested how the independent-detection model predicts the performance of an ILM search with a set-size (14 dot-line pairs) that exceeds the limit of FINST indexing.

Method

Sixteen undergraduate and graduate students at Hiroshima University participated for pay. They conducted three sets of tasks: an ILM search task and two direction-discrimination tasks, one with a variable number of dots and a single line and the other with only a pair of dot and line. Those two conditions were introduced to compare the prediction between the original independent-detection model and the modified mode. The participants judged the perceived direction of the line (either to the left or to the right) by hitting two assigned keys ("4" and "6"). In the search task and the direction-discrimination task with variable dot-line pairs, the set-size was either 4 or 14 (varied across trials). Each dot was separated from the other dots by at least 0.7[degrees] vertically and 1.4[degrees] horizontally to avoid overlapping. The order of the running tasks was counterbalanced across participants.

Results and Discussion

The results for the 16. participants in the search task and those in the direction-discrimination task are shown in Figure 9. Again, these same trends were also observed in the previous experiments: The mean error rates for both tasks were low, but they increased with set-size. The error rate for the larger set-size was still below chance levels, indicating that participants were able to see multiple ILMs. The arcsine-transformed error rates for the ILM search were submitted to two-way ANOVA with set-size (4 or 14 pairs of dot-line) as the main factor. Set-size yielded a significant effect, $F(1, 15)$ 55.40, $p < .001$.

It is clearly shown in Figure 9 that the revised independent-detection hypothesis (thin dotted line) produces a better fit to the search results than does the original model (thick dotted line). The fit of the revised model mimics the pattern of observed data, and the deviations in prediction from the measured error rate are smaller than with the original model. The advantage of the independent-detection model over the FINST model is that it provides a quantitative prediction of ILM perception even with a larger set-size that exceeds the limit of FINST indexing; the FINST model simply predicts that performance is impaired if the set-size is larger than 4. Predictions of performance outside of that limit are not the focus of the FINST model.

GENERAL DISCUSSION

In the present study, we conducted two experiments to examine the independent perception of multiple ILM. We were able to replicate the previous finding that the error rates for the ILM target search and those for direction discrimination were quite low. This is clearly consistent with findings that participants can perceive ILMs in parallel (Kawahara et al., 1996; von Grunau et al., 1996). The key finding from the present set of experiments is that the greater the number of preceding dots with no corresponding lines, the worse the ILM perception; the effect of set-size was highly significant in the discrimination task. The prediction of error rates for visual search by the original independent-detection model of ILM was lower than the measured error rates. Revision of the independent-detection model to incorporate this finding improved the fit to the measured error rates for the visual search task. The results of Experiment 2 suggest that not a diffusion of attention but a correspondence in the motion signal is critical to the deviation between the predicted and obtained search performance when multiple dots are presented.

Experiment 3 examined the contribution of top-down modulation (i.e., the participants' set for a particular direction of motion). The results excluded the possibility that top-down components play a major part in parallel ILM perception. The error rates predicted using the revised model were quite close for each set-size, even when the orientation of the line was randomly changed from trial to trial. The final experiment showed that the independent-detection model could predict search performance, even with a set-size that exceeds the limit of FINST indexing.

The present results show that multiple ILMs are independently perceptible without any capacity limit. The unsettled question in Kawahara et al. (1996) regarding the underestimation of error rates for the visual search task with the original model can be attributed to the effect of the preceding noise dots. Yantis (1996) has suggested that if participants have a set for a target, search performance showing little or no dependence on set-size cannot strictly be regarded as a preattentive, stimulus-driven search. This is because the participants might have used a specific top-down attentional set to direct attention to the output of the feature-contrast detector. The present results showing that top-down knowledge has little effect favor the preattentive and stimulus-driven account of ILM. Together with our previous finding that apparent-motion mechanisms directly respond to ILM stimuli, we thus conclude that preattentive, apparent-motion mechanisms elicit simple ILMs.

It has to be emphasized that our model is not a kind of multiple regression analysis in which adding more explanatory variables improves the prediction, but rather it predicts the target-detection performance based on a simple product of the detectability of a single ILM. That such a simple model can successfully predict the visual search performance is strong support for the hypothesis of independent-detection of ILM targets.

Contribution of Attention

It must be noted that the ability to perceive ILM preattentively can be applicable to a limited type of situation, such as that of typical ILM stimuli composed of a briefly flashing dot followed by a line. Even with quite similar stimuli, our previous research (Kawahara et al., 1996) has shown that attention might play something of a role in ILM perception because in ILM search, detection error was observed that could not be explained in our original independent-detection model. in other words, we ascribed the residual between search performance and our prediction to attention. Such an interpretation may cause ambiguity regarding the concept of attention. The present study, however, provides a clear view; with respect to the ILM sensation elicited by the simple dot-line stimuli we used in the present study, our results provide strong support for the preattentive account of ILM and imply no need for an attentional contribution.

We are not denying that attention plays a role in the perception of any ILM. Our hypothesis is that attention will determine the direction of illusory motion in stimuli that produce ambiguous motion, whereas simple ILM stimuli composed of a dot-line pair is unlikely to make any contribution of attention. For example, ILM yielded by a pop-out display (Shimojo, Miyauchi, & Hikosaka, 1992; von Grunau et al., 1996) can be explained well in terms of the attention account. In addition, recently reported types of ILM--for example, nonvisual auditory or somatosensory cues--and environmentally bound cued attention (Hikosaka, Miyauchi, Takeichi, & Shimojo, 1996; Shimojo et al., 1997) cannot be explained in terms of apparent motion.

Preattentive but Limited-Capacity View of ILM

In the present study, we found an almost unlimited parallel detection of ILM. In that multiple ILMs can be perceived in parallel, the present results are consistent with the FINST model (Pylyshyn, 1989). The FINST model implies parallel accessibility to multiple locations but presumes an upper limit for the number of available items in parallel. Schmidt et al. (1998) suggested that multiple locations (between 2 and 5) could be accessed simultaneously by using an ILM stimulus. Such upper limits, however, may be susceptible to stimulus parameters and paradigms. In fact, Schmidt et al. used 250 ms of SOA (between the cue and line), which seems unlikely to be optimal for ILM. Moreover, Schmidt et al. presented similar stimuli and asked participants to report the location(s) of a line that shot in a predetermined direction. Because their participants pointed to the probable location by clicking a mouse, their performance is vulnerable to memory decay during reporting. These stimulus parameters and paradigms thus m ight exaggerate errors in simultaneous ILM perception. On the other hand, in Kawahara et al. (1996), participants perceived dot-line pairs with very few errors in comparison to those in Schmidt et al. Kawahara et al. (1996) presented 8 dot-line pairs, with half shooting to the left and the remaining lines shooting to the right. Participants reported the shooting direction of an oddly colored line (the target). Errors in reporting the motion direction of the colored line occurred in only 5% of trials. The memory demand for reporting the motion direction of lines in the Kawahara et al. task seems to be smaller than that in the Schmidt et al. task.

In addition, it should be noted that the stimulus settings in one of the Schmidt et al. (1998) experiments might be advantageous for the attentional mechanism for accessing multiple locations. By using a precuing paradigm, Kramer and Hahn (1995) found that participants are able to ignore the distractors when the targets and distractors are presented as a non-onset item. That is, when placeholders are presented before the test display and existing items are changed into targets and distractors, the distractors did not interfere with the target judgment. However, when the targets and distractors were presented as sudden-onset stimuli, participants were unable to ignore the distractors. Note that in Experiment 3 in Schmidt et al., they presented 12 dots before presenting the cued dots and the lines. This stimulus setting could have been advantageous for the FINST model, judging from the findings of Kramer and Hahn.

Taking these facts into consideration, the finding of an upper limit for accessible location is not necessarily inconsistent with our notion. Given appropriate measures, our independent-detection model may predict performance for reporting motion direction with the Schmidt et al. parameters.

Counterevidence for an Attentional Account of ILM

In line with our results, Downing and Treisman (1997) also demonstrated that ILM is not due to attention but may be a kind of apparent motion. In their counterevidence for an attentional account of ILM, for example, they presented two pairs of dot-line stimuli side by side, e.g., " _   *   *" (the dots were presented in the first frame and the lines in the second frame). With the attentional account of ILM, the two dots should produce a facilitation gradient concentrically. Thus, the right line should be perceived as drawn from both ends simultaneously, meeting at the middle, whereas the left line should be perceived as drawn from a nearby dot. From the perspective of regarding ILM as apparent-motion, one can argue that this is a subtype of the Ternus display (Ternus 1938). More specifically, a group motion between corresponding items in two sequential displays will be seen in a typical stimulus configuration. In the case of Downing and Treisman's (1997) stimuli, the left dot is grouped with the left line, and the right dot is grouped with the right line. Therefore, an illusory motion direction will be perceived from left to right in this example. Downing and Treisman (1997) found that their participants judged the motion in both lines to be in the same direction, away from their associated dots. In addition, they found dissociation between the attention effects facilitating letter discrimination and the strength of the ILM and concluded that apparent motion is the direct source of ILM. Downing and Treisman interpreted even object-bound ILM (e.g., Hikosaka et al., 1993b) in terms of an impletion process that fills in interpolated events after a cue and line are linked as successive states of a single object in apparent motion. In contrast, our preattentive view of ILM perception leaves room for focused attentional facilitation.

Recently, Rorden, Mattingley, Carnet, and Driver (1997) observed two patients with left-sided visual extinction after right parietal damage. They reported a dissociation between the performance of the temporal-order judgment task and line-motion tasks, suggesting that motion perception does not directly correspond to perception of the relative timing of successive events. This finding weakens the basic assumption of ILM (Hikosaka et al., 1993a).

The perception of bottom-up ILM produced by simple stimuli, such as two-frame dot-line stimuli, can thus be explained in terms of an apparent motion mechanism, without the need for the difference in the time required for the visual processing of lines elicited by an attentional gradient.

(1.) We measured error rates in the experiments and found that the ILM target can be detected "effortlessly," suggesting that the target is detected in parallel. In fact, it is shown that the ILM target yields pop-out even with a speeded reaction-time task (Kawahara et al., 1996, p. 907).

(2.) The dependent measure adopted here is the error rate for target detection, whereas the literature on classical visual search primarily concentrates on reaction times. In fact, Kawahara et a!. (1996) have shown that the time required to detect the ILM target does not increase with increases in the number of nontargets. We thus assume the term parallel search can be applied to detecting a target with few or no errors among multiple nontargets.

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