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Attentional control of spatial scale: effects on self-organized motion patterns

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Abstract

Prior to the presentation of a test stimulus, subjects' attentional state was either narrowly focused on a particular location or broadly spread over a large spatial region. In previous studies, it was found that broadly spread attention enhances the sensitivity of relatively large spatial filters (increasing the perceiver's spatial scale), thereby diminishing spatial resolution and enhancing sensitivity to global stimulus structure. In this study it is shown that attentional spread also affects the self-organization of unidirectional versus oscillatory motion patterns for the directionally ambiguous, counterphase presentation of rows of evenly-spaced visual elements (lines segments; dots); i.e. qualitatively different motion patterns can be formed for the same stimulus at different spatial scales. Although the degree to which attention is spread along a spatial axis can be controlled by the perceiver, the effects of spread attention are not limited to a single axis. These results, as well as previously observed effects of attentional spread on spatial resolution, are accounted for by a neural model involving large, foveally-centered receptive fields with co-operatively interacting subunits (probably at the level of MST or higher). © 1998 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Cooperativity in motion perception has been the subject of a number of experiments studying the emergence of globally coherent motion patterns as a result of mechanisms intrinsic to the visual system. It is assumed in these experiments that the information in the stimulus that specifies the to-be-perceived motion direction is not, in itself, sufficient to account for the perception of a coherent pattern. The emergence of a coherent percept is therefore attributed to the operation of mechanisms that enhance motion perception in the direction specified by the stimulus information relative to alternative motion directions. In one such study, Chang and Julesz [1] showed that selecting less than 10% of the dots in an otherwise random cinematogram and having that small portion move in the same direction resulted in all the dots appearing to move coherently in that direction. In another, Williams and Sekuler [2] introduced coherent motion into a random cinematogram by having the motion direction for a randomly selected subset of the dots sampled from a restricted range of possible directions (the direction of motion remained random for the other dots). When the range was not too large, all the dots in the cinematogram appeared to move in the direction corresponding to the mean of the restricted range of directions.

Perceptual phenomena like these, in which the same direction of motion is established across an extended spatial region, reflect the influence of facilitating interactions among detectors with similar directional selectivity. Evidence for complementary, inhibiting interactions was obtained by Chang and Julesz [1]. They presented random dot patterns composed of horizontal bands of dots such that the bands with a specified direction of motion were vertically alternated with 'probe' bands of dots that if presented alone, would have been perceived to move in random directions. Chang and Julesz found that the perceived direction of motion of the dots in the 'probe' bands was biased towards a direction opposite to that of the bands with stimulus-specified directions of motion (reflecting

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the influence of inhibiting interactions among detectors with similar directional selectivity).

In a further study, Nawrot and Sekuler [3] systematically varied the height of alternating 'direction-specified' and 'probe' bands. When the bandheights were relatively large, they found, like Chang and Julesz [1], that the perceived motion for the dots in the 'probe' bands was biased toward the direction opposite to the perceived motion for dots in the 'direction-specified' bands (they called this heterokinesis). However, when the bandheights were relatively small, the perceived motion of the dots in the 'probe' bands was biased toward the same direction as the perceived motion in the 'direction-specified' bands (they called this homokinesis). Nawrot and Sekuler's [3] results suggest that the formation of spatially coherent motion patterns is influenced by facilitation for small interactive distances and inhibition for larger interactive distances.

Hock and Balz [4] studied the role of facilitating and inhibiting interactions in the formation of spatially and temporally coherent motion patterns that are entirely self-organized. That is, they showed that coherent pattern formation can occur in the absence of information in the stimulus that specifies to-be-perceived motion directions. On successive frames, Hock and Balz presented a long row of evenly spaced dots, then the same row of dots phase-shifted by 180° so the dots fell in the exact midpoints of the dots presented on the previous frame, followed by the first frame again, and so forth. The stimulus was called a counterphase row-of-dots. Because of the midpoint placements, there is no information in this stimulus that specifies the motion direction of the dots, so there is nothing specified that prevents the perceived direction of motion from being different at different locations along the row of dots, and nothing specified that prevents random changes in motion direction from one frame to the next. Nonetheless, Hock and Balz [4] found that spatially and temporally coherent unidirectional and oscillatory motion patterns were always perceived. For the unidirectional motion pattern, all of the dots moved in the same direction on successive presentation frames. Unidirectional motion predominated for small inter-dot distances, implying that facilitating interactions among detectors with similar directional selectivity persisted over time and maintained the same perceived motion direction from one frame to the next. For the oscillatory motion pattern, all the dots moved in the same direction during one frame, then reversed and all moved in the opposite direction on the next frame, and so on. Oscillatory motion predominated for large inter-dot distances, implying that inhibiting interactions among detectors with similar directional selectivity persisted over time and biased the perceived motion direction to reverse on successive frames. In their differential-gradient model, Hock and Balz specify that facilitation is greater than inhibition for small interactive distances, resulting in the predominance of facilitating interactions, but the greater steepness of the distance gradient for facilitation compared with inhibition results in the predominance of inhibition for relatively large interactive distances (Fig. 1)[1]

Hock and Balz [4] went on to show that changes in the perceiver's spatial scale shift the boundary-value inter-dot distance for which facilitating versus inhibiting interactions predominate for the counterphase row-of-dots. They found that brief frame durations (which increase the sensitivity of large, low spatial frequency filters relative to small, high spatial frequency filters, [5,6]) resulted in unidirectional motion being perceived for larger inter-dot distances than was the case for long frame durations. Similar effects were obtained when a static row of evenly spaced dots was presented near the counterphase row-of-dots. When the inter-dot distance for the static row was increased (which presumably increased the relative activation of larger spatial filters), unidirectional motion was perceived for the counterphase row-of-dots for increasingly large inter-dot distances.

The purpose of the experiments reported in this article was to determine whether the self-organization of unidirectional versus oscillatory motion patterns can be brought under attentional control through tasks that affect the relative activation of spatial filters of different sizes. The experiments follow upon Balz and Hock's [7] method for manipulating the extent to which the perceiver's attention is narrowly focused on a particular

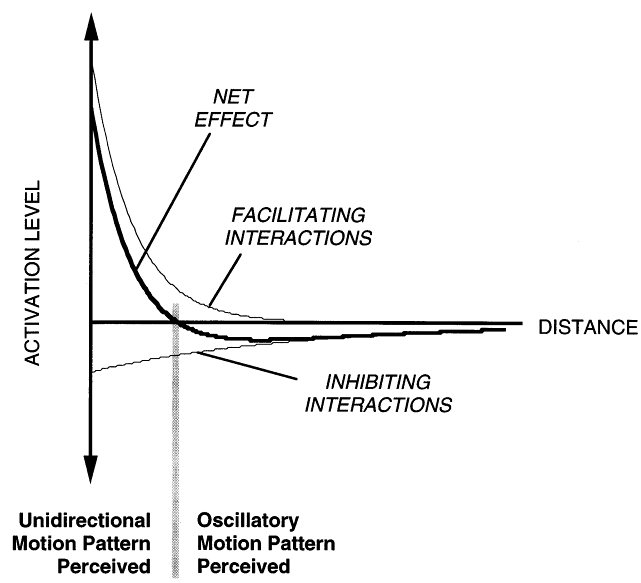

Fig. 1. The differential gradient model of facilitating and inhibiting interactions among motion detectors with similar directional selectivity [4].

[1] A more general formulation of this model was developed by [46].

location or broadly spread over a relatively large spatial region. They found that broadly spread attention reduced spatial resolution for judgments of vernier alignment and spatial separation, and concluded that broadly spread attention resulted in the pre-activation of relatively large spatial filters. Borrowing a metaphor from Hess and Hayes [8], Balz and Hock suggested that the large filters were activated in the broad attention condition because only large filters could fully 'pave' the large region over which attention was spread.

Based on Hock and Balz's [4] evidence that the perception of unidirectional motion is enhanced by stimulus conditions (e.g. brief frame durations) which increase the relative sensitivity of large spatial filters, and Balz and Hock's [7] further evidence that broadly spread attention increases the relative sensitivity of large spatial filters (as indicated by reductions in spatial resolution) it was hypothesized that pattern formation for a counterphase row of identical visual elements would be influenced by the perceiver's attentional spread. More specifically, it was predicted that the perception of unidirectional motion would be enhanced relative to the perception of oscillatory motion (i.e. it would be perceived for larger inter-element distances) when attention was broadly spread over a relatively large spatial region compared with when it was narrowly focused at a particular location.

2. Experiment 1

The methodology for the first experiment closely follows that of Balz and Hock [7]. Attention was manipulated by varying the perceiver's spread of attention [9–13]. It was either narrowly focused on the fixation dot or broadly spread over an extended spatial region on either side of the fixation dot, the object being for subjects to detect a small change in luminance for one of the 'attention' dots. With attention 'pre-set' in this manner, a horizontal row of vertical line segments located just below the 'attention' dots was then phase shifted by 180° on a succession of frames (the row of line segments was presented in counterphase). Subjects were required to indicate whether unidirectional or oscillatory motion was perceived for the counterphase stimulus.

2.1. Methods

2.1.1. Stimulus

Subjects were students at Florida Atlantic University with normal or corrected-to-normal vision. All had previous experience with the task used to manipulate attentional spread, and two, GB and KE, had extensive experience with the counterphase row-of-dots. Only GB (an author) was aware of the purpose of the experiment.

2.1.2. Stimuli

The stimuli were presented on a Macintosh IIcx 13 in color monitor against a full-screen gray background (luminance = 7.9 cd/m^2) and viewed from a distance of 126 cm (maintained by a head restraint). Each trial began with the presentation of a long (9.8°) horizontal row of 19 2.9×2.9 min, evenly-spaced white dots (luminance = 27.1 cd/m^2; dot separation = 30.9 min), and 2.9 min below it, an equally long horizontal row of evenly-spaced 2.9×11.6 min vertical line segments (luminance = 31.9 cd/m^2). The inter-line distance was varied randomly from one trial to the next. The row of line segments was laterally displaced by one-quarter of the inter-line distance (90°) with respect to the horizontal position of the central 'attention' dot.

Prior to the start of each trial, two aligned vertical line segments (each 1.0×4.8 min, with a 29.0 min gap between them; luminance = 21.6 cd/m^2) were presented in the center of the screen. Subjects were instructed to fixate on the central dot located between them.

The row of 'attention' dots and the row of vertical line segments below it were presented for either 360, 450, or 540 ms (in random order) before the presentation of a 15 ms frame during which a luminance increment could occur for one of the 'attention' dots. For the balance of each trial (900 ms), the row of line segments was displaced by 180° in spatial phase on each frame, for a series of five 180 ms frames (on each frame, the line segments were located at the exact midpoint of the line segments presented during the preceding frame). Although the motion directions of the line segments at the ends of the counterphase row of line segments were not ambiguous, their effects were negligible because the row of line segments extended far into the retinal periphery (4.9° to the left and right), well beyond the region attended to by the perceiver. The stimuli and the temporal structure of a trial are illustrated in Fig. 2.

In both the broad and narrow attention conditions, the to-be-detected luminance increment occurred on a random basis for 50% of the trials. In the broad attention condition, occurrences of the luminance increment were randomly distributed among the central dot (20% of the luminance increments) and the eight dots on either side of the central, fixation dot (four dots on the left and right, each with 10% of the luminance increments). Half the luminance increments for the central dot served as the broad attention confirmation check (described below). In the narrow attention condition the luminance increment, when it occurred, was randomly distributed among the central, fixation dot (90% of the luminance increments) and the two most peripheral positions receiving luminance increments in the broad attention condition (the fourth dot, 2.1° to the left or right of the central dot, each with 5% of the luminance increments). The luminance increments for

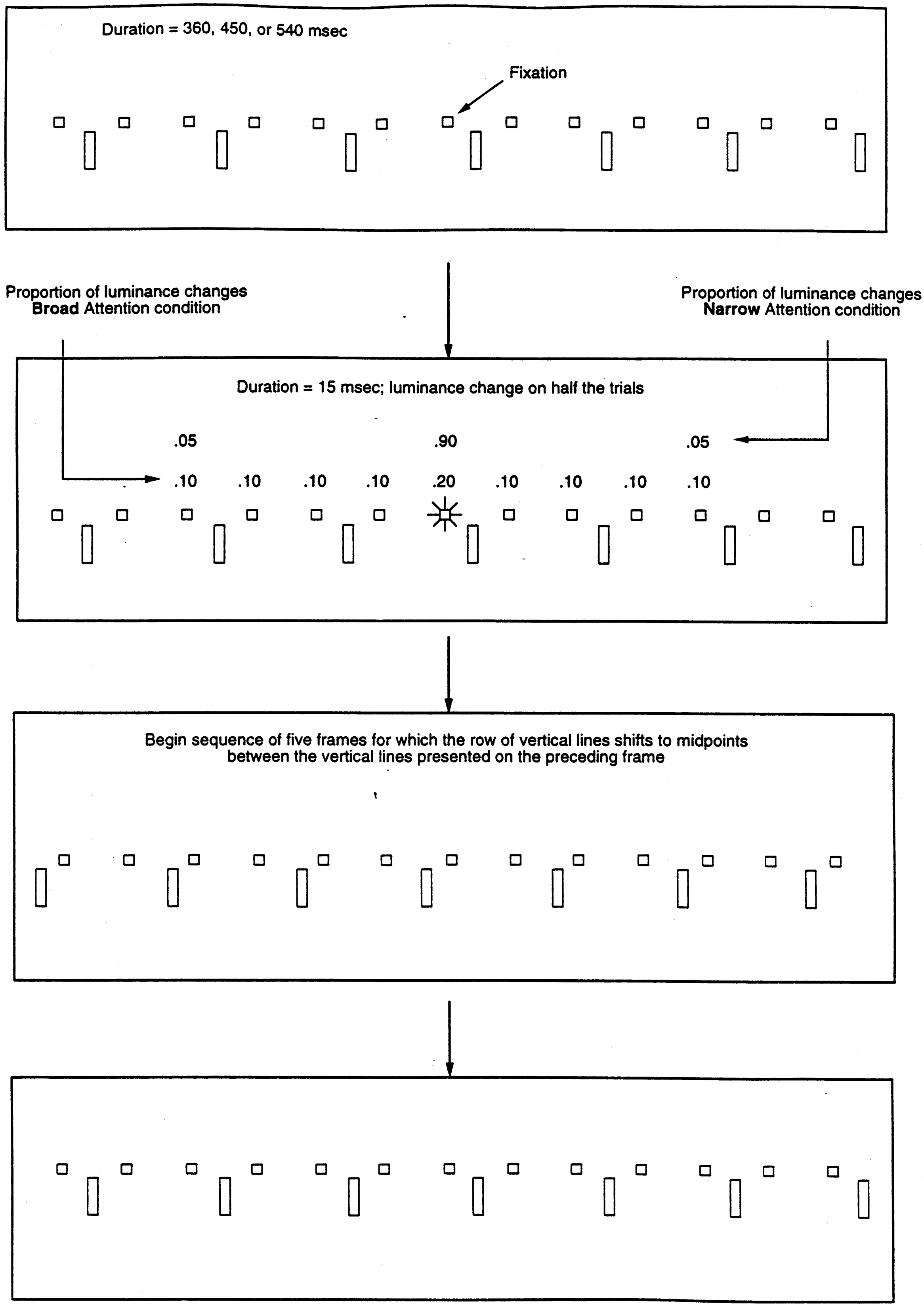

Fig. 2. The stimuli and temporal structure for each trial in Experiment 1.

the peripheral dots served as the narrow attention confirmation check (described below).

2.1.3. Procedure

At the start of every 20 trials the subject was reminded of the required attentional spread by a static display (duration controlled by subject key press) of the row of dots with either the center dot (narrow attention condition) or the central nine dots (broad attention condition) were brightly illuminated. Subjects were instructed to maintain fixation on the central dot (the dot between the vertical fixation lines) prior to and throughout each trial, and to maintain their attentional spread (narrow or broad) throughout the trial. They did not respond until the end of each trial. If a luminance change was detected, subjects responded 'yes' (by pressing a designated key on the Macintosh keyboard); otherwise they responded 'no' by pressing another key. Then, using the same keys, they indicated which motion pattern was perceived while the vertical line segments were being displaced on successive frames. They pressed one key if they perceived only the unidirectional motion pattern, a second key if they perceived only the oscillatory motion pattern, and a 'don't know' key if they were unsure or if there was a pattern change during the trial (prior to the start of these trials, subjects were shown illustrative examples of unidirectional and oscillatory motion).

Auditory feedback was provided to help subjects maintain a level of luminance detection close to their calibration values (defined in the next paragraph), as well as the required attentional spread. A brief tone sounded when subjects wrongly indicated a luminance increment (false alarm) or when they failed to detect an actual luminance increment (miss). Subjects were instructed to keep their false alarm errors to a minimum. For the broad attention condition, if the subject failed to detect luminance increments in either of the two left-most or two right-most locations on either side of center, the tone sounded twice. Feedback was not provided when subjects failed to detect the small percentage of luminance increments associated with the narrow and broad attention confirmation checks.

2.1.4. Calibration

Prior to the start of the experiment, subjects were individually calibrated with respect to the detection of luminance increments. Increments that were detectable on 75% of the trials (hit rate = 75%) were determined at each of the nine possible dot locations for the broad attention condition, and at the one, central location, for the narrow attention condition.

2.1.5. Narrow attention confirmation check

In order to confirm that the narrow attention condition was achieving its intended effects on the perceiver's distribution of attention, 10% of the luminance changes in the narrow attention condition occurred for the dots that were the most peripheral in the broad attention condition (either $+2.1$ or $-2.1°$ from center, randomly selected). The size of the luminance increment for these dots was the value the subject detected on 75% of the trials in the final calibration of the broad attention condition. Subjects were told to expect occasional peripheral luminance changes, but to be primarily concerned with luminance changes of the central, fixation dot. That subjects were indeed focusing their attention on the central dot in the narrow attention condition was confirmed if their detection rates for the $+2.1°$ and $-2.1°$ peripheral dots were lower than their detection rates for the same luminance increment in the broad attention condition.

2.1.6. Broad attention confirmation check

In order to confirm that the broad attention condition was achieving its intended effects on the perceiver's distribution of attention, 10% of the luminance increments in the broad attention condition occurred for the center dot at the value which the subject detected on 75% of the trials in the final calibration of the narrow attention condition. Confirmation that subjects were indeed spreading their attention in the broad attention condition was obtained if their detection rate for the central dot was lower for this luminance increment than the detection rate obtained in the narrow attention condition.

2.1.7. Design

There were four testing sessions, each with one block of narrow attention trials and one block of broad attention trials (their order was alternated during successive sessions). Each block was composed of 11 sub-blocks of 20 order-randomized trials. The distance between the evenly-spaced vertical line segments was either 0.13, 0.19, 0.26, 0.32, 0.39, 0.51, 0.64, 0.90, 1.16, or 1.61°. Each was presented twice per sub-block, once accompanied by a luminance increment, once not. The conditions of the luminance-increment detection task and the inter-line distance were uncorrelated. The results for the initial 20 trials were deleted from the final data tabulation.

2.2. Results

2.2.1. Detection of luminance increments

Each set of graphs in Fig. 3 presents the luminance increments for each subject that resulted in 75% detection accuracy at the conclusion of the pre-experimental, calibration phase. Directly above each luminance increment is each subject's detection (hit) rate for that increment in the narrow and broad attention testing conditions. It can be seen that with the exception of the

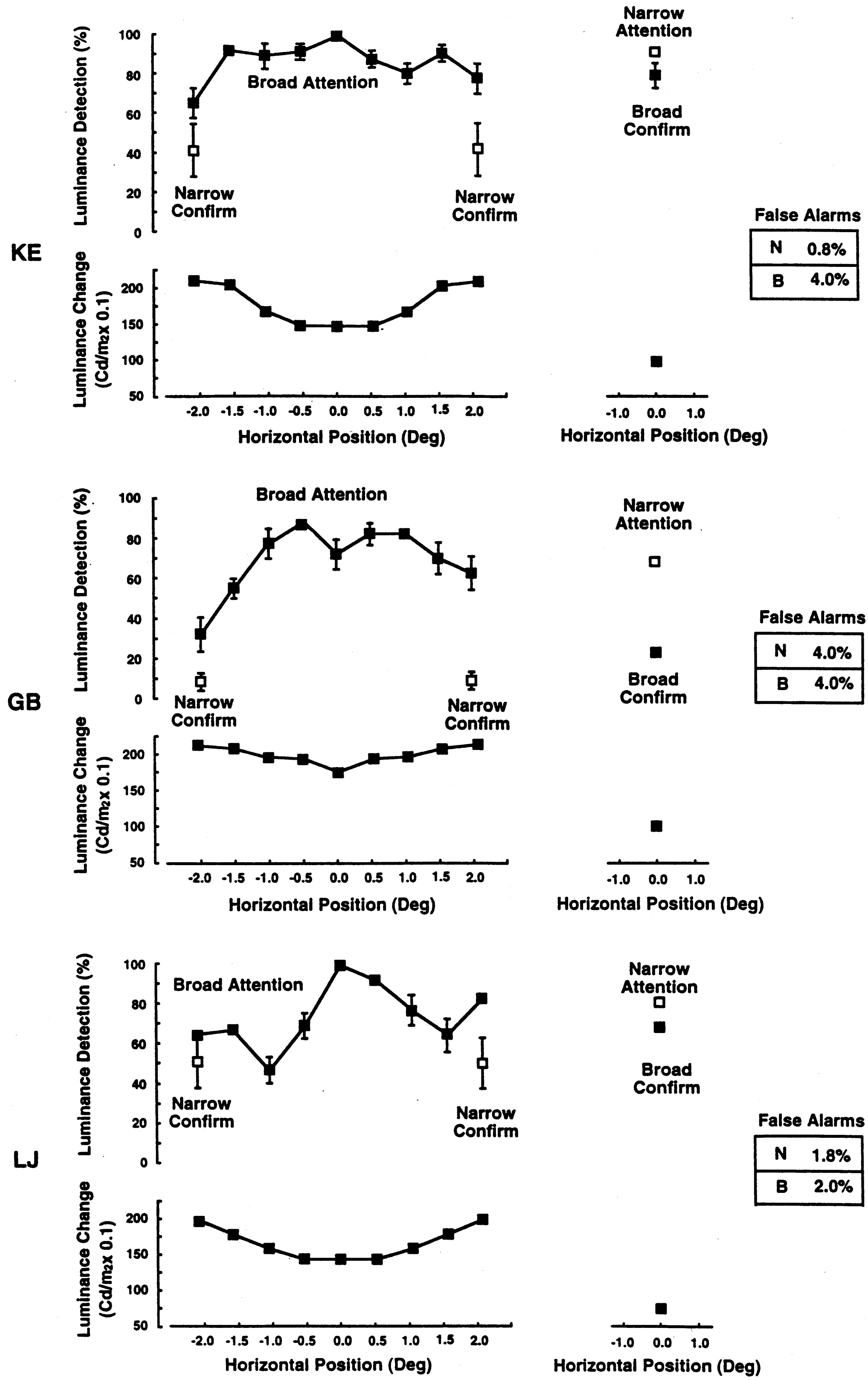

Fig. 3. Experiment 1: The luminance increments for each subject that resulted in 75% detection accuracy during the pre-experimental, calibration phase. Directly above each luminance increment is the detection rate (and the standard error of the detection rate) for that increment in the narrow (N) and broad (B) attention conditions, including broad and narrow confirmation trials (see text). Standard errors smaller than the symbol size are not shown.

confirmation trials, the 75% detection rate was maintained in the narrow and broad attention conditions (although GB's detection performance for the latter was degraded in the left periphery). It also can be seen that equal luminance increments of the central dot were detected more readily in the narrow attention condition when compared to the broad attention confirmation checks, and equal luminance increments of the peripheral dots were detected more readily in the broad attention condition when compared to the narrow attention confirmation check. Thus, subjects focused their attention sufficiently in the narrow attention condition to reduce their detection of peripheral luminance increments and spread their attention sufficiently in the broad attention condition to reduce their detection of luminance increments of the central, fixation dot. The differences for both confirmation checks were substantially greater than the standard errors of measurement except for LJ's narrow attention confirmation test in the left periphery.

2.2.2. Pattern formation

Subjects reported perceiving coherent unidirectional or coherent oscillatory motion (without) switches on almost all the trials. The proportion of these for which unidirectional motion was perceived are presented in Fig. 4 (the proportions for the perception of oscillatory motion are the reciprocal of the proportions for the perception of unidirectional motion). As in Hock and Balz [4] and Hock, Balz, and Eastman [14], the perception of unidirectional motion predominated for relatively small inter-element distances, whereas the perception of oscillatory motion predominated for relatively large inter-element distances. The effect of broad relative to narrow attention was to increase the perception of the unidirectional motion pattern for all three subjects; it was seen at inter-element distances for which oscillatory motion predominated for narrowly focused attention.[2] This was the case for the no-luminance-increment as well as the luminance-increment trials, indicating that the results were not due to the potential attention-attracting effects of the luminance increments. It could be concluded, therefore, that pattern formation in this experiment depended on both the geometry of the counterphase stimulus and the perceiver's attentional state prior to its displacement.

[2] It is noteworthy that LJ consistently differentiated between the unidirectional and oscillatory motion patterns without prior practice. This is contrary to our previous experience [4,14], in which substantial practice was required. The results for LJ suggest that learning to maintain a consistent attentional spread may have been one consequence of the extensive practice.

3. Experiment 2

In Experiment 1, horizontally spread attention increased the perception of unidirectional motion for a horizontally oriented, counterphase row-of-lines. The purpose of this experiment was to determine whether or not the effects of broadly spread attention are limited to the spatial axis along which attention is spread. That is, we investigated the effect of horizontally and vertically spread attention on motion perception for horizontally-oriented and vertically-oriented, counterphase rows-of-dots. If horizontally spread attention affects pattern formation for the vertically-oriented counterphase rows-of-dots (and vice versa for vertically spread attention), it would indicate that the activation of large spatial filters is not limited to a single spatial axis.

3.1. Method

3.1.1. Design

As in Experiment 1, there were two phases to each experimental trial, the first concerned with establishing the attentional state of the perceiver, and the second concerned with the perception of motion for a counterphase row-of-dots (in contrast with the row-of-lines in Experiment 1). In addition to broadly spread attention extending over a substantially larger region, the most important way the experiment differed from Experiment 1 was with respect to the method for establishing differences in broad versus narrow attention. Instead of detecting luminance increments in central versus peripheral locations, subjects were instructed to attend to red dots that were flickering centrally or peripherally. There were three attentional conditions, each of which was tested once (in all six possible orders) during each of six sessions. Two subjects, both authors, participated. Both had practiced extensively prior to the start of the experiment.

3.1.2. Procedure

At the end of each trial, subjects responded by pressing one key on the computer keyboard if they perceived unidirectional motion for the entire duration of presentation of the counterphase row-of-dots, by pressing another key if they perceived oscillatory motion for the entire duration of presentation of the counterphase row of dots, or by pressing the space bar if they perceived a switch between the two motion patterns, if they were unsure of which they perceived, or if they were not attending appropriately to the red 'attention' dots. Unlike Experiment 1, there was no independent procedure for directly confirming that the required attentional states were established. Confirmation depended on the convergence of the results with those of Experiment 1.

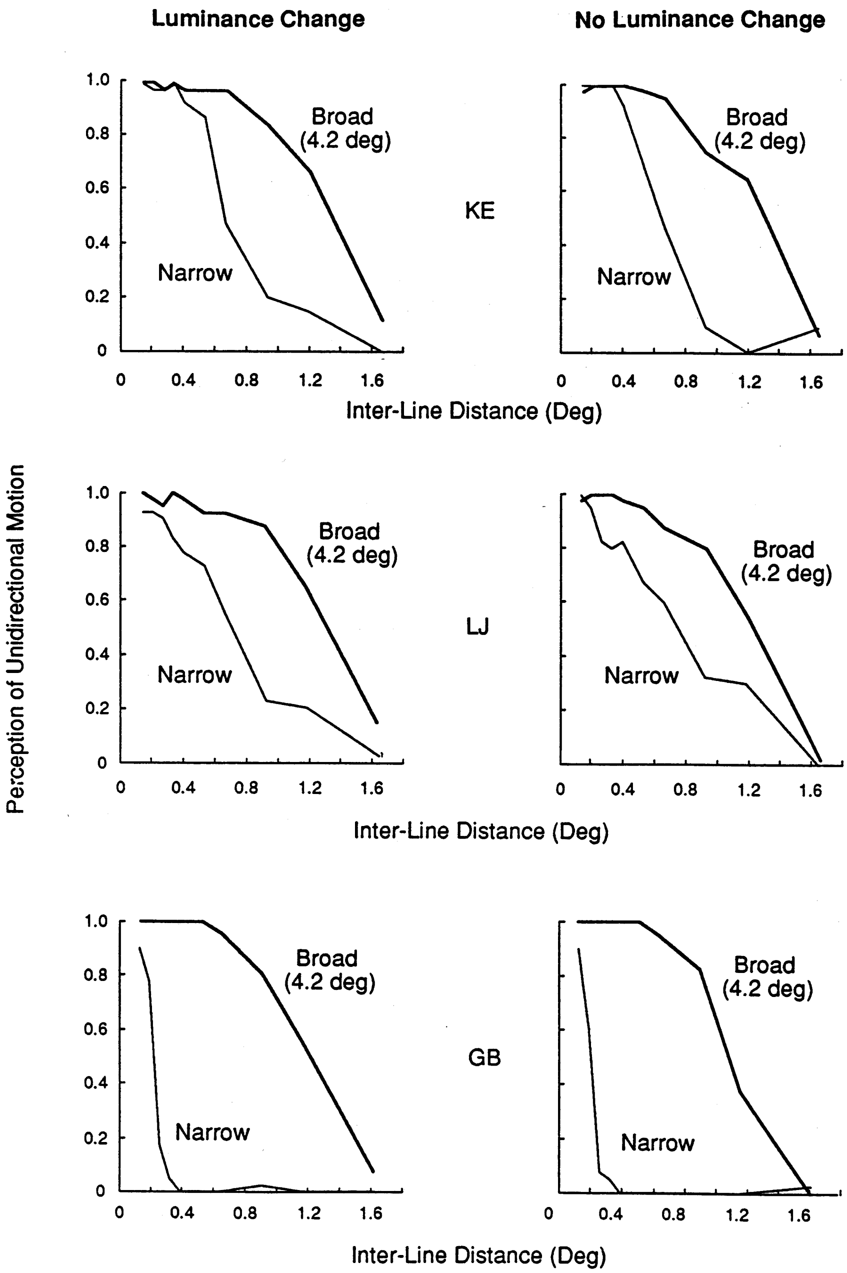

Fig. 4. Experiment 1: The proportion of trials for which the unidirectional motion pattern was perceived (the proportion of trials for which oscillatory motion was perceived was complementary) as a function of the inter-element distance of the counterphase row of line segments. Attention was either narrowly focused on the central dot or broadly spread along the horizontal row of dots. On half the trials (randomly determined) there was a luminance increment just before the sequence of frames for which the row of line segments began its counterphase movement.

3.1.3. Stimuli

In contrast with Experiment 1, stimuli were viewed from a distance of 30 cm (again maintained by a head restraint). In order to minimize effects associated with the dots at the end of the row-of-dots (their motion direction is not ambiguous) in a manner that would be symmetrical for the horizontal and vertical orientations, the luminance of each dot was diminished as a function of its ordinal position in relation to the center of the screen. Thus, the central dots were highest in luminance (12.8 cd/m^2) and the luminance of the more peripheral dots was gradually reduced so that the same number of dots appeared with the same luminance values, regardless of the inter-dot distance (the luminance was diminished by a Gaussian with a standard deviation of 1). The gradual decrease in luminance as the dots increased in eccentricity gave the unidirectional motion percept the quality of dots moving off into 'the mist' (the luminance of the dark background was approximately 0.05 cd/m^2). The inter-dot distances for the horizon-

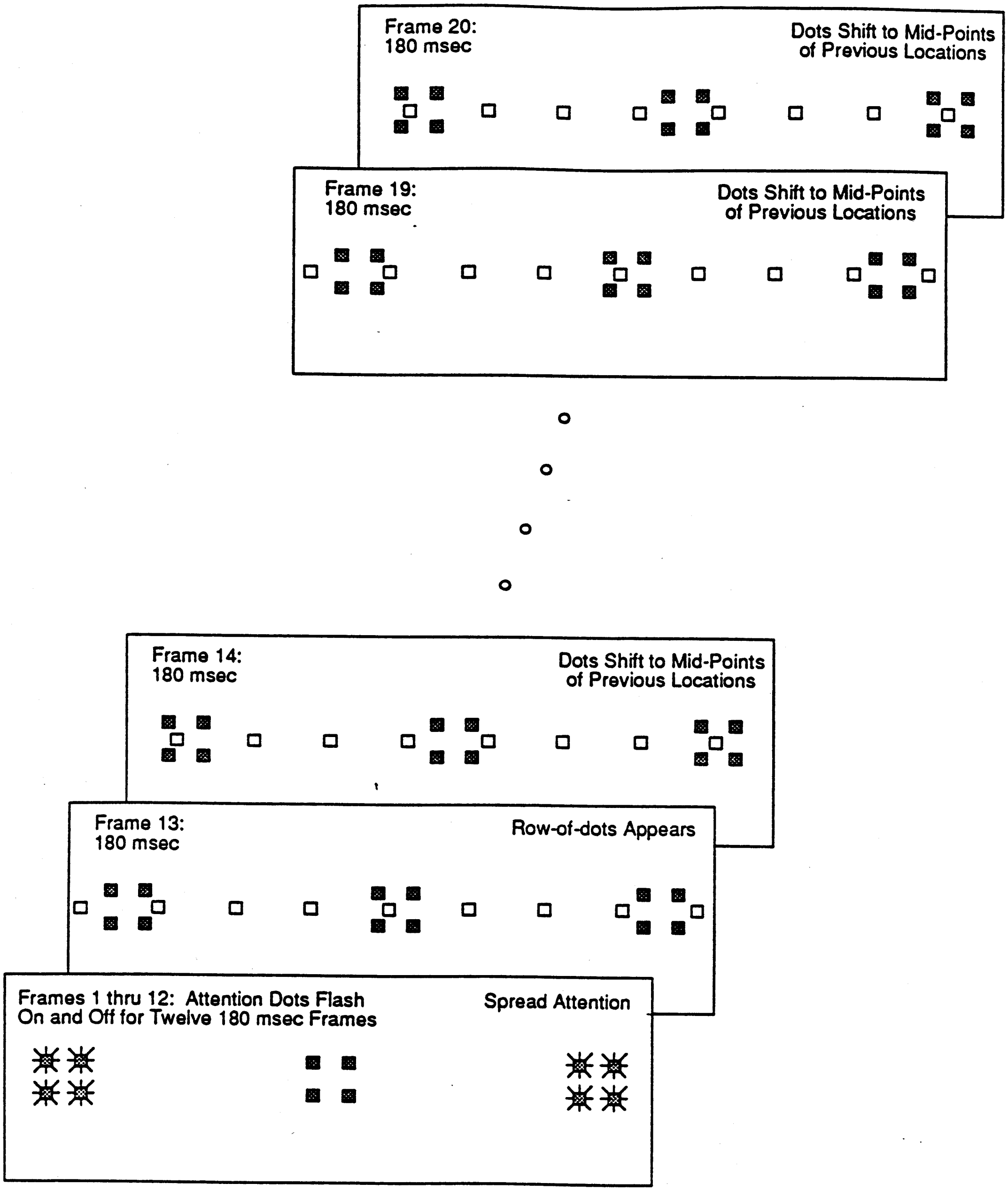

Fig. 5. The stimuli and temporal structure for each trial in Experiment 2 (in the illustration, attention is broadly spread along the horizontal axis).

tally-oriented, counterphase row-of-dots were 0.27, 0.54, 0.81, 1.08, 1.35, 1.88, 2.43, 2.96, 3.50, and 4.04°.

3.1.4. Narrow attention condition

Each trial began with the presentation of four 2×2 min red dots configured as a small 6×6 min square in the center of the screen. The dots were then flickered on and off over a series of twelve 180 ms frames. Thereupon, either a horizontally- or vertically-oriented row of evenly spaced dots appeared (each on half the trials, randomly determined). The row of dots was presented in counterphase (i.e. displaced by 180° on successive frames) over a series of eight 180 ms frames. During these eight frames, the four previously flickering 'attention' dots remained static in the center of the screen. Subjects were instructed to focus their attention in the center of the square during the first phase of each trial and to continue doing so during the entire presentation of the counterphase row-of-dots. The dots for both the horizontal and vertical row-of-dots were aligned with the center of the square defined by the four 'attention' dots.

3.1.5. Broad attention (horizontal) condition

This condition, which is illustrated in Fig. 5, differed from the narrow attention condition in that each trial began with the presentation of three sets of four red 'attention' dots, one set in the center of the screen (as in the narrow attention condition), one set 8.8° to the left of the central 'attention' dots, and one set 8.8° to their right (the total attentional spread was 17.5°). The two sets of peripheral dots were then flickered on and off over a series of twelve 180 ms frames (the central dots did not flicker). As in the narrow attention condition, either a horizontally- or vertically-oriented row of evenly spaced dots then appeared and was presented in counterphase over a series of eight 180 ms frames. During these eight frames, all three sets of 'attention' dots remained static in their central and peripheral locations. Subjects were instructed to minimize their attention to the central red dots, and to concentrate their attention simultaneously on the dots flickering in the left and right periphery in order for the flickering in the left and right periphery to be perceived as simultaneous. They were instructed to maintain this attentional spread during the entire presentation of the counterphase row-of-dots (although it is possible that their attention narrowed sometime after the appearance of the counterphase row-of-dots). The dots for both the horizontal and vertical rows-of-dots were aligned with the center of the four central dots, and the horizontal row-of-dots was aligned with the centers of the squares defined by the two sets of four peripheral 'attention' dots.

3.1.6. Broad attention (vertical) condition

This condition was identical to the broad attention (horizontal) condition with the exception that the peripheral 'attention' dots were rotated 90° so that one set of four was 8.8° above the central dots and one set of four was 8.8° below the central dots.

3.2. Results

Consistent with the results of Experiment 1 and previous studies, the perception of unidirectional motion predominated for relatively small inter-dot distances, whereas the perception of oscillatory motion predominated for relatively large inter-dot distances of the counterphase row-of-dots (as in Experiment 1, the results for the oscillatory motion pattern are the complement of those presented in Fig. 6 for the unidirectional motion pattern). This was the case regardless of the attentional condition and regardless of the orientation of the counterphase row-of-dots. Also as in Experiment 1, broadly spread attention enhanced the perception of the unidirectional motion pattern. This was the case for both directions of attentional spread and both orientations of the counterphase row-of-dots (there were no consistent differences with respect to the horizontal and vertical axes). Thus, the effect of broadly spread attention was not limited to a single spatial axis. Nor was it restricted to the counterphase stimulus that intersected the peripheral 'attention' dots.

4. Experiment 3

Given the hypothesis that broadly spread attention enhances the sensitivity of relatively large spatial filters, the results of Experiment 2 indicate that large receptive fields were sensitized over a two-dimensional region of retinal space. The purpose of this experiment was to determine whether the effects of attentional spread could be graduated. That is, will spreading attention over an increasingly large range of horizontal locations increase the sensitivity of increasingly large spatial filters, thereby expanding the range of inter-dot distances over which unidirectional motion is perceived? Furthermore, if the effects of attentional spread are not limited to one spatial axis (as indicated by the results of Experiment 2), similar effects of horizontally graduated attentional spread would be expected for the vertically-oriented row of dots.

4.1. Method

4.1.1. Design

As in Experiment 2, attention was manipulated by having subjects attend to red dots that were flickering centrally or peripherally. In this experiment, however, attention was spread only along the horizontal axis. There were four attentional conditions, each requiring a different degree of horizontal attentional spread. The condition for which attention was spread over 0° corresponded to the narrow attention conditions of the preceding experiments. For the other three conditions, the peripheral attention dots were either 3.0, 6.0, or 9.1° from the central red dots, resulting in attentional spreads of 6.1, 12.1, and 18.2° (compared with 4.2° in Experiment 1 and 17.5° in Experiment 2). Each of the four attention conditions was tested once (in all four possible orders) during each of four sessions (the two subjects were authors). As in Experiment 2, the counterphase row-of-dots was either horizontally or vertically oriented (their order varying randomly from trial to trial). The response criteria were as described in Experiment 2.

4.2. Results

Once again, the perception of unidirectional motion predominated for relatively small inter-dot distances and the perception of oscillatory motion predominated for relatively large inter-dot distances. Moreover, as the distance over which attention was spread increased, unidirectional motion was perceived over increasingly large inter-dot distances (Fig. 7). This was the case for

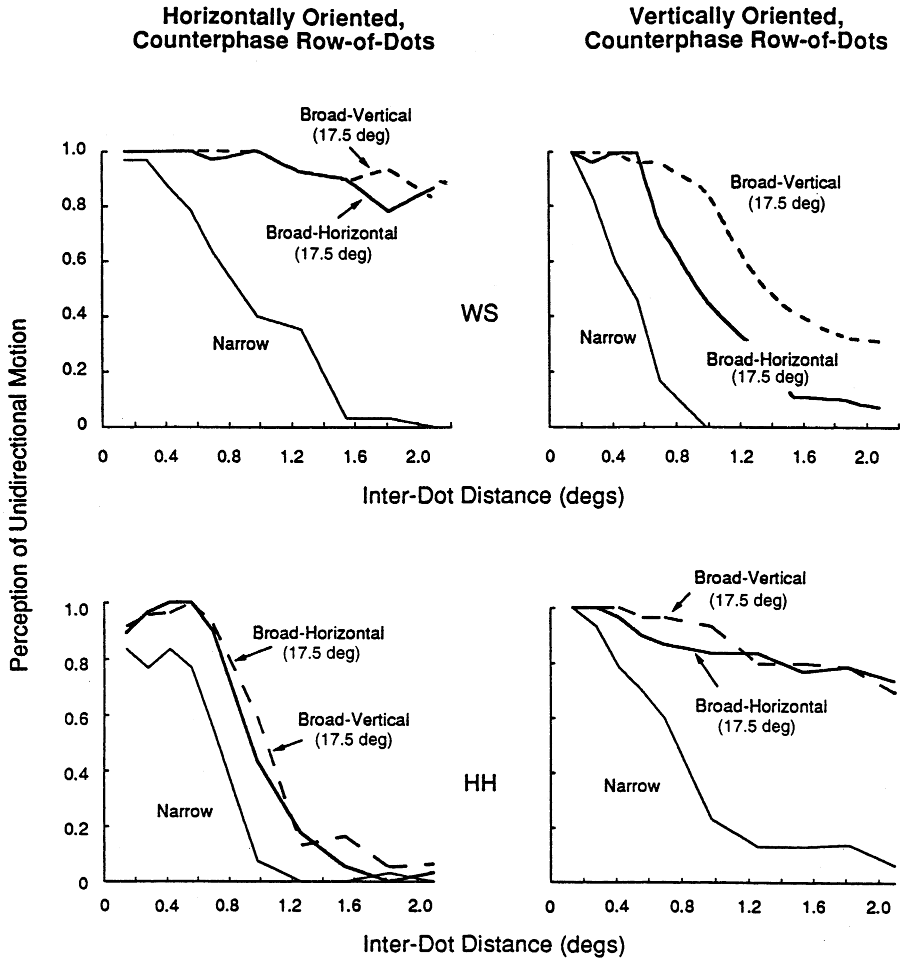

Fig. 6. Experiment 2: The proportion of trials for which the unidirectional motion pattern was perceived (the proportion of trials for which oscillatory motion was perceived was complementary) as a function of the inter-element distance of the counterphase row-of-dots. Attention was narrowly focused in the center of the screen, broadly spread along the horizontal axis, or broadly spread along the vertical axis prior to the presentation of either a horizontally- or vertically-oriented, counterphase row-of-dots.

both the horizontally-oriented and vertically-oriented counterphase row-of-dots. In order to establish the consistency of the effect of attentional spread, the mean proportion of trials for which unidirectional motion was perceived was calculated for each attentional condition by averaging over the 10 inter-dot distances (Fig. 8). Increases in unidirectional motion with the size of attentional spread was consistently observed for each subject over each testing session (designated by one through four on the graphs), even though the order of the four trial-blocks with different attentional spreads was counterbalanced over the four sessions.

5. General discussion

The results of the experiments described above indicate that the perceiver's attention can be pre-set in a manner that influences self-organized pattern formation. Three questions arise in accounting for these results: (1) Are the effects due to selectivity of attention? (2) Does attentional spread affect the relative sensitivity of spatial filters of different size? (3) What is the relationship between spatial filter size and the spatial interactions that are the basis for self-organized motion perception?

5.1. Attentional selectivity?

That the perceived motion patterns in this set of experiments are entirely self-organized is critical. Since there is no information in the stimulus that specifies either of the to-be-perceived motion patterns, the effects of attentional spread we've observed cannot be attributed to the selective aspects of attention. For example, there is no stimulus feature specifying unidirectional motion that can be selectively attended

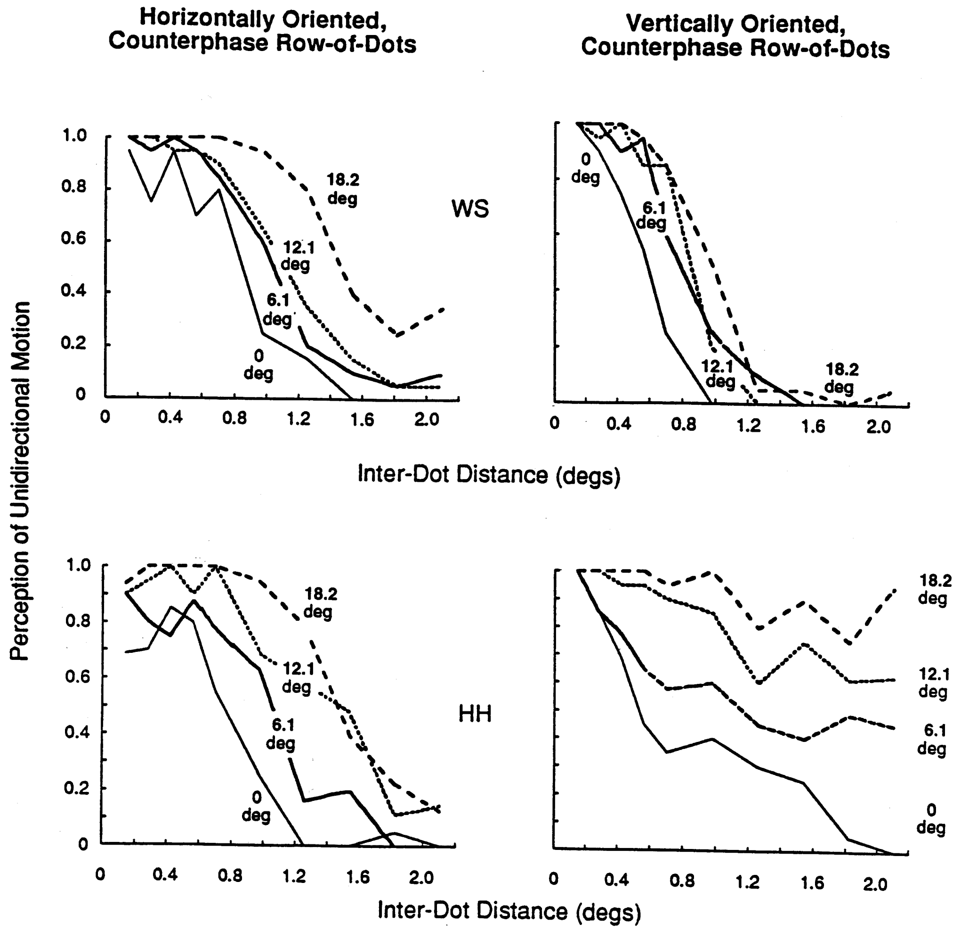

Fig. 7. Experiment 3: The proportion of trials for which the unidirectional motion pattern was perceived (the proportion of trials for which oscillatory motion was perceived was complementary) as a function of inter-element distance of the counterphase row-of-dots. Attention was either narrowly focused (0° spread), or spread along the horizontal axis over a span of 6.1, 12.1, or 18.2° prior to the presentation of either a horizontally- or vertically-oriented, counterphase row-of-dots.

to in the broad compared with the narrow attention condition.[3] With selective attention ruled out, the effects of spread attention were attributable to the size of the spatial filters that are pre-activated as a function of the extent of attentional spread. That is, broadly spread attention can affect pattern formation for the counterphase row-of-dots because of its effects on the perceiver's spatial scale [15].

5.2. Does attentional spread affect spatial filter size?

Balz and Hock [7] have shown that broadly spread attention decreases spatial resolution (e.g. vernier acuity), implying the activation of relatively large spatial filters. These results converge with Chung, Levi and Bedell's [16] evidence that the rapid movement of vernier targets decreases acuity (increased speed enhances the relative sensitivity of large spatial filters; Kelly [17]). Also relevant are the studies based on compound stimuli; e.g. alphabet letters composed of smaller alphabet letters [18]; processing the global structure of these stimuli is likely to involve broadly spread attention, whereas processing their local structure is likely to involve more narrowly focused attention. Shulman [19] has shown that attending to the global versus the local structure of a compound stimulus affects contrast sensitivity for low versus high spatial frequency sine gratings, Shulman et al. [20] have found that the processing advantage of (broad) attention to the global structure of a compound stimulus is reduced by pre-adaptation to low spatial frequency gratings, and Hughes et al. [21] have shown that the global (broad attention) advantage in processing compound stimuli can be eliminated by reducing the low spatial frequency content of its constituent elements (i.e. by using 'balanced' dots).

[3] It could be argued that a tendency to selectively attend to motion in one direction would increase the range of inter-dot distances for which unidirectional motion is perceived. There is, however, no basis for assuming that such a bias would be specifically tied to the broad attention condition. Moreover, we have found in additional testing that there is no apparent increase in the perception of unidirectional motion when selective attention is focussed on the motion direction that is already favored by the perceiver.

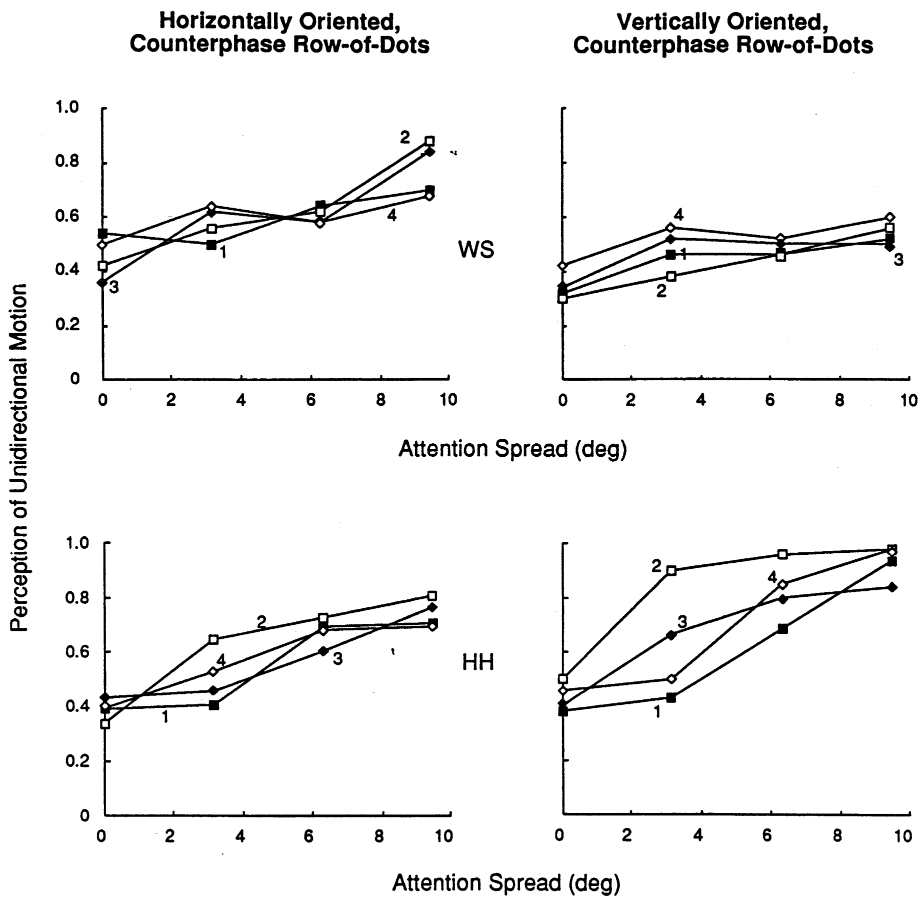

Fig. 8. Experiment 3: Effect of horizontal attentional spread on the perception of unidirectional motion averaged over the varying inter-dot distances of the counterphase row-of-dots (horizontally- or vertically-oriented). Results are similar for the four testing sessions (designated by one through four on the graphs) despite the order of the attention conditions being different during each session.

The effect of attentional spread on spatial filter size logically follows from increases in the average size of receptive fields as a function of retinal eccentricity. The greater the attentional spread around the fovea, the greater the activation of the relatively large receptive fields found with increasing retinal eccentricity. Following Hess and Hayes [8], large filters are activated by broadly spread attention condition because only large filters could fully 'pave' the large retinal region over which attention is spread.

5.3. *How does spatial filter size affect the self-organization of motion patterns?*

One possibility, suggested by Hock and Balz [4], is that spatially spread attention enhances the strength of facilitating interactions relative to that of inhibiting interactions. This explanation, however, ignores the relationship between attentional spread and spatial filter size, which was discussed in the preceding section. A more likely account, which is illustrated in Fig. 9, has four essential features: (1) The relevant receptive fields are composed of much smaller subunits, the size of the subunits increasing with increases in the size of the receptive field. This was first demonstrated by Hochstein and Shapley [22,23] for Y-type retinal ganglion cells. (2) There are facilitating interactions among nearby subunits and inhibiting interactions among more distant subunits (as specified by Hock and Balz's differential gradient model). This was first reported for various locations within the same striate complex cells by Movshon et al. [24]. (3) The complex receptive fields must be large enough to encompass attentional spreads at least as large as those studied in this article (maximum of 18.2°). Receptive fields of sufficient size first appear in the magnocellular pathway (we are concerned with the formation of motion patterns) at the level of MST [25]. (4) The complex receptive fields must be centered on the fovea; larger receptive fields, with larger subunits, extend further into the retinal periphery. Again area MST (or higher) is indicated. It is the first level in the magnocellular pathway for which the positive relationship between the size of the receptive field and the eccentricity of the receptive-field center no longer holds [26].

Following multiple channel models of static pattern formation [27,15], a multi-layered array of complex receptive fields is proposed. The layer with the smallest receptive fields (and the smallest subunits) receive input from the center of the fovea; layers with larger receptive fields (and larger subunits) remain centered on the fovea, but receive input over a region extending further into the retinal periphery. Finally, facilitating and inhibiting interactions among the subunits are scaled in terms of the number of spanned subunits, irrespective of their size. For purposes of illustration (Fig. 9), facilitating interactions predominate for the four closest subunits and inhibit interactions for the four more distant subunits, for both small and large receptive fields.

On this basis, broadly spread attention activates complex receptive fields that are large enough to encompass the attended region, increasing the perceiver's spatial scale. This has two effects: (1) it reduces spatial resolution in the fovea [7] because the large receptive fields activated by broadly spread attention are composed of increasingly large subunits, and (2) it increases

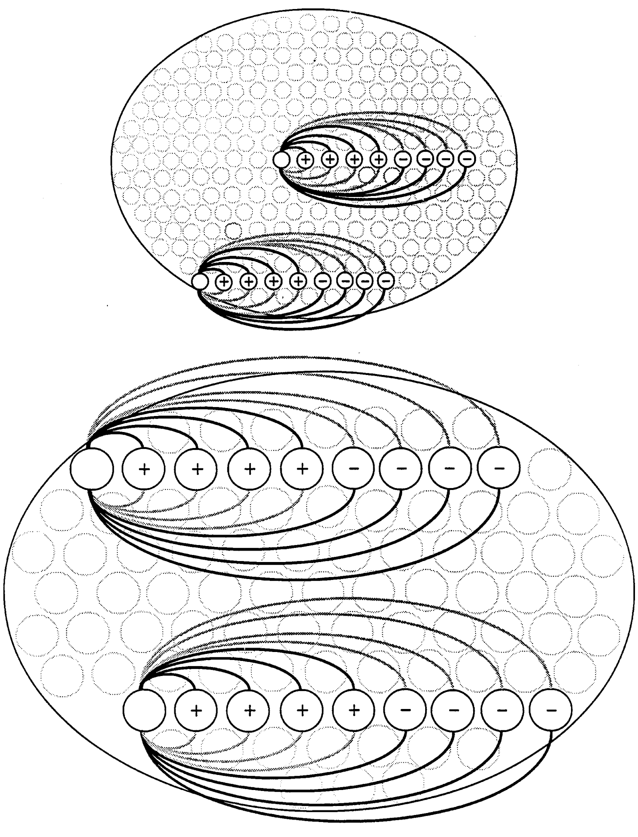

Fig. 9. Hypothetical, foveally-centered complex receptive fields at the level MST or higher. It is proposed that the receptive fields, and their constituent subunits, vary in size as a function of spatial scale. The layers that are most activated (determining the perceiver's spatial scale) depend on both attributes of the stimulus (e.g. frame duration) and the state of the perceiver (e.g. the breadth of attentional spread). Also indicated are the facilitating and inhibiting interactions among the subunits that are the proposed basis for the self-organization of spatially and temporally coherent unidirectional and oscillatory motion patterns.

the perception of unidirectional motion for the counterphase row-of-elements because distances between local motions that were outside the span of facilitating subunit-interactions when the spatial scale was relatively small, lie within that span when the spatial scale is relatively large (resulting in facilitating interactions predominating for larger inter-dot distances). It is also arguable that increases in the value of d_{max} that are obtained when random cinematograms are low-pass filtered [28–30] are the result of enhanced facilitation for broad spatial scales. That is, the low-pass filtering sets a broad spatial scale, so the distance over which detector-activations are enhanced by mutually facilitating spatial interactions is increased.

5.4. Limitations in attentional control

There is much evidence to indicate that the perceiver can voluntarily control where his or her attention is allocated in space [31]. However, there are limits to the extent this control can be exercised. Thus, Eriksen and Hoffman [32] and others have shown that attention spreads beyond the location to which the perceiver intends to narrowly focus his or her attention (at least for targets away from fixation; [33]). The results of all three experiments reported in this article are consistent with previous experiments which show that attention can be spread intentionally over a designated area [9–13], and the results of Experiment 3 indicate that the amount of attentional spread can be controlled (graduated) by the perceiver. However, the results of Experiments 2 and 3 suggest the possibility of a further limitation in attentional control. That is, they suggest that when attention is voluntarily spread along a spatial axis, its effects may involuntarily transfer to the orthogonal spatial axis. Although this would be consistent with our proposal that attention is spread over a region through the activation of sufficiently large, foveally-centered, two-dimensional receptive fields, further investigation is required. Such an investigation would determine whether: (1) the transfer of attentional state between horizontal and vertical spatial axes depends on the relative frequency of presentation of the horizontally- and vertically-oriented rows of dots, (2) the self-organization of horizontal and vertical motion patterns at a particular spatial scale depends on the activation of common, multi-directional, complex receptive fields, or on the simultaneous activation of different complex receptive fields with different directional selectivities, and (3) attention transfers to diagonal spatial axes, and if so, whether the transfer varies with spatial scale.

5.5. Attentional dynamics

As indicated earlier, subjects were instructed to maintain their attentional set for the entire presentation of the counterphase stimulus. Although the extent to which they did so was not assessed, informal observation suggested that changes in attentional spread while the counterphase row-of-dots was being perceived occasionally produced spontaneous switches between the perception of unidirectional and oscillatory motion, especially for inter-element distances near the boundary value separating the two motion patterns (subjects in this study were instructed to 'discard' trials with pattern switches).

The tendency to change, which is described above, reflects the dynamic quality of spatial attention. Attention can change in response to stimulus changes or in response to changes intrinsic to the observer; i.e. attentional orienting can be exogenous or endogenous [34]. However, responsiveness to change, whether exogenous or endogenous, is not sufficient to characterize attention as dynamic. Susceptibility to change without the presence of stabilizing forces would results in a system that responds immediately to every stimulus change, however minor, and responds immediately to every internal fluctuation, including those due to random neural noise. To be dynamic, attention must also have 'state'. In the cases that have been studied, this means that once attention is allocated to a particular location, it resists being immediately switched to another. This has been observed in conjunction with delays in moving attention in response to spatial cues [35,36], delays in the initiation of saccadic eye movements while attention is being released from a point of fixation [37], and resistance to interrupting stimulation [38][4]. It has been observed also in experiments involving changes in attentional spread [39]. Confirmation of the dynamic, state-dependent character of attentional spread could be obtained by gradually increasing and decreasing the perceiver's attentional spread prior to the presentation of a counterphase row-of-dots and obtaining hysteresis effects; when attentional spread is gradually decreased prior to the presentation of a counterphase row-of-dots, the unidirectional motion pattern would be perceived for attentional spreads that would otherwise result in the perception of the oscillatory motion pattern, and vice versa when attentional spread is gradually increased.[5] With respect to the multi-layered neural model described above, hysteresis in the control of attentional spread would reflect the presence of competitive (inhibitory) interactions among layers with different size receptive fields (i.e. different spatial scales), and would complement psychophysical evidence for inhibitory interactions among channels with different spatial frequency selectivity [40,41].

[4] Once attention is 'released' from a particular location, the time required to shift attention to a new location apparently does not necessarily change as a function of distance [44,45].

[5] This could be done, without the confounding effects of response bias, using a modified version of the method of limits [42,43].

5.6. Conclusion

The multi-layered neural model proposed in this article is consistent with evidence that motion can be perceived at multiple spatial scales [29]. This, however, does not mean that motion perception is qualitatively the same at all spatial scales. That is, the results of this and previous studies indicate that there can be qualitative differences in the motion patterns formed at different spatial scales. This is the case regardless of whether differences in spatial scale are established by characteristics of the stimulus (e.g. frame duration) or by characteristics intrinsic to the perceiver (e.g. attentional spread).

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