The effect of similarity and duration on spatial interaction in peripheral vision

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Abstract—Spatial interactions are extensive in the peripheral visual field, extending up to about half the retinal eccentricity of the target (Toet and Levi, Vision Res. 32, 1349–1357, 1992). In the present study it is shown that the degree and extent of peripheral spatial interaction depends in large measure on the similarity between test and flanking stimuli. The stimulus consisted of a test T surrounded by four distracting flanking Ts, each randomly oriented. The task was to determine the orientation of the test T. The test and flanking Ts differed in contrast polarity, shape, depth, color, eye of origin, or contrast. When the target and flanks differed in contrast polarity, depth, or shape, performance improved markedly for all observers. A color difference enhanced the performance of most but not all observers. Eye-of-origin had no effect, that is, spatial interaction was identical when the target and flanks were presented to the same eye, or to opposite eyes. The role of stimulus duration in spatial interaction was examined in two additional experiments. In the first, the stimulus viewing duration was increased in order to allow the observer time to serially search for the test T. In the second experiment, a postmask was presented at the location of the test T. The results of these experiments showed that the influence of similarity was independent of stimulus duration and the postmask, and suggest that serial search does not play an important role in the spatial interaction effects reported here. The extent of spatial interaction is correlated with the ability to do parallel search.

INTRODUCTION

Letter recognition is profoundly degraded by the presence of neighboring contours, especially when the letters are presented in the retinal periphery (Ehlers, 1936; Flom et al. 1963; Bouma, 1970; Jacobs, 1979; Strasburger et al., 1991; Nazir, 1992; Toet and Levi, 1992). The degree of this spatial interaction depends critically upon the distance between the target and the neighboring contours (Flom et al., 1963; Flom, 1991). In the fovea, spatial interaction extends over a distance of a few minutes of arc (Flom et al., 1963; Jacobs, 1979; Toet and Levi, 1992); however, in peripheral vision the extent of this spatial interaction is quite large (even when compared to the observers' resolution limit). For identical target and flanks, the extent of peripheral spatial interaction was found to be about one tenth of the target's retinal eccentricity (0.1 × ecc) in the tangential direction (Toet and Levi, 1992), but extended up to about half the retinal eccentricity (0.5 × ecc) in the radial direction (Bouma, 1970; Toet and Levi, 1992).

A number of studies suggest that the degree and extent of spatial interaction in the periphery may depend on the degree to which the targets and flanks are similar. Orientation similarity between target and flanks strongly affects line tilt sensitivity (Andriessen and Bouma, 1976). The sensitivity of the visual system for
detecting a small angle of line tilt is more severely degraded in the presence of similarly oriented flanking lines than in the presence of differently oriented flanking lines. The spatial extent of interaction is about 0.4 times the eccentricity of the test line for flanks having the same orientation as the test line, and up to about 0.25 times the eccentricity for flanks perpendicular to the test line. Shape similarity between target and background has been shown to strongly affect letter recognition (Estes, 1982). Letter targets were more difficult to detect against a background of letters, than against a background matrix of dots the same size as the letters. Size similarity and shape similarity of flanks can affect the recognition of Landolt ring targets viewed peripherally (Nazir, 1992). Her results show clearly that flanking bars, Es and Os all reduce recognition; but that the extent is strongest with flanking Os that are the same size as the target. Other studies examined color (Bouma, 1969) and intensive properties (i.e. brightness or contrast, see for example Estes, 1982). More recent work in which contrast thresholds were measured for a Gabor test patch in the presence of supra-threshold Gabor masks also shows that spatial interaction is strongest when the target and mask have similar spatial frequencies and orientations (Polat and Sagi, 1993).

From these studies it appears that the degree of spatial interaction depends not only upon the spatial separation between target and flanks, but also on the degree to which the target and flanks are similar. Of course these studies are not easily comparable, because they involve different targets, flanks, experimental procedures and observers. Thus the purpose of the present study was to investigate systematically the effect of similarity on spatial interaction. Specifically, we ask how both the degree and extent of spatial interaction depend upon the degree to which the target and flanks are similar along several dimensions; namely, contrast polarity, shape, depth, color, eye-of-origin, and contrast. We choose these particular dimensions because each of these represents a distinct aspect of the stimulus, and may have a distinct neurophysiological representation (DeYoe and van Essen, 1988).

A closely related question is, to what extent spatial interaction is related to 'popout' (Wolfgang and Chambers, 1983; He and Nakayama, 1992). The probability of detecting a target embedded in a background is known to increase as the target and background elements become increasingly dissimilar (Krose, 1987; Duncan and Humphreys, 1989). For example, it is difficult to detect a green T embedded in a display of green Ls; however, a red T will 'popout' from a background of green distracters. Differences in color, polarity, shape, or depth lead to good object segregation, perceptual grouping, boundary detection and contour formation (Julesz, 1964, 1975, 1984a,b; Beck, 1966, 1967, 1982; Attneave, 1970; Olson and Attneave, 1970; Treisman and Gelade, 1980; Enns, 1990). Segregation of objects from the features of the background in which they are embedded is a critical task of the 'early' or pre-attentive visual system. This segregation requires pre-attentive grouping of features into those that belong to the object and those that belong to the background. The Gestalt psychologists first demonstrated that features were often grouped together based on 'similarity'. Treisman and Sato (1990) have recently reviewed much of the work in this area, and they conclude that: 'A prerequisite for features involved in the initial segregation of objects and background surfaces is that they should be detected in parallel across space'. Many studies dealing with attention use the time taken to respond (reaction time) as the critical measure to separate pre-attentive from attenve mechanisms. A target that is pre-attentively detected in parallel pops out from the background, and gives short reaction times (Treisman and Sato, 1990). A target that is not pre-attentively detected can be detected by focusing attention on it; a process called serial search (e.g. Broadbent, 1958; Neisser, 1967).

In the experiments described here, we examine how a relatively simple letter recognition task is affected by dissimilarities along several different feature dimensions. The target letter T is presented at an eccentricity of 10 deg, flanked by four other Ts which are different along the dimensions of color, contrast polarity, shape, stereoscopic depth, or eye-of-origin. In the main series of experiments, the question we address is to what extent are changes within each dimension effective in reducing the degree and extent of spatial interaction. In order to assess a possible relationship between spatial interaction and popout, spatial interaction was also measured for different durations of stimulus presentation and for post-stimulus masking.

METHODS

Apparatus

An IBM compatible PC with a VGA board and a multisync color monitor (NEC multisync 3D in The Netherlands; Sony-CPD1304HG in Houston) were used to generate and present the stimuli and to record the responses. The display area was 640 pixels (about 32 deg) wide and 480 pixels (about 24 deg) high. At the 44 cm viewing distance, one pixel equaled approximately 3.0 arcmin in both the horizontal and vertical directions.

The display was viewed in a dimly lit room. A small white fixation dot was continuously visible 10 deg above the center of the test T. Outside of an 8 x 8 deg region surrounding the target, a grid of low contrast lines was continuously visible to aid proper accommodation. Viewing was monocular with the dominant eye, except for the experiments involving depth and eye-of-origin. During the experiments, observers were seated with their head supported by a chin- and head-rest.

Stimuli

The stimulus consisted of a test T surrounded by four flanking elements. The test T was always positioned 10 deg peripherally in the inferior visual field, in one of four orientations (up, down, left, or right). Unless otherwise stated, the flanks also were randomly and independently oriented Ts (Fig. 1). Each T in the stimulus was constructed from two bars of equal length (1 and −), 6 arcmin wide and 30 arcmin long. The viewing distance of 44 cm was chosen to yield close to 100% correct scores when the test T was presented without flanks. The flanks were either identical to the test T, or differed from the test in one of several ways, described in detail later.

For the dichoptic experiments the stimulus configuration was drawn twice, one for the left and the other for the right eye, and fusion was accomplished with the use of a four-mirror stereoscope. A fixation point and the surrounding grid
assisted in fusion of the two images. In the depth experiments, stereoscopic disparities were produced by shifting the Ts out (uncrossed) or in (crossed) with respect to the fixation plane. The test T was given 9 arcmin of crossed disparity and the flanks 9 arcmin of uncrossed disparity. Pilot studies showed that with much larger disparities diplopa resulted and with smaller disparities the depth was less visible. The depth was clearly noticeable, except at the smallest target-flank separation.

**Procedure**

The subject started a run by pressing a key on the computer keyboard. The stimulus was presented after a delay of 0.8 s. Unless otherwise stated (e.g. in the depth experiment and the duration studies), the stimulus duration was 150 ms. The subject's task was to report the orientation of the target T by pressing one of four corresponding response keys. The observer's response was followed by an auditory feedback signal (a high tone to indicate a correct response and a low tone to indicate an incorrect answer) and the initiation of the next trial. For each stimulus condition the percentage of correct responses was measured as a function of the separation between test and flanking Ts. Five flanking separations were randomly interleaved with solitary (unflanked) presentations of the test T. Each run consisted of 140 trials: twenty for each separation and forty for the solitary target T. Each condition was tested at least four times, resulting in a minimum of eighty trials per data point.

**Observers**

Seven highly trained observers participated in the main experiments. All observers with the exception of the authors were naive to the purposes of the experiment. All observers had normal color vision. Most observers (AT, FK, DL, HD, and ST) wore spectacle corrections; the others (JT and PN) did not require any correction. Observers AT, PN, and JT were tested in The Netherlands, DL...
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and HD in Houston, and FK and ST at both locations. Similar results were obtained at the two locations.

RESULTS

Spatial interaction was measured with the spatial configuration shown in Fig. 1, for flanking Ts that were the same and for flanking Ts that were different with respect to the target Ts. The flanks were made different from the target in one of several ways: contrast polarity, shape, depth, color, or eye-of-origin.

Contrast polarity

The five Ts were all white, all black, or mixed (white test with black flanks or the reverse). These stimulus configurations are illustrated in Fig. 1. The effect of contrast polarity difference on target recognition is shown in Fig. 2. The percentages of correct responses are plotted against the separation between test and flank for five observers. The rightmost point on the graph represents the isolated T (no flanks) condition, for all psychometric functions plotted throughout this paper. The background luminance was set to yield approximately equal scores for the black and white Ts in isolation (no flanks) and the rightmost point is the combined percent correct. The error bars represent the standard error of the percent correct response, calculated using the binomial theorem. Note that for all observers, flanks decrease the recognizability of the test T. When the test and flanks have the same polarity, performance decreases steadily as separation decreases, to near chance at the smallest separation (1.25 deg). This is the well-known effect of spatial interaction. However, for all observers, there is a striking difference in the effect of the flanks when the polarity of the flanks is reversed. When the test and flanks are of opposite polarities, there is a very significant improvement in recognizability for each subject, as shown by the elevation of the open symbols above the filled symbols. For example, for PN, at a target-to-flank separation of 2.5 deg, correct detection increases from near chance (≈ 25%) to almost 90%.

Cumulative normal distribution functions were fit to the data of each condition (excluding the rightmost point), using probit analysis (Finney, 1971). The separation corresponding to the 62.5% point on the curves (i.e. midway between chance (25%) and 100%; indicated by the horizontal dotted line) was considered the threshold separation. We take this threshold separation to be an indication of the extent (size) of the spatial interaction. Figure 3 summarizes the effect of contrast polarity on the extent of spatial interaction for all five subjects tested. Note that for same polarity targets and flanks (solid histograms), the extent of the spatial interaction ranged from almost 4 deg to about 7 deg, with a mean value of 5.7 deg, equal to about half of the 10 deg eccentricity of the target (Toet and Levi, 1992). All observers showed a significant reduction in the extent of the interactions in the mixed polarity conditions (hatched histograms). For opposite polarity stimuli, the mean extent of spatial interaction shrank to approximately 2.0 deg.

Shape

In the shape experiment, the flanks were bars produced by leaving out one of the
two segments that make up the T. Figure 4 shows the percentage of correct responses for four observers. The extent of the interactions is summarized in Fig. 5. All four observers showed significant reduction in both the magnitude and extent of interaction when the target and flanks differed in shape (stippled, open symbols) compared with the case when they were similar in shape (hatched, closed symbols).

In the experiment described above, since the luminous flux (or area) of the flanking bars was half that of the T, it could be argued that the reduced interaction resulted from weaker flanks. However, in one control experiment, the flanking bars were doubled in width (triangle and bowtie in Fig. 6) to equal the flux of the Ts. In this experiment, the flanks were fixed in orientation rather than randomized as in the previous experiments. The flanking Ts were always oriented with their 'i'-oriented component oriented away from the target, and the 'i' pointing away from the target. The 'i'-oriented shape flank has the 'i'-oriented component of the T only (but double the width). This corresponds quite closely to the stimulus used by Flom et al. (1963), but with their Landolt C target replaced by a T. The 'i'-oriented shape flank contains the 'i'-oriented component of the T only (but double the width). There are several points of interest. First, we found that the pattern of results did not change when the flanking bars were doubled in width (triangle and bowtie in Fig. 6) to equal the flux of the Ts; that is, spatial interaction was stronger when the target and flanks were both Ts than when the target and flanks were different shapes. Second, the

'=' and 'ii' shapes produce identical results (triangle and bowtie respectively). This is interesting because if spatial interaction was governed by the leading edge of the flank, then one might expect spatial interaction to be stronger with the '=' flank (similar to the flank configuration used by Flom et al., 1963) than with the 'ii' flank. Another interesting observation is that the spatial interaction with the fixed 'T' flanks (squares in Fig. 6) is quite similar to that obtained with the randomly oriented 'T' flanks shown in Fig. 4 and both have a spatial extent of about 4 deg.

In an additional control experiment, the flanks were Hs. These H flanks have a higher luminous flux than the target T, but contain the same component orientations as the T. When the flanks consisted of Hs (triangles in Fig. 6) performance was similar to that obtained with Ts (squares). Therefore, we conclude that similarity in the component orientations of the test target and the flanks (an H has all the orientations that a T has) appears to be a primary factor
Depth

In the depth experiment, stimulus duration was lengthened to 600 ms to give observers enough time to develop a good depth percept. A depth difference between test and flanks increased the percentage of correct responses (Fig. 7) and decreased the extent of interactions (Fig. 8). For example, at 2.5 deg separation, the introduction of a disparity improved performance from near chance to near perfect. Note that the binocular stimulation, which is necessary to create the impression of depth, results in increased visibility of the test T and a reduced extent of spatial interaction when compared to the monocular data.

Color

In order to examine the influence of a color difference on spatial interaction, the target and flanks were either of the same color (red or green), or of opposite

determining the degree and extent of spatial interaction; the flux of the flanks (the H has higher flux than both the bars and the Ts) seems to be secondary at best. These results are in agreement with the earlier reports that the interaction drops with a decrease in the degree of similarity in shape or component orientations between the target and the flanks (Andriessen and Bouma, 1976; Estes, 1982; Nazir, 1992; Polat and Sagi, 1993).

Figure 5. The extent of interaction for the shape experiment. The extent of interaction for different shape (stippled histograms) is compared with same shape (hatched histograms).

Figure 6. Additional results for the shape experiment. A reduction in spatial interaction is obtained when the flanking bars are doubled in width (triangle and bowtie) to equal the flux of the Ts. The H flanks (triangles) result in the same amount of interaction. Note that the H flanks have a higher luminous flux than the target T.

Figure 7. Results for the depth experiment. A depth difference (9 arcmin disparity—open squares) between test and flanks increases the percentage of correct responses compared to stimuli in which target and flanks are in the same depth plane (0 disparity—solid squares). The triangles show the data obtained under monocular conditions.
(complementary) colors (red target with green flanks or the reverse). The dark background luminance was set low enough to produce high contrast letters and high enough to make room reflections invisible. The red and green colors were set to approximate equiluminance, determined using the minimum flicker method. Table 1 provides the intensities and chromaticities of all colors and grey shades used.

Results are shown in Fig. 9. For some observers (PN, AT, DL, FK), the complementary color condition yielded a very significant improvement in correct recognition, while for observers ST and JT there was very little improvement in performance with complementary colors. Further experiments on other (naive) observers showed the same dichotomy.

This inter-observer variability is rather intriguing. Apparently the observers who showed marked improvement were able to utilize the additional color information. For the observers who showed no improvement, either performance may already have been at its optimum or maximum without the color difference, or the observers may have been deficient in their ability to make use of the color difference.

Eye-of-origin

The degree of spatial interaction in the fovea does not change if test and flank are presented in opposite eyes, rather than in the same eye (Flom et al., 1963). We repeated this experiment with our stimuli centered at 10 deg in the periphery. The test T and the four flanking Ts were randomly presented in the left or right eye, using the same methods and procedures described above. In one condition both test and flanking Ts were in the same eye; in the other condition test and flanks were in opposite eyes. The Ts were white and were presented on a grey background. Two subjects participated in this experiment.

Our results confirm and extend the findings of Flom et al. (1963) that spatial interaction for ipsilateral and contralateral stimulation is identical (Fig. 11). On
the one hand, this result is surprising since placing target and flanks in opposite eyes is about the largest dissimilarity one can think of. On the other hand, it is not surprising in light of the lack of popout seen with the contralateral stimulus. In fact, during the experiment observers reported not being aware whether all Ts were presented in the same eye or not, suggesting that eye-of-origin information is lost (Enoch et al., 1969; Blake and Cormack, 1979; Barbeito et al., 1985).

Contrast differences

The letters in the previous experiments were all of high contrast. We also examined spatial interactions with test and flanking Ts which had different contrasts. Figures 12 and 13 show data for four conditions: test and flanks both have high contrast (83.6%; triangles); test and flanks both have low contrast (28.6%; hourglass symbols); high-contrast test and low-contrast flanks (squares);

Figure 12. Results for the contrast experiment. The psychometric functions of four observers under four conditions: test and flanks both have high contrast (83.6%; triangles); test and flanks both have low contrast (28.6%; hourglass symbols); high-contrast test and low-contrast flanks (squares); low-contrast test and high-contrast flanks (bowties). The background was grey. Spatial interaction is weakest when the target is high contrast and the flanks are low contrast (squares).
The magnitude and extent of spatial interaction was found to be strongly dependent on contrast differences. The spatial interaction was weakest when the target was high contrast and the flanks were low contrast (squares and right-hatched). For all observers, the extent of interactions shrank to about half the size found with high-contrast test and flanks. Interestingly, the converse was not necessarily true. A naive expectation is that spatial interaction should be strongest when the target contrast is low, and the flank contrast is high; however, this was not the case for three of the four observers. For a low-contrast target, making the flanks high contrast increased the extent of interaction for one observer (ST), decreased it for two (HD and FK) and left it unchanged for one (AT). For three of the four observers, spatial interaction was greatest when the target and flanks were the same contrast (triangles and hourglass in Fig. 12; solid and left-hatched in Fig. 13). These results suggest that the effect of the flanks depends upon both the strength of the flanks relative to the target, and on the degree of similarity.

Figure 14 summarizes the results by plotting the extent of spatial interaction for similar stimuli (i.e. targets and flanks) against the extent of spatial interaction for dissimilar stimuli for all conditions and observers. Several interesting points can be seen: (i) The most striking result is that opposite polarity flanks (squares) markedly shrink the extent of spatial interaction for all observers. (ii) Differences in shape (diamonds) also significantly reduce the zone of interaction in all observers, although the magnitude varies from about 17% (observer AT) to about 45% (observer ST). (iii) In the depth experiment the extent of spatial interaction was measured under binocular conditions with the test and flanks either in the same plane or in different planes. It is interesting to note that the extent of spatial interaction is smaller under binocular than under monocular conditions for the same observers by about 11%, when the test and flanks are similar. Placing test and flanks at different depth planes reduces the zone of interaction for all three of the observers (triangles in Fig. 14). This reduction ranges from 23% (PN) to 40% (FK). (iv) Color differences have a smaller effect. This seems surprising because color differences produce strong perceptual 'popout'. Interestingly, for the two observers (PN and JT) with the largest extent of interaction for similar stimuli (the two rightmost circles at an ordinate value of about 6 deg), color differences halve the extent of interaction for one observer (PN) and have essentially no
effect on the other (JT). (v) Placing the flanks and target in the same eye, or in contralateral eyes has no effect on the size of the zone of interaction (crosses in Fig. 14) suggesting that the spatial interference effects measured here, like those of Flom et al. (1963) are supraretinal. (vi) The effect of the flanks depends both upon the strength of the flanks relative to the target, and on the degree of similarity. When the flanks are lower contrast than the target, spatial interaction is substantially reduced; however, making the flanks higher contrast than the target does not have a systematic or consistent effect on spatial interaction. (vii) This summary plot (Fig. 14) also makes evident the substantial individual differences.

**Duration**

In the experiments described above, we found that spatial interaction was generally stronger when the targets and flanks were similar than when they were different. If spatial interaction is related to pre-attentive perceptual grouping, serial search could potentially be helpful in identifying a test T in a strongly grouped stimulus configuration (i.e. one with similar test and flank), whereas test T does not 'popout'. In this case, longer stimulus durations might be expected to improve performance. With our weakly grouped configuration (where test and flanks are different) 'popout' would be experienced and serial search would not be necessary. Here longer durations would not improve performance. In order to examine the role of serial search, we repeated the basic experiment using longer stimulus durations.

The polarity and color experiments described above were repeated at an exposure duration of 1 s. Results are summarized in Fig. 15. This figure follows the same format as Fig. 14. For color differences (squares—long duration, triangles—short duration), increasing the duration increased the detectability for both similar target and flanks and different target and flanks, and this is evident as a shift along the 45 deg line. On the other hand, increasing the duration has little effect on the extent of interaction for different polarity targets and masks, although it does result in reduced interaction for opposite polarity stimuli. This can be seen by the substantially downward shift (but minimal leftward shift) of the polarity data with increased duration (circles—short duration, diamonds—long duration). Note that any simple serial search hypothesis would predict that spatial interaction for similar stimuli would be selectively diminished at longer durations, because observers ought to be able to serially read each T.

It could be argued that increasing the stimulus duration did not have a differential effect on spatial interaction for the two stimulus configurations because even with brief stimulus presentations, there may have been substantial neural persistence. The color experiment was repeated with a post-mask in order to test if observers were making use of short-term memory or afterimages to determine their responses at the short (150 ms) duration. The test T as described above was masked after 90 ms by a box of the same color and luminance, slightly larger than the test T (36 by 36 arcmin). Perceptually, this post-mask produced strong masking. The extent of interaction (data not shown) was 5.4, 4.9 deg for subject ST (same and complementary color), and 8.4, 3.8 deg for subject FK (same and opposite contrast polarity). It is interesting to note that while the absolute extent of interaction is greater with the post-mask than it is in the unmasked condition shown in Figs 3 and 10, the relative extent of similar and opposite test and flanks is the same. For FK, the extent of interaction with opposite polarity is approximately half that obtained with same polarity, similar to the factor of two difference obtained without the post-mask (Fig. 3). For ST the extent of interaction is only slightly larger with same color than it is with complementary color, as was the case without the post-mask (Fig. 10).

**DISCUSSION**

**Similarity**

The most important new result is that the magnitude and extent of spatial interaction are dramatically reduced when the target and flanks differ in their contrast polarity. Spatial interaction is also reduced when the target and flanks differ in depth or shape (i.e. component orientations). The reduction in spatial interaction seen with a color or contrast difference was neither as dramatic nor as universal; however, it was still very significant for some observers. One question that arises...
is whether the strong effects of polarity are qualitatively different than those obtained with, for example, color. Thus, it could be argued that the perceptual difference between black and white is larger than the perceptual difference between red and green. If so, the strong effect of polarity may simply be a reflection of the large difference in the neural representation of black and white. Conversely, the weak effect of color differences could be due to the much smaller difference in the neural representation of red and green. To test this notion, we repeated the polarity experiments at two lower contrasts (46 and 23% above and below the background). The results are summarized for observer ST in Fig. 16. Clearly the effect of reversing the polarity is to shrink the extent of interaction at all contrast levels. It is important to note that for the same observer, color differences have no effect on the extent of interaction. The present data suggest that the absence of an effect of color cannot be simply attributed to low visibility of the stimuli. Perhaps opposite polarity stimuli are so effective because black and white stimuli are represented separately very early in the visual pathway. The ON-center and OFF-center ganglion cells have been shown to segregate anatomically in two distinct laminae of the inner plexiform layer (Nelson et al., 1978; Wässle et al., 1983) and remain segregated in the LGN (Schiller, 1984).

![Figure 16](image)

**Figure 16.** The effect of contrast. The abscissa shows the extent of interaction for same polarity targets and flanks; the ordinate shows the extent of interaction for opposite polarity flanks. The different symbols represent different contrast levels (circles—23%, triangles—46%, and squares—88%). Note that opposite polarity flanks result in shrinkage of the extent of interaction at all contrast levels.

**Eye-of-origin and depth**

Earlier studies found no reduction in foveal spatial interaction when the test and flanks were presented to different eyes (Flom et al., 1963). The present study extends this finding to the periphery. Spatial interaction as measured here is therefore likely to be an entirely central phenomenon, and not mediated by retinal receptive fields. In addition, information regarding eye-of-origin appears to be lost since observers cannot distinguish between the two conditions.

The contrasting results with stereoscopic depth and contralateral stimulation make an interesting comparison. The latter is, in a sense, the largest possible binocular difference; yet the visual system is unable to use this difference to disentangle the test T from the flanking Ts. Yet very small stereoscopic shifts in position allow the visibility of the test T to jump from chance to near perfect in some observers. The steep improvement in performance with increasing separation is consistent with the results of a similar study (Nakayama and Silverman, 1986). They showed that different depth planes are processed serially, with parallel search being performed within each depth plane and also that attention could be focused on a particular depth plane.

**Relation between spatial interaction and popout**

We interpret our results to mean that spatial interaction and pre-attentive popout are distinct yet related processes based on several lines of evidence.

If the reduction in spatial interaction were a direct result of popout one would expect that the degree of reduction would be directly related to the degree of popout. To a first approximation this relation holds. When a target object is defined by a conjunction of stimulus features, search has to be conducted serially, indicating that the visual system is incapable of conducting a parallel search over two dimensions simultaneously. Earlier research has shown that there are two exceptions to this finding. One dimension can be searched in parallel if the other dimension is stereoscopic depth (Nakayama and Silverman, 1986) or relative motion (McLeod et al., 1988). We have recently found a third exception (Theeuwes and Kooi, in press): a conjunction of polarity and shape can also be searched in parallel. Taken together these results suggest that a strong reduction in spatial interaction is correlated with the ability to do parallel search.

The crucial distinction between 'pre-attentive' and 'attentive' search is the time required to find or identify a certain target. In our main experiments the available time is fairly short (150 ms). If pre-attentive availability of the target T is the reason for the superiority of the similar over the different conditions at the short duration, this superiority should disappear at longer durations. The finding that spatial interaction was not differentially reduced for similar stimuli at long durations argues that the observer cannot use serial search to access the target.

A number of reaction-time experiments have yielded results that are clearly related to the ones discussed and presented here. For example, Kramer and Jacobson (1991) tested reaction time for the recognition of a dotted or striped foveal line embedded in flanks. The flanks could be either the same color as the test, or different, and could be made to appear as one object with the test line or separate. Both a difference in color and grouping based on closure decreased the reaction time. Baylis and Driver (1992) and Driver and Baylis (1989)
demonstrated profound effects of color, good continuation, and 'common fate' on response competition as measured with reaction times (Eriksen and Eriksen, 1974). The results of these reaction time experiments are usually interpreted as evidence for an object-based attentional mechanism: 'Selection of targets is strongly determined by Gestalt configuration properties like good continuation and featural similarity that produce good perceptual groups'. 'Identifying a single target is more difficult when the target is embedded among distracters as part of a perceptual group than when it is outside that group' (Johnston and Dark, 1986, p. 56).

Wolford and Chambers (1983) argue that lateral masking consists of two distinct processes, one lower level or 'hard-wired' and the other higher level. The first, spatial interaction, would occur at close separations and the other, attention, at larger separations. The size and shape of peripheral interaction (Toet and Levi, 1992), the specificity with regard to contrast polarity, depth and shape or component orientation, and the decrease in interaction at all separations when the target and flanks differ in these dimensions, argues in favour of lower level neural interactions.

Local structure, local position code, and pre-attentive popout: phenomena with a common origin?

Attention appears to be automatically drawn to the location of the most salient object (Julesz, 1984a; Koch and Ullman, 1985; Nakayama and Mackeben, 1989; Theeuwes, 1992). And, as is shown here, the local structure of an object is more visible if it is unique in particular ways, e.g. contrast polarity. A very similar effect is observed in determining the local position code of an object (Morgan et al., 1990). If an object is surrounded by other similar objects, its local code is lost. If the object is unique, the local position is more readily available. We suggest that a common mechanism might underlie all these phenomena, viz. local structure, local position, and popout.

Nakayama, and Mackeben (1989) proposed a similarity vetoing mechanism for attention. According to this proposal, the response to a stimulus feature is inhibited if similar features are detected in the neighborhood. In cats, physiological evidence of this inhibition has been observed as early as striate cortex. Gilbert and Wiesel (1990) showed that the orientation selectivity of some cells in the cat striate cortex is influenced by oriented elements far beyond the classical receptive field. (Note that the spatial interaction also extends far beyond the size of the classical receptive fields presumably involved in detecting the orientation of the target T). Similar inhibitory mechanisms have been found for orientation sensitive cells in area 18 of the cat (Blakemore and Tobin, 1972), for motion sensitive cells in pigeons (Frost et al., 1981; Frost and Nakayama, 1983) and in primates (Allman et al., 1985a,b), and for disparity sensitive cells in cat and monkey (Nelson et al., 1977; Poggio and Fischer, 1977). Such an inhibitory network might act to segregate objects according to specific features (e.g. polarity, color, shape, and depth). If a target is different from its surroundings in one or more dimensions the inhibition is released. Such an automatic, bottom-up, release of inhibition may be responsible for the quick reaction times in search experiments, as well as for the availability of local shape and position. (To restate: the local shape, position, color, etc., of a unique object become immediately available.) Note that it is not necessary that the inhibition (or its release) be equally effective across stimulus features.

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NOTES

1. We found no systematic differences in the scores for black targets with black flanks and white targets with white flanks, so these were combined and plotted as 'same polarity' in Fig. 2. Similarly, there were no systematic differences between the scores for black targets and white flanks, and white targets with black flanks, so these were combined and plotted as 'opposite polarity' in Fig. 2.

2. This fits assumes an upper asymptote of 100%. For most of our data sets the unfanked score was above 90%; however, a few data sets (e.g. in Figs 9 and 12) have significantly lower unfanked scores. For these data sets, the upper asymptote was fixed at the unfanked performance score.

REFERENCES


