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Glass pattern studies of local and global processing of contrast variations ☆

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Abstract

Using Glass patterns [Nature 223 (1969) 578; Nature 246 (1973) 360; Perception 5 (1976) 67], we have studied the role of contrast differences in local and global processes of form perception. The virtue of these patterns (composed of a set of randomly distributed elements combined with a geometrically transformed copy) for studying object formation is that they allow ready isolation of local processes, the combination of dots to form a perceptual pair, from global processes, the combination of dipoles into the percept of an overall rotational or translational pattern. We find that a contrast difference within dot-pairs reduces the ability to resolve local features; large differences totally abolish the perception of the pattern. Contrast differences between dot-pairs lessen, but do not abolish, the global integration among local features. In both cases the effect is proportional to the ratio of the two contrast levels employed. Effects which differ for rotations and translations, are consistent with the greater areal integration required to resolve rotational patterns.

Keywords: Form; Contrast gain; Pattern; Segmentation/integration; Glass patterns

1. Introduction

Scenes in the natural environment contain significant local luminance correlations (Atick & Redlich, 1992; Burton & Moorhead, 1987; Field, 1987; Field, 1993, 1994; Gallant, Braun, & Van Essen, 1993). In the initial stages of processing form information, the visual system must selectively respond to the presence of these correlations. Extraction of still more extensive and complicated pattern characteristics requires the integration of local spatial units (Gallant, Connor, Rakshit, Lewis, & Van Essen, 1996; Pasupathy & Connor, 1999; Webster & Miyahara, 1997; Wilkinson et al., 2000). These integrative mechanisms are often termed mid-level processes.

Numerous psychophysical studies of contour integration utilizing Gabor patches (Braun, 1999; Dakin & Hess, 1998, 1999; Elder & Zucker, 1993; Field, Hayes, & Hess, 1993; Hess & Dakin, 1999; Hess, Dakin, Kapoor, & Tewfik, 2000; Hess, Ledgeway, & Dakin, 2000; McIlhagga & Mullen, 1996; Mullen, Beaudot, & McIlhagga, 2000; Pettet, 1999) have lent support to the notion of an "association field" in which co-aligned elements are "associated", and thus integrated, producing a contour that is segregated from background noise elements. This association is robust to luminance contrast variations (Hess, Dakin, & Field, 1998) and to chromatic differences (McIlhagga & Mullen, 1996; Mullen et al., 2000). Circular, or simply closed, smooth configurations facilitate contour integration (Kovács & Julesz, 1993; Pettet, McKee, & Grzywacz, 1998), but sensitivity to contour structure is reduced when spatial phase is inverted between adjacent elements (Field, Hayes, & Hess, 2000). Models of such local enhancement mechanisms posit lateral connections between similar orientation columns in different V1 regions (Li, 1998; Polat & Sagi, 1994) operating in a "binding" fashion, rather than higher-level mechanisms commonly postulated by pattern perception models (Landy & Bergen, 1991; Olzak & Thomas, 1999; Wilson & Wilkinson, 1998; Wilson, Wilkinson, & Asaad, 1997).

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Studies of the statistics of natural scenes indicate that spatial frequency and orientation selective Gabor-like receptive fields observed in V1 (Daugman, 1980; De Valois, Albrecht, & Thorell, 1982; Hawken & Parker, 1987; Jones & Palmer, 1987) would efficiently code local luminance variations in the early visual processing of natural images (Bell & Sejnowski, 1997; Hoyer & Hyvärinen, 2000; Hyvärinen & Hoyer, 2000; Hyvärinen, Hoyer, & Inki, 2000; Olshausen & Field, 1996; Rao & Balard, 1998). Further studies of natural scenes suggest an important role for the integration of these local units into larger entities, such as circular contours, at a later processing stage (Geisler, Perry, Super, & Gallogly, 2001; Sigman, Cecchi, Gilbert, & Magnasco, 2001).

In this report we examine early- and mid-level processes using Glass patterns (Glass, 1969; Glass & Pérez, 1973; Glass & Switkes, 1976), which consist of a combination of two arrays of elements (dots, Gaussians, etc.), the second being a geometrically transformed copy of the first. When seen together, a distinct percept of over-all structure arises (see Fig. 1). At the local level, mechanisms that initially extract form information must integrate paired dots to construct dipoles. This can be accomplished with Gabor-like local filters. However, at a subsequent level, additional processes must integrate these local elements in order to detect the global relationship among the dipoles. The manner in which Glass patterns are constructed allows one to manipulate separately the properties of the pattern elements at each of these levels. By altering the luminance contrast of one of the dots within a dipole, one can determine how the input to local orientation–extraction mechanisms is affected by contrast variation. By manipulating luminance contrast between dipoles, one can determine how global luminance variations influence integration of the output of oriented units. And finally, by studying both translational and rotational Glass patterns, one can compare integrational mechanisms which may operate over differing spatial scales. Thus, Glass patterns are an ideal class of stimuli to address questions of local and global integration mechanisms.

Our results indicate that local luminance integration is readily accomplished between elements with similar achromatic contrasts but diminishes with increasing contrast *ratio* of the elements of a dot-pair. Furthermore, we show that a simple model employing Gabor filters with divisive normalization could provide a mechanism for such a decreasing ability of the visual system to isolate local orientational features when the dot contrasts differ. Our findings also support the notion that there must be higher-level mechanisms operating under the closed-contour integration paradigm, as previously suggested by others (Prazdny, 1984; Wilson & Wilkinson, 1998). At this more global level, we find that, when all dot-pairs have the same contrast polarity, patterns of correlated dipoles are more easily segregated from noise dipoles as the contrast difference between the signal and noise components increases. However, when the signal component and noise component dipoles differ in contrast polarity, we find that the effect of noise depends on whether the pattern contains translational or rotational correlations.

2. Experimental methods

2.1. Stimuli

In the majority of experiments, we used translational and rotational (see Fig. 1) Glass patterns (Glass, 1969; Glass & Pérez, 1973; Glass & Switkes, 1976). Our patterns were composed of circular dots (with a 0.09° visual angle plateau) with Gaussian tapered edges totaling 0.36°. Because of our interest in comparing achromatic

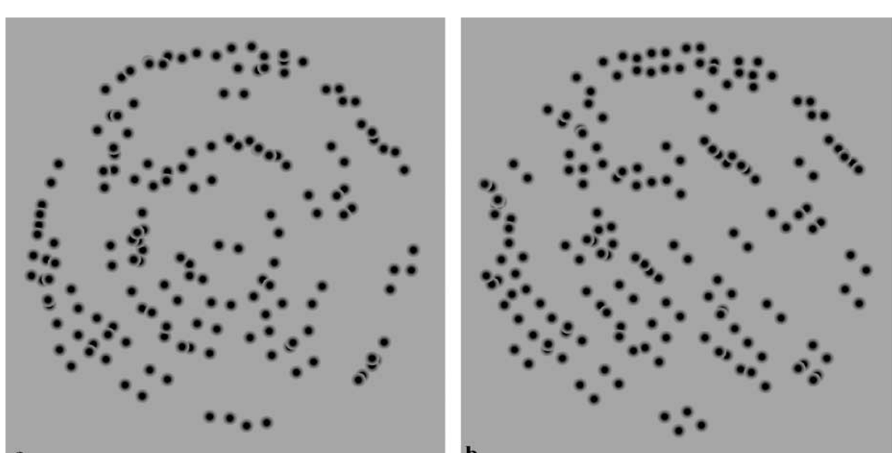

Fig. 1. The two types of patterns we used in all experiments. On the left (a) is a ‘rotational’ pattern in which dot displacement is fixed rather than varying as a function of radius. On the right (b) is a translational pattern corresponding to an oblique displacement.

to chromatic Glass patterns we used large and tapered pattern elements, to minimize chromatic aberrations (Wilson, 1999; Wilson, Switkes, & De Valois, 1999). The contrast increments or decrements of dots were specified as $|(\text{lum}_{\text{dotplateau}} - \text{lum}_{\text{background}})|/\text{lum}_{\text{background}}$. The overall pattern density was approximately 140 elements/pattern (70 dipoles). The separation of dots within a dot-pair was 0.37° for both translational and rotational patterns; and the total size was 7.4° presented within a circular window. Stimuli were presented for 750 ms at full contrast, with 100 ms up/down ramps. The grey background had chromaticity of Illuminant C and a luminance of 37 cd/m^2.

2.2. Procedure

In a two-alternative spatial forced choice, using the method of constant stimuli, observers discriminated between two side-by-side Glass patterns, with centers horizontally displaced by 9.7°. Observers were allowed to free-view the patterns. On any given trial, one of the paired patterns contained a varying fraction of dot-pairs that were arranged in a manner consistent with rotational or translational structure, and the second contained randomly oriented dot-pairs. Experiments were blocked into runs of 100 trials with a minimum of 400 trials per threshold estimate. Reported thresholds correspond to the fraction of aligned dot-pairs required for 75% correct discrimination and were estimated via probit analysis (Finney, 1971).

2.3. Subjects

One of the authors (JAW) and three naïve observers took part in these experiments. All had normal or corrected to normal 20/20 vision. The naïve observers, undergraduates at the University of California, Berkeley, gave signed consent and were paid an hourly wage to participate. Observers CT and JAW were well experienced observers with Glass patterns, while JR and MM had no prior experience.

3. Results

3.1. Experiment 1: local contrast variations

In an ordinary Glass pattern, the two dots that form each dipole are identical to each other. In this first series of experiments, we measured the effect of contrast variations on the *local* integration process of forming perceptual dipoles, by producing a contrast difference between members of each dipole. We confirmed the demonstration by Glass and Switkes (1976) that it is impossible to see structure in a pattern in which the two dots in a dipole are of opposite polarity (see Fig. 2) even when contrasts in the opposite directions were very small (0.1 and −0.1, data not shown). Thus we limited our contrast manipulations to patterns in which both members of the dot-pair had a contrast of the same sign, but differed in magnitude. We examined both contrast increments and contrast decrements relative to the background grey at two "reference" contrasts (0.1 and 0.9) for one dot in each pair. For the 0.9 reference increment and decrement conditions, one dot in each dipole had a contrast of 0.9 and the other some lower contrast; for the 0.1 reference conditions, one dot was 0.1 contrast and the other some higher contrast. At both reference contrasts and polarities, we examined four to five different intra-dipole contrast levels increasing in the magnitude of difference.

Fig. 3a shows the estimated thresholds resulting from intra-dipole contrast variation for translational patterns, plotted as a function of contrast ratio for two of the four observers (all observers showed similar results). Luminance increments from the background grey are shown

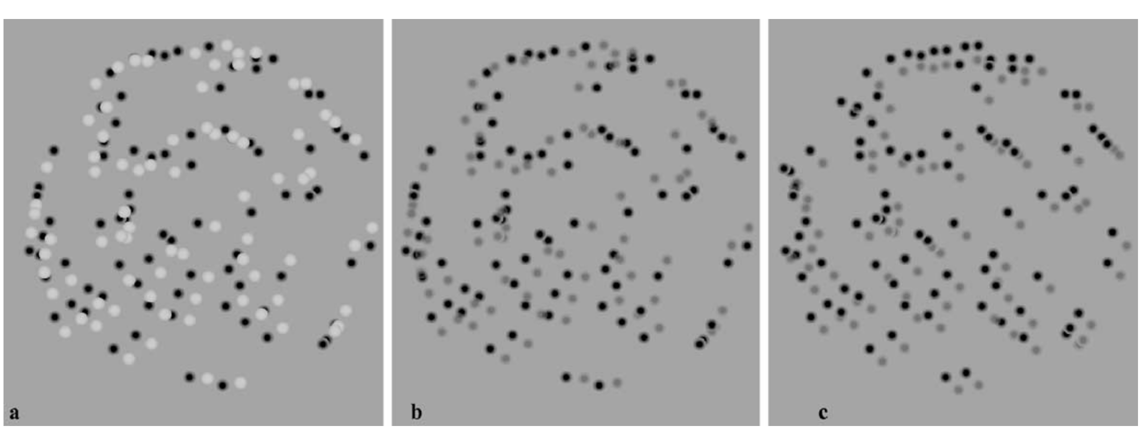

Fig. 2. Some examples of an 'intra-dipole' pattern manipulation. In (a) are opposite polarity intra-dipole elements for a rotational arrangement. In (b) is the same pattern as in (2a) with dipoles of the same polarity but with one member of the dipole reduced in contrast. In (c) is a translational arrangement of the dipole elements in (b).

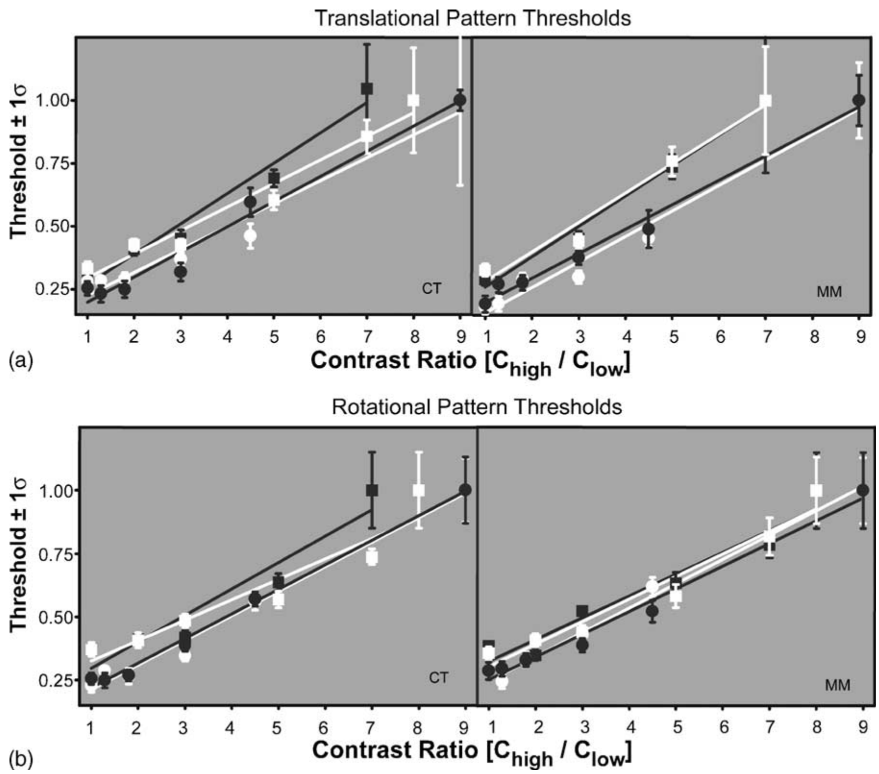

Fig. 3. Intra-dipole results. In (a) are translational pattern thresholds as a function of intra-dipole contrast ratio for two naïve observers. In (b) are rotational pattern thresholds as a function of intra-dipole contrast ratio for the same two naïve observers. Thresholds for patterns composed of luminance increments are shown in white and decrements in black. Reference contrasts of ±0.1 are displayed as squares (■) and reference contrasts of ±0.9 as circles (●). Solid lines are linear regressions. See text for additional details.

in white and luminance decrements in black. Low contrast (0.1) references are plotted as squares (■) and high contrast (0.9) references as circles (●). The error bars represent ±1 standard deviation. The linear regression lines demonstrate the approximate linearity of this relationship. Data from the same observers in Fig. 3b show an identical trend for rotational patterns with this local contrast manipulation.

These results address one of the primary questions we raised, whether local spatially-correlated luminance variations *of the same sign but differing contrasts* can in fact be integrated. The answer is that dots of differing contrast can be integrated to form a perceptual dipole, but this capability is degraded as the contrast ratio increases. At the most extreme differences (0.1 paired with 0.9), integration did not occur at all; even though thresholds for 0.1 paired with 0.1 and 0.9 paired with 0.9 were comparable. Large contrast differences of the same sign thus function like opposite-polarity contrasts (Glass & Switkes, 1976). Furthermore, this occurs similarly for both of the spatial configurations tested: translations were no different from rotations. We note that for observer CT (for rotations and translations) and MM (for translations), thresholds for the 0.1 contrast paired with 0.1 are, as one might expect, slightly higher than for the respective 0.9 paired with 0.9 contrast thresholds. However this is a small effect relative to the large increase in threshold as intra-dipole dot contrast increases. This is similar for both reference contrasts.

3.2. Experiment 2: global contrast variations

In a second series of experiments, we kept the contrast between members of the paired dots the same, but varied the contrast between dipole pairs. The intent here was to investigate the effect of contrast on mid-level integration and segregation. First, we examined how the perception of the pattern was influenced by the presence of randomly oriented dipoles of different contrast and polarity. In this case, the pattern to be detected was one in which half the dipoles were systematically arranged (i.e. contained a proportion of appropriately oriented dipoles). The remainder of the dot-pairs were orientationally-uncorrelated dipoles whose contrast was varied between runs. We refer to these sub-patterns as "signal" and "noise," respectively. In most cases, the signal dipoles were all at 0.9 contrast and the noise dipoles were of some other contrast that varied across conditions. In a forced choice procedure, observers discriminated these signal plus noise patterns from ones that contained only randomly oriented dipoles at the same two contrast levels. Thus, in this experiment we wanted to determine how additive noise of variable contrast and polarity affects the detection of a fixed signal (see Fig. 4). We examined five noise contrasts in each of two polarities for both translations and rotations.

Fig. 5a shows the results for *translational* patterns for three observers. On the abscissa are the inter-dipole contrast ratios and on the ordinate the estimated thresholds ±1 standard deviation. Solid black circles indicate thresholds where the signal and noise had the *same* polarity and white squares show thresholds where noise polarity was *opposite* to that of the signal. Interestingly, both luminance decrements and increments

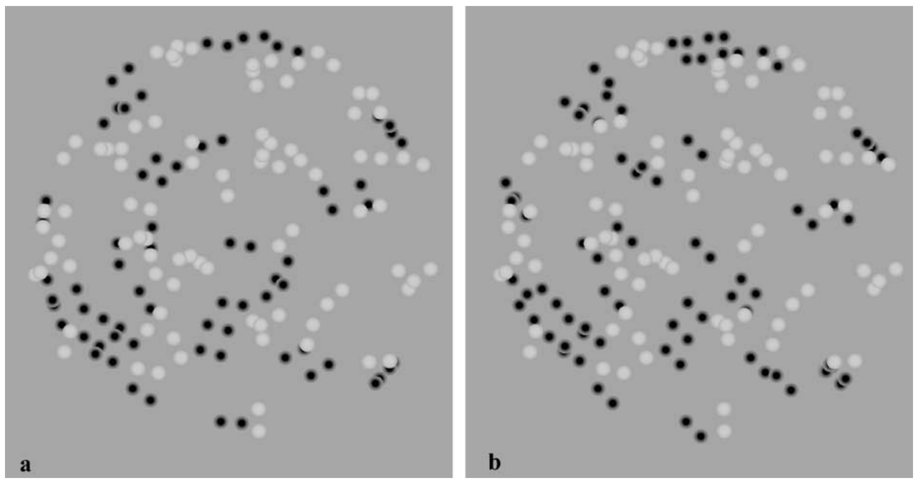

Fig. 4. Inter-dipole patterns. Some examples of 'signal' plus 'noise' inter-dipole patterns. In (a) is an opposite polarity 'noise' pattern (white) interlaced with a high correlation (1.0) 'signal' pattern (black) for a concentric Glass pattern. In (b) are the same 'noise' and 'signal' configuration for an oblique translational arrangement.

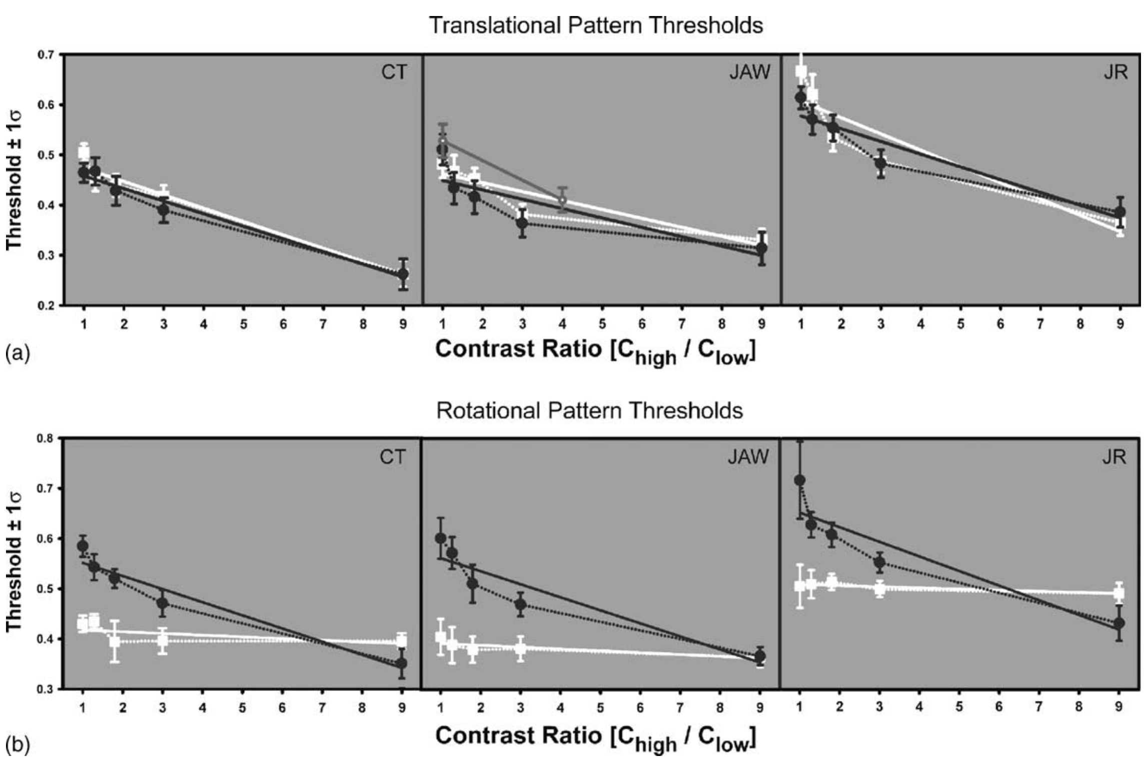

Fig. 5. Inter-dipole 'signal' plus 'noise' results for three observers. Estimated threshold is plotted as a function of inter-dipole contrast ratio. Black circles indicate thresholds where the signal and noise had the same polarity (both luminance decrements), white squares indicate thresholds in which signal and noise had opposite polarities ('signal' pattern decrements and 'noise' pattern increments). For most cases the contrast of the 'signal' component was 0.9 and that of the 'noise' component had lower magnitude. In (a) are the results from translational patterns. For observer JAW, we have included thresholds (grey open circles) where the signal contrast was low (0.25) and the noise contrast high (0.25 and 1.0). In (b) are thresholds for rotational patterns.

degrade performance. Furthermore, performance improves at the same rate (same slope), regardless of polarity, as noise contrast is decreased. For comparison to high-contrast signal and low contrast noise ratios, we have included (in the open grey circles), thresholds for observer JAW where the signal was low (0.25) contrast and the noise increased in contrast. In this case, the low/high contrast pairings are (0.25, 0.25) and (0.25, 1.0), and are of the same luminance polarity. These data show that the effect of inter-dipole noise on the detection of translations is primarily determined by the contrast *ratio* of signal and noise, rather than by the absolute contrast of either. This situation is similar to that observed for intra-dipole contrast variation.

Fig. 5b shows the results for *rotational* patterns for the same three observers as in Fig. 5a. In the case, where the signal and noise have the same polarity, rotational thresholds show a similar dependence on noise contrast as was the case for translational thresholds. That is, when signal and noise have similar contrasts, thresholds are high, but they decrease linearly with increasing contrast ratio. However, when the noise is of the *opposite polarity* as the signal, thresholds for rotational patterns show no dependence on noise contrast. Noise of opposite luminance polarity does *not* interfere at all with the detection of rotational Glass pattern structure.

Having shown that the ability of the visual system to *segregate* opposite polarity noise elements differs for rotational and translational configurations, we inquired whether *integration* of orientationally correlated dipoles (signal) would show the same effect. To test this, we used a stimulus similar to the one above, but in this case both half-density patterns (still of differing polarity) contained a similar fraction of correlated dipoles (see Fig. 6). In this case, a pattern contrast of 0.5 indicates that both decrements and increments were of 50% contrast. Fig. 7 shows the results for two observers (CT and JAW) at three contrast levels for interleaved opposite polarity patterns and one contrast level (50%) for a single half-density pattern. For both translational and rotational patterns, correlated patterns containing differing polarities have similar thresholds relative to analogous patterns containing only one polarity (viz: similarity of bar heights and dashed line). We also measured the correlation thresholds for rotational and translational pattern of uniform dot contrast (0.5) but with dot density one-half that of our other experiments (i.e. the density of each sub-pattern). For the parameters in our experiment, we find, as did Wilson and Wilkinson (1998, their figure 5), that thresholds for rotational Glass patterns of a single contrast and polarity are more sensitive to dot-density than are those for translational patterns (viz: Fig. 7a–b, half density versus dashed line). This is consistent with the interpretation that areal integration is smaller for translational than for rotational patterns (see Section 4).

The most provocative result of experiment 2, the differing ability to segregate circular versus translational patterns from opposite polarity noise, motivated us to repeat the "signal" plus "noise" tests for two additional classes of Glass patterns: radially oriented dot-pairs and hyperbolically arranged dot-pairs. In all cases dot separation within a pair was fixed at 0.37°. Data were collected for luminance-decrement "signal" patterns at 90% contrast combined with both luminance- decrement and luminance-increment "noise" patterns at contrasts of 10%, 50%, and 90%.

Data in Fig. 8 indicate that: (i) decremental (same polarity) noise has the expected effect of increasing thresholds with increasing noise contrast for all four pattern types (although thresholds for detection of radial and hyperbolic correlations are somewhat higher

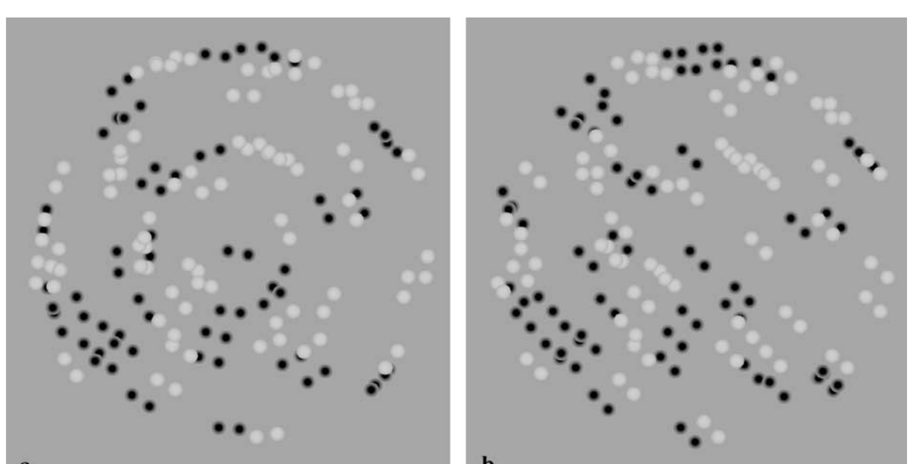

Fig. 6. Inter-dipole 'signal' plus 'signal' mixed patterns. Examples of the types of patterns used to examine integration of opposite polarities in the second variation of Experiment 2. In (a) is a rotational pattern composed of half-density patterns each of which has all dipoles in proper orientations (1.0 correlation). In (b) are the same pattern elements in a translational arrangement.

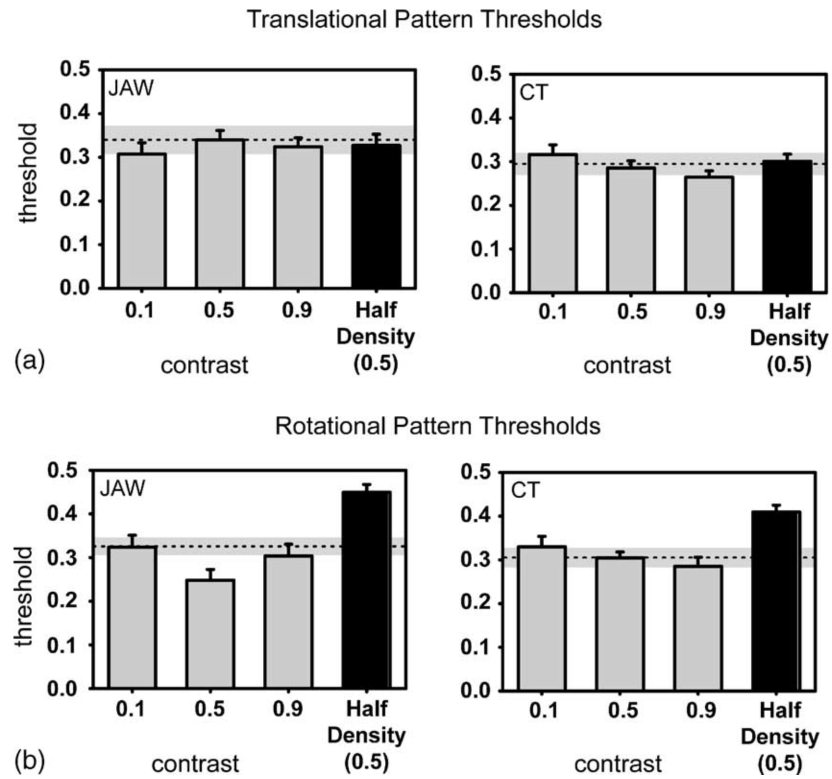

Fig. 7. Results for interleaved 'signal' plus 'signal' patterns. The two component patterns have opposite polarities; data is shown for two observers. (a) Translational pattern thresholds. In (b) are rotational pattern thresholds. Both panels also include thresholds for one half-density pattern where all dot elements had a contrast of 0.5. For comparison to full density patterns of same polarity, the dashed line represents the mean threshold for each observer from Fig. 3 for conditions where both dots had the same contrast; the surrounding grey area is the SD of the mean.

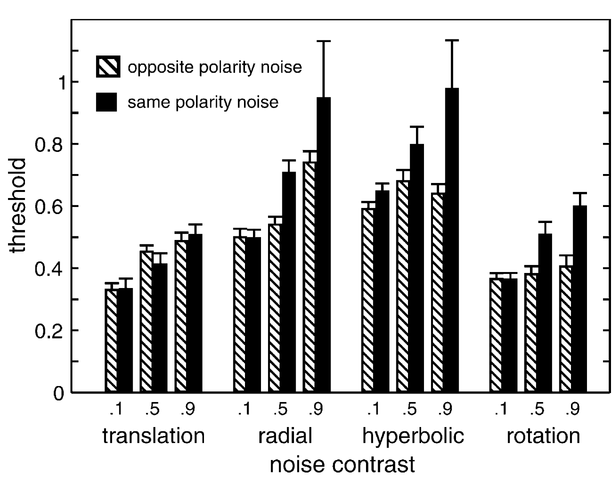

Fig. 8. Comparison of the effects of same and opposite polarity noise on detection of correlations in translational, rotational, hyperbolic, and radial Glass patterns. Stimuli are 'signal' (luminance decrement, 90% contrast) plus 'noise' patterns of specified contrasts: black bars, 'signal' plus luminance decrement 'noise'; striped bars, 'signal' plus luminance increment 'noise'.

than those for rotational and translational correlations); (ii) for hyperbolic correlations an opposite polarity noise component (luminance-increment) has little effect on pattern detection at any noise contrast; and (iii) for radially correlated dot-pairs, opposite polarity noise increases detection thresholds as noise contrast increases, but to a lesser degree than with same polarity noise. Thus the effect of inter-pair contrast variation is similar for hyperbolic and rotational correlations while the results for radial correlations are intermediate to those observed for rotations and translations.

4. Discussion

4.1. General results

The major aims of this study were to investigate the ability of the visual system to integrate elements of differing contrast at both the early- and mid-levels of processing. By utilizing both translational and rotational Glass patterns, we compared how these abilities might differ in detection tasks which may require differing extents of areal integration (Wilson & Wilkinson, 1998). The surprising effects of opposite polarity contrast in mid-level processing were further probed using radial and hyperbolic Glass patterns.

In Experiment 1, we examined local integration processes: how do contrast differences affect the detection of oriented elements in a Glass pattern? We showed that elements of greatly differing contrasts are not grouped into basic oriented-feature elements, and as a result they cannot support pattern detection. The effect depends on the ratio of the intra-dipole contrasts rather than on the absolute contrast of either member of the dot-pair. Furthermore, this contrast dependence was found with both translational and rotational patterns.

In Experiment 2, we studied the global processes by which oriented elements are, or are not, grouped into the percept of an overall rotational or translational pattern. We found that contrast differences play quite a different role here. The global process of parsing the visual world into objects can be thought of as having two interrelated aspects: that of integrating some stimuli (signal) to form a global percept, and that of segregating those stimuli from others. When the signal and noise have the same contrast polarity, noise of the same contrast as the signal was found to interfere with pattern detection, with the effectiveness of this noise masking decreasing as the contrasts of the signal and noise increasingly differed. This was true for all four pattern types used in these experiments. However, when signal and noise patterns differed in polarity, we found that the opposite polarity noise reduced detectability of translational patterns (with the effect decreasing with increasing difference in signal and noise contrasts) but was ineffective at all contrasts examined for concentric and hyperbolic patterns. For radial patterns, opposite polarity noise reduced detectability but to a lesser extent than for translational ones.

4.2. Local processing

The first stage of visual processing concerned with Glass pattern detection involves integrating individual dot-pairs, which for our intra-dipole variations had differing contrasts, into an oriented element. There has been some discussion in the Glass pattern literature as to whether token matching or 'energy' is involved in this initial local grouping into dipole elements (Dakin, 1997; Earle, 1999; Prazdny, 1984; Stevens, 1978). However, linear energy models are insufficient to explain the properties of cortical simple cells, which show such non-linearities such as thresholding, compression, and saturation. Such non-linearities need to be incorporated in any model of how local elements differing in contrast are integrated into dipoles. In developing a model to explain the observed dependence of correlation thresholds on the ratio (rather than on absolute levels) of dot contrasts, we consider two aspects: (i) how does the response of a local orientation-specific filter vary with intra-dipole dot contrast? and (ii) what are the relative responses of filters tuned to differing orientations (i.e. does one orientation 'stand out' when compared to others)? With regard to the first issue, our results are consistent with physiological data (Albrecht & Hamilton, 1982; Ohzawa, Sclar, & Freeman, 1985) which show that V1 neurons have a form of contrast normalization which has been incorporated into models with promising results (Heeger, 1992). This mechanism is referred to as *contrast gain control*, and has not been addressed in previous discussions of Glass patterns and intra-dipole grouping. Such a mechanism would explain why increasing the 'energy' of one dot within a dipole would not necessarily lead to a greater response in a local orientation detector (with a resulting increase in pattern detection). Linear models predict that an intra-dipole contrast pairing of 0.9 and 0.1 would yield significantly larger responses than for a 0.1 and 0.1 pairing, while our data show that pattern detection is more facile with the latter pair. On the other hand, divisive normalization, even local normalization occurring over a small subsample of overlapping cells, yields similar absolute responses for these pairs (see Fig. 9 and model described below).

The second issue (of one orientation of filter standing out with respect to others) is addressed by modeling a comparison of the responses of filters at various orientations as a function of the relative contrast of the dots. We implemented a simple divisive normalization model developed by Vinje and Gallant (1998). The stimulus pattern was a single dipole oriented at 0°. The filters had spatial parameters which matched those of the stimulus and were oriented at 0°, 45°, 90°, and 135°. The centers of the modeled receptive fields tiled the region including and surrounding the dot-pair. The Vinje and Gallant gain-field contrast weighting was chosen to maintain roughly equal average activity for the various combinations of intra-dipole contrasts. We applied the model to dot-pair contrast combinations similar to those reported in Fig. 2. Fig. 9a–c shows histograms that represent the total output power for the mechanisms at the respective orientations and illustrates how this model correlates with our experimental observations. When the dots within a pair are of similar contrast, filters at the preferred orientation show much greater activity than do filters at other orientations; as the ratio of the within-dipole contrast increases, the level of activation of filters at various orientations is more uniform and thus a preferred orientation becomes detectable. These model data are similar to our experimental data with reference contrasts of 0.1 and 0.9. A statistical measure (Fig. 9d), expressed as the asymptotic P-value approximation of the output (0° output/sum of all other orientations), shows decreases in probability of determining the orientation of the dipole with increasing difference in contrast *ratio*, independent of absolute contrast value. Similar decreases in sensitivity have also been experimentally observed when the contrast between elements of a vernier acuity, two-frame motion, and stereopsis task are different (Stevenson & Cormack, 2000), although the authors note that divisive normalization alone fails to adequately describe their data.

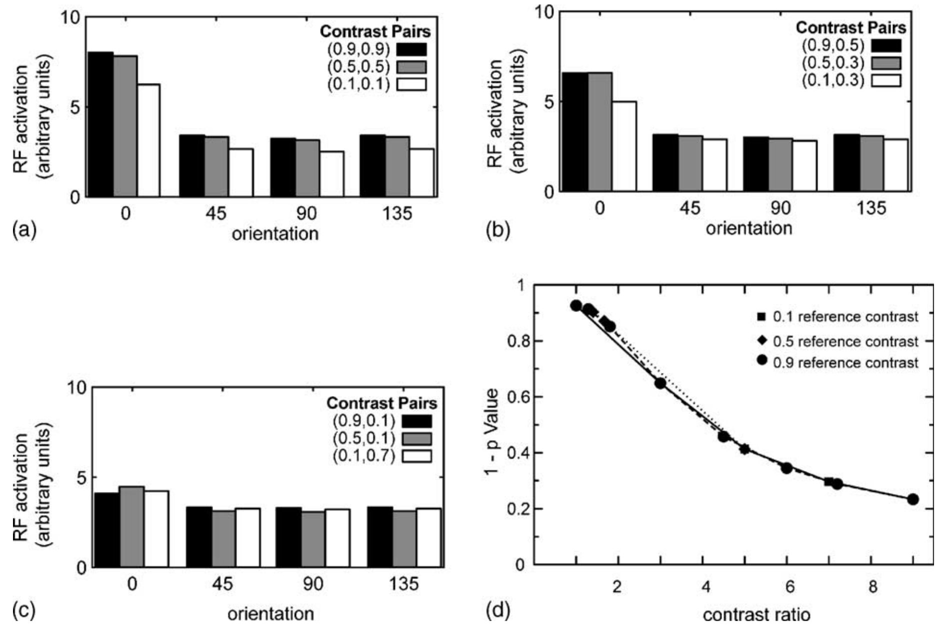

Fig. 9. Simulation using Vinje–Gallant model: Activation of V1-type receptive fields by a dipole oriented at 0°, having elements of differing contrast. Histograms (a)–(c) show the total activation of units tuned to 0°, 45°, 90°, 135° with various contrast combinations for the dot elements: (a) low, unit, contrast ratios of 1 : (0.9,0.9), (0.5,0.5), and (0.1,0.1); (b) intermediate contrast ratios 1.4 (0.9,0.5), 1.7 (0.5,0.3), and 3 (0.1,0.3); (c) high contrast ratio 9 (0.9,0.1), 5 (0.1,0.5), and 7 (0.1,0.7); (d) is the probability, $(1 - p)$, of properly detecting 0° relative to the pooled response of all other orientations as a function of the contrast ratio of the component dots.

The ability of such a "front-end filter" model to rationalize the results of our intra-dipole contrast variation experiments speaks to the possibility that the local orientation signature used in detecting Glass pattern correlations could be coded strictly in terms of the properties of V1 units. However our analysis does not preclude the applicability of more cognitive "token matching" strategies as an additional mode for identifying the paired elements, especially when the elements have more complex structural features than the tapered dots used in our studies.

4.3. Global processing

In Experiment 2 we wanted to determine the extent to which the integration of local oriented elements, and their segregation from other elements, is influenced by contrast differences among the elements. The contrast variation within natural scenes is high (Brady & Field, 2000). Much of this high variance arises from between objects contrast and especially from the effects of occlusion (Balboa & Grzywacz, 2000). Regions where contrast changes abruptly tend to indicate the presence of a border; thus low-contrast elements should be segregated from same-sign high-contrast elements. Although Balboa and Grzywacz (2000) do not address the question explicitly, their study suggests that the early- and mid-levels of the visual system should be concerned with segregating the differing contrasts that represent two objects even if they are the same sign. In addition, distinct objects are often of opposite contrast with respect to the background (Field et al., 2000), providing a salient cue for segregation. Thus, luminance sign changes, like large contrast differences, should also serve to indicate object borders.

Based on these ideas, we expected that our opposite-polarity noise manipulation would *not* degrade performance while same-polarity, similar contrast noise would degrade performance, irrespective of pattern configuration. Our results of Experiment 2 indicate that this is indeed the case for rotational and hyperbolic patterns. The detection of translational patterns, on the other hand, was degraded by opposite-polarity as well as by same-polarity noise. We propose that this may be due to differences in the degree of areal integration employed in resolving the various types of correlations.

For translational patterns, an observer with prior information about pattern orientation can discern signal from noise on the basis of the orientations of individual dot-pairs; furthermore the signal orientation is independent of the position of the dipole within the pattern. However for concentric or hyperbolic patterns that have curved contours, information about form is contained only in the relationships among several dipoles. We therefore postulate that the extent of spatial sampling required for integration of two classes of patterns differs, a suggestion that has also been made by earlier investigators (Wilson & Wilkinson, 1998).

The results from Experiment 2 show that reducing the contrast of the noise dipoles with respect to the signal decreases thresholds for all pattern types: translations, rotations, radial, and hyperbolic. This result is not unexpected, given that a reduction in contrast of the noise is similar to reduction of explicit external noise, which reduces thresholds in numerous paradigms. However we also show that signal can be partially segregated from noise even when the noise is of higher contrast than the signal (Fig. 5a, JAW). For translations the reduction in threshold is not dependent on the contrast polarity of the noise, an effect consistent with a model in which all oriented elements contribute individually to determining detection thresholds. Since interactions between elements are not necessary to resolve the pattern, segregation based on contrast polarity does not occur. We thus propose that the reason rotational and hyperbolic thresholds are immune to opposite polarity noise is that comparison among a number of dipoles must occur prior to the determination of global pattern structure (these ideas are similar to those articulated by Wilson & Wilkinson (1998)). The visual system accomplishes this intermediate grouping utilizing information about the relationship among dipoles of similar polarity, ignoring noise of opposite contrast.

Although not completely resolving the issue of integration of opposite polarity signals, the results of Experiment 2b (Fig. 7), in which oriented dipoles of both polarities contribute to pattern detection, are consistent with the interpretation above. Translational pattern thresholds give results which appear to indicate that mechanisms responsible for integrating translational elements are not polarity selective. The case for rotational patterns is not as clear. Thresholds for interleaved dipoles of mixed polarities, in which both polarities are signal, are similar to thresholds for a single polarity and are lower than would be observed for either polarity alone (i.e. the half-density threshold). Although this might be taken to indicate integrated processing of signal dipoles irrespective of polarity, it is also consistent with individual processing of each sub-pattern polarity. The lower threshold relative to the half density pattern could result from probability summation, arising from individual detection of each sub-pattern polarity. No such decrease in thresholds (relative to half-density) is observed for translational patterns, consistent with the purported individuality of dipoles of the two polarities in the detection process.

To further examine the idea that detection of rotational patterns requires greater global processing than detection of translational ones, we calculated how differing spatial sample sizes might affect the an observer's ability to detect a correlated pattern versus a noise pattern. For dot-pairs within a series of spatial sampling windows varying from 2^2 to 32^2 pixels in size, two strategies were applied to detection of each type of pattern correlation: (i) comparison of the *absolute orientation* of individual dot-pairs within the window to an expected set of orientations in a fully correlated version of the pattern type; and (ii) comparison of the *relative slopes* of dot-pairs within the window to expected relative slopes.

Expected dipole orientation generally requires that the observer evaluate the position of the dot-pair relative to the origin of the pattern. Since exact estimation of spatial position cannot be expected of a psychophysical observer, an uncertainty in absolute position of the patch (but not the relative positions of the dipoles within the patch) was included in the simulations (see Appendix A for details of the algorithms). With moderate (15%) positional uncertainty, the *absolute orientation strategy* fails completely for all patterns except translations. However, with this same positional uncertainty, the *relative slope strategy* yields reasonable detection for all pattern types. Thus we suggest that translational Glass patterns can be most effectively detected on the basis of the orientation of individual dipoles while detection of rotational (and hyperbolic) correlations requires comparison of the orientations of nearby dipoles.

In Fig. 10 simulations of a forced-choice procedure (i.e. selecting which of a pair of sampled 'signal' and 'noise' patches has statistical properties closer to that expected for fully aligned dot-pairs) are presented for

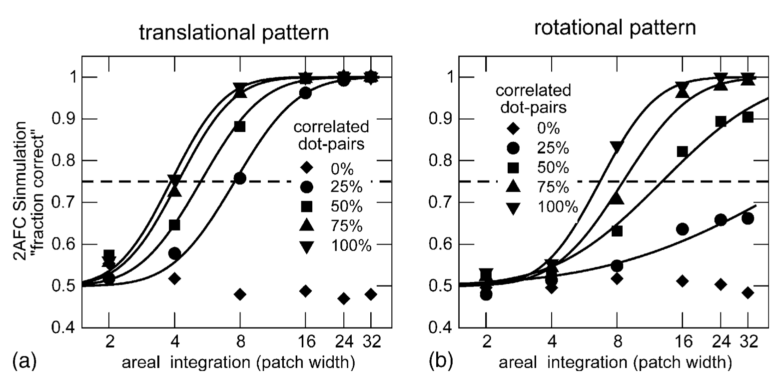

Fig. 10. Results of simulation of pattern detection as a function of correlation and of areal integration. Results for (a) translational patterns based on *absolute orientation* statistics of dot-pairs and (b) rotational patterns based on relative *slope statistics* of dot-pairs, after 500 simulations. See text for details.

translations and rotations. The dashed lines indicates the threshold (75% correct) level for the simulations. For translations (Fig. 10a), simulations based on the *absolute orientation strategy* indicate that the areal integration required to reach threshold varies from an area of 7.6^2 for patterns with low (0.25) correlations to 3.8^2 for patterns with all dot-pairs aligned (1.0 correlation). Our analysis of rotational patterns, based on the *relative slopes* of nearby dot-pairs (Fig. 10b), produced markedly different results. At low correlations (0.25) threshold is not reached even with large 32^2 samples. Patch sizes required for threshold vary between 12.4^2 and 6.7^2 for correlations from 0.5 to 1.0. Simulations for hyperbolic Glass patterns based on the *relative slope* strategy gave similar results [patch sizes of $(12.8 \pm 1.2)^2$ and $(6.04 \pm 0.5)^2$ at correlations of 0.5 and 1.0].

These results demonstrate that locally-sampled translational patterns of intermediate to high signal correlation contain sufficient information to reliably discriminate signal patterns from noise patterns. Rotational (and hyperbolic, not shown) patterns, on the other hand, require comparisons among dot-pairs and a more extensive sample size. Such a differing dependence of detectability on sampling area for rotations and translations was empirically demonstrated by Wilson and Wilkinson (1998).

We believe these results help to explain why rotational (and hyperbolic) patterns are immune to opposite polarity noise. In integrating information about the concentric relationship of dipoles, the visual system must take numerous samples and compare the orientations of local features to discern whether a concentric global relationship among pattern elements exists. Such an integration presumably occurs among dipoles of like polarity at a mid-level, where resolution of form is likely to occur. Opposite polarity information, lacking in structure, is treated separately and relegated to the background. However, translational patterns are sufficiently described by the absolute orientations of a small number of dot-pairs and as a result only local sampling is necessary. With such local sampling, the orientation of a dipole, and thus its possible contribution to a translational pattern, does not require comparison with nearby dipoles. Thus, local sampling makes translational integration prone to noise of both polarities.

5. Conclusions

Results of Experiment 1 show that the ability to resolve the orientations of local dipoles depends on the ratio of the contrasts of the individual elements. Application of a model, based on the relative responses of oriented filters exhibiting gain control, indicates that simple V1 mechanisms, rather than symbolic matching (Stevens, 1978; Earle, 1999) or 'energy' (Prazdny, 1984), could be responsible for the advantage of "contrast-paired dots" in the ease of detecting correlations among local orientations. In addition, local integration is not dependent on the global arrangement of dipole elements, thresholds for translations and rotations showing similar effects. This is consistent with the idea that similar detection of individual oriented features occurs in each case. Results of Experiment 2 show that *both* translation and rotation thresholds are affected by same-polarity noise while only translation thresholds are adversely affected by opposite-polarity noise. These results are consistent with our computer simulations which show how this effect could be explained by spatial sampling. Spatial sampling must be larger for more complicated patterns, implying that mid-level mechanisms, which presumably use contrast similarity to segregate figure-from-ground, are primarily concerned with more global arrangements.. This interpretation was confirmed by the absence of masking by opposite polarity noise in hyperbolic Glass patterns.

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Appendix A

A.1. The pattern analysis algorithm

Glass patterns, of size 64×64 and dipole density 0.25, were dynamically generated for all of these simulations. We selected 5 correlation levels for examination (0.0, 0.25, 0.5, 0.75, and 1.0). Inasmuch as we were concerned with the joint orientation-spatial statistics of the patterns, rather than the problem of isolating correlated dots (Stevens, 1978), all of our examinations were conducted with vectors described by a location (x, y) and orientation (θ). In individual comparisons spatial samples were constrained to the same localized region of the 'signal' (variable correlation) and 'noise' (correlation = 0.0) patterns. Patches varied in size for differing presentations (2^2, 4^2, 8^2, 16^2, 24^2, and 32^2) and the position of the patch within the 64×64 pattern was randomly selected for each presentation.

For each presentation, statistics for the orientation of dot-pairs from the simulated 'signal' and 'noise' test patches were compared to those for a reference patch containing 100% correlated dot-pairs. A decision was made on the basis of the relative similarity (see below) of each test patch to the reference patch. To mimic our forced-choice psychophysical experiments, a small random noise component was introduced and served to settle the frequent statistical 'ties' in similarity to the reference that may occur for small patch sizes. The calculations were based on precise knowledge of the relative position of the dot-pairs within the patch, but an uncertainty in the absolute position of the patch relative to the center of the pattern was introduced (the results in Fig. 10 correspond to an average uncertainty of 15% in the absolute position of the patch). In the simulation, the patch chosen as "signal" was the one whose probability distribution function (pdf) had a smaller Euclidean distance (was more similar) to the reference pdf. The data of Fig. 10 represent 500 comparisons for each condition.

Two strategies were used to compare the local orientation statistics of the patches. In the first instance, the difference between the *absolute orientation* of each dipole and the expected orientation of a properly aligned dipole (calculated on the basis of pattern type and the 'noisy' estimate of the absolute position of the patch) were collected in bins of 10° width. The reference pdf (perfect correlation) consists of a 1 in the 0°–10° bin and 0's elsewhere. The data and estimated probit curves calculated for translations are shown in Fig. 10a. Using similar simulation parameters, this strategy was unable to yield thresholds (reach the 75% correct level) for concentric, hyperbolic, or radial Glass patterns (a result arising from the effect of positional uncertainty in estimating the expected dipole orientation for these pattern types).

A second detection strategy employed the *relative slope* of nearby dipoles (i.e. local curvature). Here the difference in orientation of pairs of dipoles was compared to expected orientation change (calculated on the basis of pattern type, the relative position of the dipoles, and the same noisy estimate of absolute position of the patch used in the first strategy). The pdf entry for each pair was inversely weighted by the distance between the dipoles. Again, uncertainty was introduced into the estimate of the absolute position of the patch (average uncertainty 15%) and the reference pdf contained a 1 in the 0° −10° bin and 0's elsewhere (i.e. all relative angles exactly as expected with no positional uncertainty). The data for concentric correlations calculated using *relative slopes* are presented in Fig. 10b. Simulated detection of hyperbolic and radial correlations (not shown) had a similar dependence on areal integration. Applying this *relative slope strategy* to translational correlations gave somewhat smaller threshold integration areas for detection [19.0^2, 10.0^2, and 6.0^2 pixels at 0.25, 0.5, and 1.0 correlations]. However these were less efficient than the areal integrations found for translations using the *absolute orientation* strategy (Fig. 10a).

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