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Dissociation of Short- and Long-Range Apparent Motion in Visual Search

Richard B. Ivry
University of California, Santa Barbara

Asher Cohen
Indiana University

The visual search paradigm was used in four experiments to investigate apparent motion perception. The addition of distractor items led to a linear increase in reaction time under long-range (LR) conditions (>35 min of arc displacement), whereas reaction time was independent of display size under short-range (SR) conditions (<18 min of arc). Although clear performance differences were obtained, Ss had difficulty in distinguishing between the two types of apparent motion displays when asked to make such judgments (Experiment 2). Experiments 3 and 4 explored some variables that may constrain the search process. Search times under LR conditions were reduced when some of the distractors were stationary or the motion of the distractors was homogeneous. Form and motion were found to be separable, whereas color and motion were not. Varying the color (and brightness) interfered with the processing of motion information.

The manner in which different sources of information are abstracted has long been of central interest to researchers of visual perception. Consideration of this problem has resulted in the hypothesis that early vision involves parallel processing of independent stimulus dimensions. Simply put, perception is viewed as an analytic and synthetic process: The stimulus is first analyzed by independent processing modules that abstract separable aspects of information (Treisman & Gelade, 1980; Treisman & Gormican, 1988). At later stages the output of these modules is used in more synthetic processing such as that involved in object recognition (Kahneman & Treisman, 1984; Treisman, 1986). Identification of the independent dimensions that serve as the building blocks of visual perception has remained one of the key endeavors of perception research.

Data from neurophysiology, neuroanatomy, and experimental psychology indicate that motion information is one of the fundamental stimulus properties derived in the early stages of visual perception. Neurophysiological recordings have shown that neurons in the posterior bank of the superior temporal sulcus (area MT) respond as a function of the direction and speed of a moving stimulus (Allman, Miezin, & McGuinness, 1985; Maunsell & Van Essen, 1983; Zeki, 1980). Given the retinotopic specificity of these units, area MT is viewed as a cortical map for motion perception (Maunsell & Van Essen, 1983, 1987). The response profiles of neurons in other prestriate areas have been found to correlate best with stimulus dimensions such as orientation or color (Hubel & Livingstone, 1987; Van Essen & Maunsell, 1983; Zeki, 1978). Neurons in area MT are minimally affected by variations in these dimensions. The concept of dimension-specific, cortical maps has become one of the cornerstones for the parallel processing hypothesis.

The existence of a cortical region responsive to motion cannot in itself be taken as evidence that motion perception is one of the fundamental aspects of visual processing. It is not possible to make direct links between the outputs observed from single cells and phenomenal experience. Other criteria must be included in order to claim that a particular dimension qualifies as one of the perceptual building blocks. Converging data from human psychophysics and chronometric investigations support the dimension-specific, parallel processing hypothesis.

Treisman and her associates (Treisman & Gelade, 1980; Treisman, Sykes, & Gelade, 1977) used a reaction time task that has proved useful in differentiating between the elementary features of visual perception and those aspects that require higher level processing. Their visual search paradigm examines the time needed to detect a specified target stimulus among a background of distractor stimuli. Treisman and Gelade (1980) found that search time is independent of the number of distractor stimuli when the target and distractors differ on a single dimension such as color, form, or orientation. In contrast, search time is a linearly increasing function of the number of distractor objects when a conjunction of features is needed to differentiate the target from the background objects. Thus a blue X is easily found (it "pops-out") among a background of red Xs and green Os, whereas the same blue X is difficult to find when the background is composed of red Xs and blue Os. Treisman (1986; Treisman & Gelade, 1980) argues that featural differences that produce pop-out effects are indicative of those dimensions that are coded independently and in parallel during the course of early visual processing.

The present research was originally designed to determine whether motion led to pop-out effects in a visual search task. We expected that the presence of a moving stimulus among

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Correspondence concerning this article should be addressed to Richard B. Ivry, Department of Psychology, University of California, Santa Barbara, California 93106.

motion with stimulus "velocity."[1] Specifically, the stimulus "velocity" in the long-range condition was twice that in the short-range condition because the displacement distance was doubled. In Experiment 1, the movement of each stimulus spans the same total distance over the same time period, thus equating "velocity." Short-range conditions are created by including an additional presentation of each stimulus object at a point halfway along the path of motion. Objects are presented only at the path endpoints (as in the other studies) in the long-range conditions.

This manipulation also allows us one additional control that was not present in the Dick et al. (1987) study. The interdot distance in that study was fixed at approximately 75 min of arc in the original placement of the dots. However, as some of the dots moved, the distance between these dots and the stationary background dots became smaller in the long-range condition due to the greater displacement in comparison to the short-range condition. Similarly, the interdot distance became smaller in the long-range condition between the target (when present) and the distractor dots moving in the opposite direction. That is, two dots originally spaced 75 min of arc apart would move within 25 min of arc of each other in the long-range condition, whereas the same two dots would only move within 60 min of arc of each other in the short-range condition. Because the amplitude of movement is identical for both motion conditions in our experiment, the minimum distance between the display objects is equal.

Method

Subjects. Ten undergraduates at the University of California, Santa Barbara, participated in the experiment, in partial fulfillment of a course requirement.

Apparatus and stimuli. The stimuli were presented on a Zenith ZCM-1490 monitor controlled by an AST Premium/286 computer. The display size was manipulated by presenting either 1, 7, or 13 achromatic *X*s on a black background. Each object measured about 0.30 cm (width) × 0.40 cm (height). Based on a viewing distance of 100 cm, the letters subtended a visual angle of 10.3 × 13.8 min of arc.

Each *X* was randomly placed on the screen with the following restrictions. First, in placing the objects in the display, the algorithm required a minimum distance of approximately 2.35° between objects in both the horizontal and vertical direction. This restriction was adopted to ensure that the distance an object moved was considerably less than the distance between objects. Thus, there should be little confusion in establishing the correspondence between the two presentations of each moving object. Furthermore, this restriction avoided collisions between moving stimuli and minimized the possible formation of higher order perceptual units such as see-saws or arrows. Second, the location of a target, if present, was selected first, thus ensuring that every location was equiprobable.

Each object moved in an oscillatory path. This effect was created by switching back and forth between two frames of the computer display with each object displaced in the second frame. The target oscillated horizontally and the distractors oscillated vertically. The amplitude of the oscillatory motion spanned 35.8 and 35.3 min of visual angle for the horizontal and vertical displacements, respectively. The distances are not equal due to the characteristics of the monitor. These distances satisfy Braddick's criterion (1974) for long-range motion. For subjects in the short-range condition, a third frame was used in which the stimuli were displaced to a point halfway between the two endpoint screens. Thus, each successive presentation of the target was displaced 17.9 min of arc.[2] Oscillatory motion was chosen so that the display could remain visible until the subjects responded. We found in a pilot experiment that error rates became extremely high if a single exposure of each frame was used. Dick et al. (1987), using a single exposure, reported error rates as high as 34%.

The SOA was 100 ms in the long-range (LR) condition. This duration was halved to 50 ms in the short-range (SR) condition because the distance moved in each successive frame was halved. Thus the oscillatory period and "velocity" was the same in both conditions. The interstimulus interval was zero, and masking was not used.

Design. On the target present trials, one stimulus object oscillated horizontally. The distractors, when present, moved vertically. The direction of oscillation for the distractors was varied: At any given time, half of the distractors appeared to move up and the other half appeared to move down. That is, one half of the distractors were 180° out of phase from the other half.

The experiment was divided into two blocks, each of which consisted of 120 trials for a total of 240 trials. In each block there were 10 trials of each of 12 conditions (2 motion types × 3 display sizes × 2 target present/absent) for a total of 20 trials per condition. The short- and long-range trials were randomly interspersed within each block of trials. Order of trials and display locations were independently randomized for each block. The test blocks were preceded by a practice block of 60 trials.

Procedure. Each subject was instructed that a single *X* would be moving horizontally on half of the trials. They were to press the left key on a response board if the target was present and the right key if all of the *X*s were oscillating vertically.

Each trial began with the illumination of a fixation point (a plus sign); 1,000 ms later, the stimulus appeared and remained visible until the subject responded. The clock for measuring reaction times was started at the point at which movement first occurred. Thus, this temporal event is 50 ms earlier for the short-range trials than for the long-range trials. If the subject's response was incorrect, the word ERROR appeared on the screen for 1,000 ms. Nonetheless, the instructions indicated that reaction time was of primary interest and that the subjects should not be concerned if they made "a couple of errors each block." The intertrial interval was 2,000 ms.

Results and Discussion

Reaction times. Figure 1 presents the reaction time data for trials in which the response was correct. The data were entered into a 2 × 3 × 2 analysis of variance (ANOVA; Motion: SR/LR × Display Size: 1, 5, 9 × Target: present/absent.) All

[1] *Velocity* is an ambiguous term in apparent motion displays. Because the stimuli jump from one location to another, there is no continuous velocity, but rather only an instantaneous, near-infinite velocity. Throughout this article, the term refers to an integral measure of the amplitude of oscillation divided by the time needed to traverse that distance. For this reason, the word "velocity" is enclosed in quotation marks.

[2] This value is at the upper limit for short-range motion according to Braddick (1974). However, the distance between two successive presentations could be calculated between closest edges, rather than between corresponding points. Following this convention, the spacing between successive presentations of the target would be 7.6 min of arc.

4.5%. This outcome makes it clear that the difference in response latencies between the SR and LR trials cannot be accounted for by a speed–accuracy trade-off.

In summary, the results of Experiment 1 are in agreement with the earlier reports of Nakayama and Silverman (1986) and Dick et al. (1987). The direction of movement of a stimulus can be rapidly detected across the visual field (Nakayama & Silverman, 1986), but only if the motion is within the conditions of the short-range processing system (Dick et al., 1987). The detection of a horizontally oscillating target was minimally affected by the presence of vertically oscillating distractors when the extent of the movement was limited to steps of 17.9 min of arc. For movement spanning 35.8 min of arc, detection time continued to increase as more distractor objects were added to the display. The amplitude, period of oscillation, and minimum spacing between display objects were equal in both the SR and LR conditions. Therefore, variables that were confounded in the earlier reports were eliminated. Moreover, because the SR and LR were randomly intermixed, it is unlikely that the observed differences could arise from shifts in overt processing or response strategies.

Experiment 2

In Experiment 1, a striking difference was observed between subjects' ability to rapidly detect motion under short-range conditions and long-range conditions. Following the logic of the search paradigm (Treisman & Gelade, 1980; Treisman & Gormican, 1988), it can be inferred that directional motion detectors are preattentively activated only under the short-range conditions. When the display involves long-range apparent motion, attention must be directed to each object in order to determine the direction of movement. This dissociation is a performance-based distinction: Differential processing modes are assumed, based on the reaction time profiles.

An unanswered question is whether this performance dissociation is mirrored at the level of phenomenal experience. Shepard (1984) presented a hierarchical model of perception in which the levels are resonant to different aspects of the stimulus. He further proposed that although the processing at one level may be based on inputs from other levels, the source of the input need not be retained; that is, the computations performed at a given level need not retain any record of the source of stimulation. This conjecture is related to the idea of information encapsulation (Fodor, 1983). According to Fodor, processes that operate on the output of an encapsulated module do not have access to the computational primitives or operations that yielded the output.

Motion perception offers an opportunity to test this idea. Whereas the impression of movement can be quite compelling across a wide variety of different stimulus conditions ranging from real movement to different types of apparent movement, computational models underlying the similar percepts are quite distinct (e.g., Ullman, 1981). In Experiment 2, we investigate whether subjects are able to consciously discriminate between short- and long-range apparent motion displays. Processes involved in the conscious interpretation of a stimulus may, in Shepard's (1984) terms, be at a different level than those guiding performance under speeded instructions. This hypothesis would be supported if it were found that the information used to make the present–absent decisions was insufficient for discriminating between the SR and LR displays.

Method

Subjects. Ten undergraduates at the University of California, Santa Barbara, participated in the experiment in partial fulfillment of a course requirement.

Apparatus and stimuli. The apparatus was the same as that used in Experiment 1, as were the procedures in creating the stimulus displays. A given display contained either 1, 7, or 13 achromatic *X*s on a black background. Viewing conditions were also the same as in Experiment 1. The only change in the displays was that all of the objects always oscillated horizontally. Thus, the extent of motion was 35.8 min of arc for all of the objects. Long-range displays were created by only presenting the objects at the two ends of the oscillatory path. Short-range displays included a third frame in which the objects were displaced to a point halfway between the two endpoint screens. The SOAs were 100 ms and 50 ms for the LR and SR conditions, respectively. Thus, as before, the oscillatory period was the same in both conditions. The direction of oscillation was varied so that at any given time, half of the distractors appeared to move leftward while the other half appeared to move rightward.

Design. There were four types of trials. Each trial type consisted of the presentation of two stimulus displays. The displays either were of SR or LR motion, and the four types include the inclusive pairwise combination of the two motion displays. Thus, the four trial types were the pairs SR–SR, SR–LR, LR–SR, and LR–LR, where the first member of the pair describes the motion for the first display and the second member describes the motion of the second display. The subjects' task was to indicate whether the motion was the same or different in the two displays. There were a total of 12 conditions (4 trial types × 3 display sizes).

The number of objects in the two displays was the same for a given trial. For example, if a trial involved the SR–LR pair and the display size was 7, the first display contained 7 objects satisfying the criterion of short-range apparent motion and the second display contained 7 objects satisfying the criterion of long-range apparent motion.

Procedure. Each trial consisted of the following events. First, a fixation point appeared for 1,000 ms. Then, the first stimulus display was presented for 700 ms. This display was followed by an interstimulus interval of 1,500 ms in which the monitor was blank. The fixation point then reappeared for 1,000 ms, followed by the second stimulus display for 700 ms. After a brief pause, the monitor instructed the subjects to respond by pressing the left key on a response board if the two displays contained the same type of motion and the right key if the two displays contained different types of motion.

Note that the exposure duration was fixed at 700 ms for each stimulus display. Within this time, each object completes three cycles of oscillation. This value was chosen because the results of Experiment 1 had indicated that subjects require approximately 700 ms to make present–absent judgments under SR conditions.

The experimental session began with two demonstrations. First, subjects were shown vivid examples of the two ways that apparent motion would be simulated. The experimenter explained that in one type of apparent motion, the objects would oscillate in a single step between two endpoints (*one step*), whereas the other type of apparent motion would include a third position located between the two endpoints (*two step*). The experimenter presented five demonstrations of each type of movement in which the SOA was 500 ms in order to make the difference apparent to the subjects. The number of objects present in these displays was either 1, 7, or 13. It was

Experiment 3

In Experiment 1, we found that the detection of long-range motion is strongly influenced by the complexity of the display. As more distractor elements are added, reaction time increases. The factors leading to this increase, however, have not been systematically addressed. Treisman and Gelade (1980; also Townsend & Ashby, 1983) have postulated that the specific shape of the latency functions in a visual search task can be indicative of the type of processing. They report on two distinct ways in which a search task may be difficult. The first would be when the discriminability between the target and distractors is small, and successful performance requires serial fixations with foveal vision. Although this search mode may require a serial process such as successive fixations, the processing of the stimulus objects need not be serial. The second arises when the search task requires the conjunction of two separable perceptual features. In this situation, Treisman hypothesizes that focused attention must be directed in a strictly serial manner to each object in the display.

Treisman and Gelade (1980) argue that these two types of search modes can be distinguished by the shape of the latency functions. When the search task involves a difficult discrimination, reaction time will increase as more objects are added to the display. However, the function should be negatively accelerated if the display area is constant because, as more objects are added, display density increases and more information can be processed within each fixation. In contrast, conjuctive searches are characterized by strictly linear functions. Moreover, the slope for the trials in which a target is present is half the slope of the trials in which the target is absent because, on average, the target is detected after half the objects have been examined and the search can terminate at this point. Functions that meet these two criteria of linearity and a slope ratio of .50 are interpreted as resulting from a serial self-terminating search.

Experiment 3 was conducted to examine the shape of the search functions for long-range motion. If the directional bandwidth in the long-range process is more broadly tuned than in the short-range process, the processing required to detect a horizontally moving stimulus among vertically moving distractors may be best viewed as a discrimination problem. On the other hand, long-range motion perception may involve the integration of (undefined) features abstracted during the early stages of visual perception.

Method

Subjects. Eight undergraduates at the University of Oregon participated in the experiment in partial fulfillment of a course requirement.

Apparatus and stimuli. The stimuli, Os, were presented on an Apple II color monitor controlled by an Apple IIe computer. The dimensions of the Os were 0.48 cm (width) × 0.62 cm (height). Based on a viewing distance of 110 cm, the letters subtended a visual angle of 15 × 19 min of arc. Display sizes of either 1, 5, 11, or 21 objects were used. The minimum distance between objects was reduced to 0.75° × 0.97° to accomodate the larger displays.

As before, apparent motion was induced by switching between two frames of the computer. A target, if present, oscillated horizontally and was displaced 30 min of visual angle across frames. Moving distractor objects oscillated vertically over an amplitude of 38 min of arc. The SOA was fixed at 150 ms. The reaction time clock, therefore, started 150 ms after the initial presentation of the stimuli.

Design. Four types of background displays were randomly intermixed. In the single condition (single), only the target moved and the background objects were stationary. In the synchronized condition (syn.), the distractors moved in unison. In the desynchronized condition (desyn.), half of the distractors were 180° out of phase as in Experiment 1. In the remaining display type (half), half of the distractors were stationary and the other half operated as in the desynchronized condition. Note that the target was identical in all of the conditions.

The experiment was divided into two test blocks. In each block there were eight trials per condition (4 display sizes × 4 background types × 2 present/absent). However, because the display size of 1 is redundant across the background types, this condition was not repeated.[4] Thus there were a total of 416 trials. The experiment began with a practice block of 78 trials.

All other details of the method were identical to those of Experiment 1 with two exceptions. First, a filler trial followed any erroneous response. Second, the intertrial interval was 2,500 ms.

Results and Discussion

The four panels of Figure 2 present the mean reaction time data for the different conditions and the slope values derived from linear regression analyses. The plotted points for the displays consisting of a single element do not represent independent measures and are depicted only for graphic purposes. No differences were found when the analyses were recomputed with these data.

The error rates for the present and absent trials were 6.3% and 1.6%, respectively. Again, as is found in search experiments, most of the errors occur when subjects miss a target. The vast proportion of errors were made in those conditions that required the longest decision times. Because the error pattern is in agreement with the reaction time data, these results will not be discussed further.

Both the present and absent functions are flat in the single condition. Coupled with the other results, we believe this effect should not be attributed to the parallel detection of long-range movement, but rather to the detection of a change in the display (see Dick et al. 1987, for a more thorough examination of this situation).

Of central interest in Experiment 3 are the search functions for the other three conditions in which at least some of the background objects were moving orthogonally to the target. All of these functions are quite steep, implicating a serial process. The percentage of variance that can be accounted for by a linear component is over 99% for each of the functions. The ratios of the reaction time slopes on target present to target absent trials are .44 and .51 for the half and desyn.

[4] In the target absent condition with an array size of one, the single distractor object oscillated vertically. Therefore, this data cannot be directly compared with the data for the larger arrays in the single condition in which the distractors were stationary.

ance of the null hypothesis for the half and desyn. conditions. However, the results were so consistent that we believe more conservative analyses would be superfluous.

The type of search model that can account for the results in the syn. condition is unclear. The functions for the target present and target absent conditions are suggestive of a serial process in which all of the objects are examined before a decision is made (Shiffrin & Schneider, 1977). Alternatively, the data can also be explained by capacity limited hybrid models that postulate a parallel search of chunks of stimuli, the chunks being selected in serial (Pashler, 1987; Townsend & Ashby, 1983). In the present situation, this could arise if the distractors are processed as a group or in groups due to their synchronized motion. Indeed, this possibility matches our intuition when viewing the displays of the syn. condition.

Given the linearity of the functions and the .50 slope ratio in the conditions in which the movement of the distractors were out of phase, the search process can be characterized as serial and terminating. The search rate was 97 ms/object in the half condition and 150 ms/object in the desyn. condition. To repeat, the only difference between these two conditions is that half of the distractors were stationary in the half condition. The results indicate that the serial scanning process is largely restricted to moving stimuli. The faster search rate in the half condition suggests that the search mechanism does not examine the stationary objects. However, the presence of stationary stimuli in the half condition did have some effect because the search rate in the desyn. condition is not twice as slow.

Following the logic of Treisman (Treisman & Gelade, 1980; Treisman et al., 1977), these results indicate that the detection of directionally specific long-range motion requires the conjunction of features abstracted during a preliminary stage of processing. This hypothesis is similar to the hypothesis proposed by Ullman (1981) that long-range motion perception involves a two-stage matching process. First, features such as edges, lines, or blobs are identified and localized. Second, corresponding features are matched over time in order to detect changes in position (i.e., motion). The last experiment explores possible constraints on the input to the matching process.

Experiment 4

Cross-disciplinary evidence is supportive of the hypothesis that the processing of motion information occurs separately from the processing of other stimulus features (see Livingstone & Hubel, 1987, for an overview). As discussed in the introduction, anatomical studies and neurophysiological recordings have demonstrated the existence of neurons whose response profiles are a function of the motion of a stimulus (Maunsell & Van Essen, 1983). These authors found that many cells in area MT of the monkey could be driven by bars at any orientation or even nonoriented stimuli such as dots as long as the stimulus moved in the cell's preferred direction. Thus the sensitivity to motion is, at least to some degree, independent of form.

Psychological research has also addressed the question of whether the processing of motion and form information is separable.[5] Kolers and Pomerantz (1971) found that the verisimilitude of an apparent motion display was minimally affected when the stimulus changed form in comparison to conditions in which the form remained identical. Navon (1976), using ambiguous apparent motion displays, observed that the perceived movement path did not always preserve form identity. Krumhansl (1984) reported that judgments of the form and motion of a stimulus are independent. In each of these studies, form and motion are independently manipulated. However, as shown by Cutting, Moore, and Morrison (1988), independence is not observed when the dimensions are covaried.

Investigations of the separability of color and motion have been less direct. Maunsell and Van Essen (1983) report that area MT neurons respond equally well across the visible spectrum. Psychophysical studies have also shown that the motion system is not sensitive to chromatic variations (Cavanagh, Tyler, & Favreau, 1984; Ramachandran & Gregory, 1978). Both studies demonstrated that motion perception is reduced considerably at equiluminance. For example, Ramachandran and Gregory constructed random dot kinematograms in which the displaced dots created an emergent figure that appeared to move laterally across successive patterns. Although the effect persisted when there were luminance differences between dot pairs, color differences in isoluminant patterns failed to elicit the motion illusion.

In Experiment 4, we investigate the separability of motion perception from form and color in a visual search paradigm. As before, the task was to determine if one of the stimulus objects was oscillating horizontally. In separate conditions, the form or color of the moving stimuli either remained constant throughout a trial or alternated between successive computer frames. This manipulation was examined under both short- and long-range conditions. This variable has not been systematically applied to the separability question. The stimulus conditions in Krumhansl (1984) and Cavanagh et al. (1984) meet the criterion of short-range motion, whereas those in Kolers and Pomerantz (1971) are clearly of the long-range type. Ramachandran and Gregory (1978) found that chromatic differences were sufficient for producing motion effects under long-range conditions. However, this result only indicates the minimal conditions necessary to induce long-range apparent motion. It does not address the question of whether motion perception is separable from the processing of color information.

[5] We have chosen to speak of *separability* rather than *independence*. Ashby and Townsend (1986) provide an excellent discussion of this distinction. Following their definitions (see also Garner, 1974), we believe our task can only access the question of separability. Specifically, we examine whether the processing of motion information is affected by variations on the irrelevant dimensions of form and color. This task best matches their first operational definition of separability (Ashby & Townsend, 1986, p. 163).

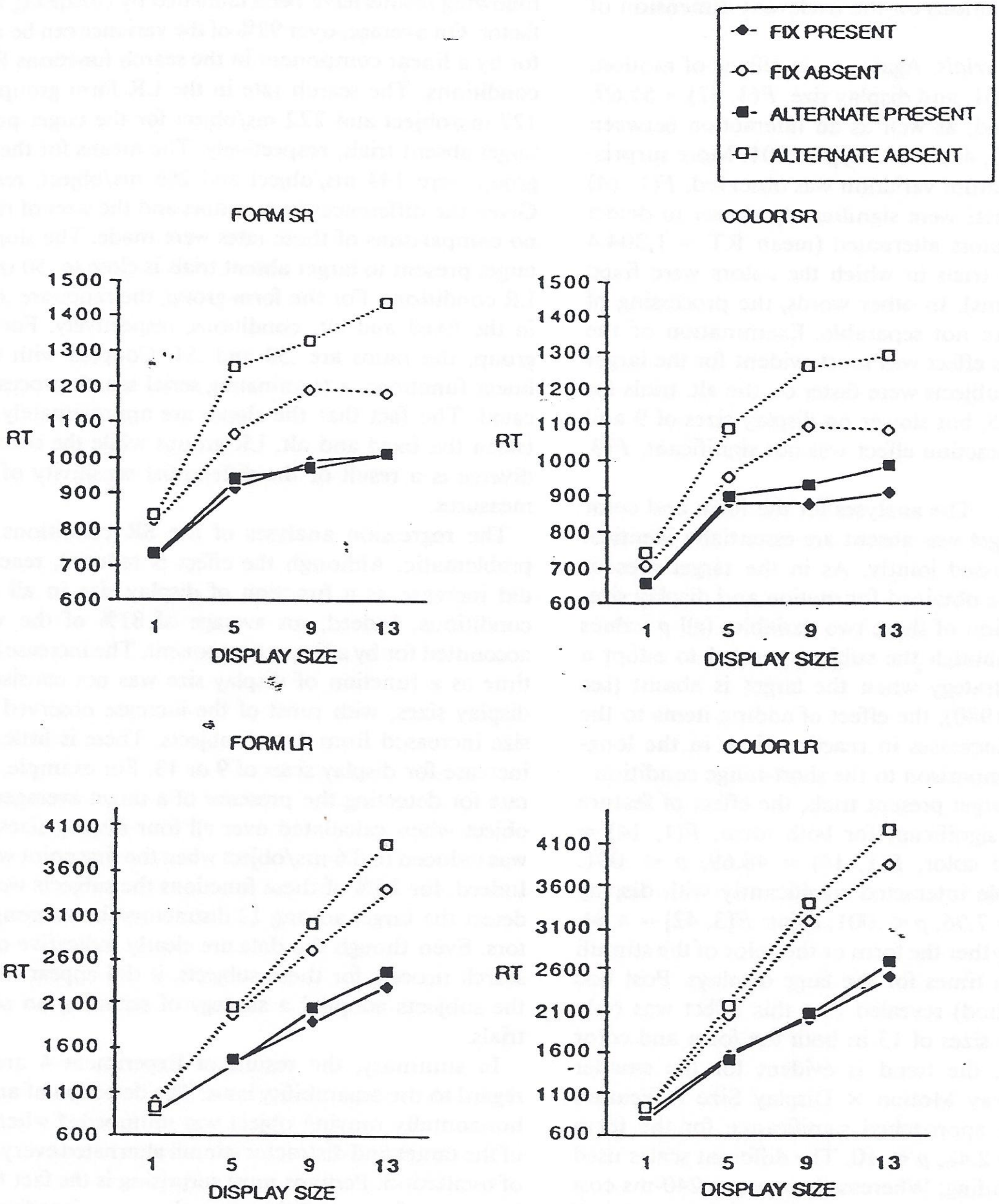

Figure 3. **Mean reaction times (in milliseconds) for the conditions of Experiment 4. Left panels are for conditions in which the form of the stimuli was either fixed or alternated, right panels are for the conditions in which the color of the stimuli was either fixed or alternated, for target absent trials. Top panels are for conditions with short-range (SR) motion displays, bottom panels are for long-range (LR) motion conditions. (Due to near-identical values, some of the data points are obscured. Note the differences in scale. Standard deviations for array sizes of 1, 5, 9, and 13, respectively, were as follows: Form: SR fix present: 126, 200, 294, 249; SR fix absent: 115, 319, 378, 471: SR alt. present: 122, 268, 271, 348; SR alt. absent: 115, 478, 523, 608; LR fix present: 172, 278, 385, 444; LR fix absent: 230, 378, 684, 1319; LR alt. present: 159, 405, 486, 689; LR alt. absent: 110, 425, 744, 1171. Color: SR fix present: 77, 153, 139, 160; SR fix absent: 47, 183, 300, 289; SR alt. present: 84, 191, 235, 153; SR alt. absent: 95, 200, 321, 320; LR fix present: 219, 362, 667, 640; LR fix absent: 156, 690, 1175, 1463; LR alt. present: 166, 440, 644, 842; LR alt. absent: 189, 687, 1303, 1812.)**

in Experiment 1. These effects indicate that displays with long-range motion require a slow, scanning process, whereas response latency is generally independent of display size for short-range motion.

Of central interest to this experiment are the results for feature variation. This variable did not achieve significance, not did either of the other two variables interact with it (all p values > .25). In summary, under current conditions, subjects

colors of the stimuli are not stable. Furthermore, it must be noted that the different colors were not equated in terms of luminance. Thus, the color changes are correlated with changes in brightness and the failure of separability may be between motion and brightness. These issues will be the subject of future experimentation.

Finally, in both the form and color conditions, subjects were slower to determine that a target was not present when the objects varied on an irrelevant dimension. As has been found in many studies, a number of secondary factors may influence reaction times on trials in which the target is absent (e.g., Treisman & Gelade, 1980). The results suggest that one such factor is instability on an irrelevant dimension.

General Discussion

Movement of a stimulus has long been recognized as a rich source of information in visual perception (see Nakayama, 1985, for a recent review). Not only can motion perception facilitate recognition processes but, perhaps even more important, motion can also provide essential information concerning the location and action of a stimulus. It would seem reasonable to expect the visual system to be organized in a manner that allows for the rapid extraction of motion information.

The experiments reported in this article are strongly supportive of the hypothesis that motion information is one of the fundamental stimulus properties derived in the early stages of visual perception. Subjects were able to rapidly detect the presence or absence of a target defined solely on the basis of movement information. These results are in accord with those previously reported by Nakayama and Silverman (1986) and Dick et al. (1987).

As pointed out by Dick et al. (1987), the visual search paradigm provides an additional converging operation in support of the conjecture that different mechanisms underlie the perception of short- and long-range apparent motion (Braddick, 1974; Ullman, 1981). Following the terminology of Treisman and Gelade (1980), Dick et al. argue that the detection of short-range motion can be performed in parallel across the visual field as indicated by the flat search functions. Long-range motion, in contrast, requires an attentional process in which each object in the display is examined in a serial fashion. Our data support this conjecture. Alternative interpretations of their data, based on the fact that they confounded short- and long-range apparent movement with the extent and "velocity" of movement as well as interobject spacing, are ruled out by Experiment 1. Our design allowed these factors to be unconfounded. Nonetheless, the same difference between the short- and long-range conditions was obtained. Note that our method introduces a new potential confound. By inserting a third frame at a halfway point in the short-range condition, more pixels are illuminated during each oscillatory cycle. However, the results of the judgment task would appear to indicate that, at least consciously, subjects were not sensitive to this confound.

The judgment task of Experiment 2 provides another point of interest. Short- and long-range apparent motion displays produce a novel dissociation between performance and awareness (e.g., Marcel, 1983; Nissen & Buellmer, 1987). Whereas all of the subjects in Experiment 1 were markedly slower on the long-range trials, some of the subjects in Experiment 2 were near chance in discriminating between the two types of displays, and no subjects were very proficient at this task. Citing similar phenomena, Fodor (1983) claimed that central processing systems have only limited access to the computational processes of the perceptual modules. Short-range motion detection appears to be a consequence of the output from a rapid processing module designed specifically for motion perception. Long-range motion is dependent on more elaborate (i.e., higher level) processing. However, the results suggest that the level of representation of movement on which the judgment task is based may not clearly differentiate between the two processing routes (see Shepard, 1984), at least when the stimulus parameters are similar. Thus, even when the display conditions produce clear differences in reaction time, subjects may be unaware of the source of this difference. We believe that this proposal must be constrained. For instance, after a few hundred trials of practice, one of the authors was able to perform the judgment task with few errors. The reason for this change is unclear. A second-order variable such as a brightness confound (two vs. three screens) may be relevant. Alternatively, although the oscillatory frequency is identical, the "velocities" may not phenomenally appear equal. Future study is needed to address this problem.

The results of the final two experiments present a different set of constraints for the motion processing system. The finding in Experiment 3 that slope values are reduced when only half of the distractor objects are moving may indicate one source of constraint. In this interpretation, stationary stimuli are not analyzed by the system. Under long-range conditions, only moving stimuli may trigger a movement analysis process (see Egeth, Virzi, & Garbart, 1984, for similar evidence in search tasks of color and form). Alternatively, the improved performance may reflect changes in the serial comparison process. Stationary stimuli may be evaluated more quickly than stimuli moving orthogonally to the target direction.

In Experiment 4, motion perception was found to be separable from form perception. This result was observed under both short- and long-range conditions on trials in which a horizontally moving target was present. The result is not surprising in the short-range conditions. Indeed, the interpretation of parallel pop-out is based on the notion of independent feature maps (Hulbert & Poggio, 1986; Treisman 1986). More interesting is the finding that the separability was maintained under long-range conditions. This result indicates that the long-range process does not rely on detailed form information, because instabilities in form did not interfere with the motion detection process. It would appear that the tokens that Ullman (1981) postulates serve as the input to the long-range matching process must, at best, be a crude representation.

Information derived from low-pass spatial frequency filtering operations may provide the appropriate representation (Ramachardran, 1987). However, low spatial frequency information useful for short-range apparent motion perception may be quite different than that used under long-range con-

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