Local and global visual grouping: Tuning for spatial frequency and contrast

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Glass patterns are visual textures composed of a field of dot pairs (dipoles) whose orientations are determined by a simple geometrical transformation, such as a rotation. Detection of structure in these patterns requires the observer to perform local grouping (to find dipoles) and global grouping to combine their orientations into a percept of overall shape. We estimated the spatial frequency tuning of these grouping processes by measuring signal-to-noise detection thresholds for Glass patterns composed of spatially narrow-band elements. Local tuning was probed by varying the spatial frequency difference between the two elements comprising each dipole. Global tuning was estimated using dipoles containing one spatial frequency and then estimating masking as a function of the spatial frequency of randomly positioned noise elements. We report that the tuning of local grouping is band-pass (ie, it is responsive to a narrow range of spatial frequencies), but that tuning of global grouping is broad and low-pass (ie, it integrates across a broader range of lower spatial frequencies). Control experiments examined how the contrast and visibility of elements might contribute to these findings. Local grouping proved to be more resistant to local contrast variation than global grouping. We conclude that local grouping is consistent with the use of simple-oriented filtering mechanisms. Global grouping seems to depend more on the visibility of elements that can be affected by both spatial frequency and contrast.

Keywords: texture, form, Glass patterns, spatial frequency

Introduction

Visual grouping refers to the process of revealing structure in images by selectively associating local features with one another. It serves a computational role in reducing the redundancy of our descriptions of the world (Watt, 1988). For example, if one encounters a swarm of bees, it is computationally more efficient to compute ones position relative to a (single) cloud of insects, than to first estimate one's position relative to each bee, and then average these distances. The latter offers no functional advantage over the former, assuming one's goal is simply to avoid the collective.

Over the last 30 years, Glass patterns (Glass, 1969) have been used extensively to probe grouping mechanisms in human vision. These patterns were originally generated by splattering paint over a silk screen and then making a composite image of the resulting random-dot pattern and a transformed (eg, rotated) version of it. Although the technique used to generate these patterns is now different, the impression gained from inspecting them is similar: compelling orientation structure corresponding to the generative transformation (eg, rotation in Figure 1a). Glass patterns have remained of theoretical interest because our ability to see structure in them indicates that we are grouping members of the same dipole, and then combining those local groupings into a global impression of overall (eg, circular) structure. These two types of associations are referred to as local and global grouping, respectively.

The local grouping processes underlying Glass patterns have been the focus of a number of previous studies. For high-density patterns, it is difficult to group dipole members together simply because each dot/element will tend to have a large number of elements closer to it than its dipole correspondent (Stevens, 1978). A variety of psychophysical data support the idea that local structure is being derived not by specialized "token" matchers (Stevens, 1978; Stevens & Brookes, 1978; Marr, 1982), but from the output of linear spatial filters (Zucker, 1985; Prazdny, 1986; Dakin, 1997a,b; Dakin 1999). The simplest demonstration of this is that our ability to see veridical structure in these patterns is dependent on dipole elements being the same contrast polarity (Figure 1). Given that any positional tokens are unaltered between Figures 1a and 1b, our inability to see circular structure in Figure 1b is likely to be because a pair of opposite contrast-polarity features do not collectively stimulate the same subregion of a filter.

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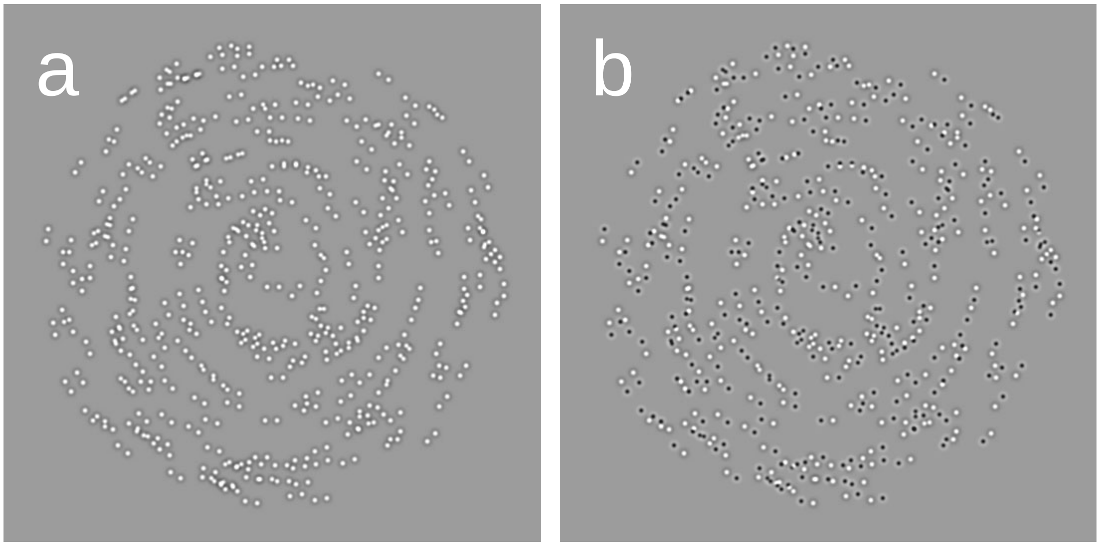

Figure 1. A rotational Glass pattern formed from spatially narrow-band, isotropic Laplacian-of-Gaussian elements (a). The same pattern where one element from each dot-pair has been contrast reversed (b); the perceived rotational structure is generally reported as weaker.

Furthermore, filtering mechanisms predict that local anti-correlation of luminance structure, introduced by contrast-polarity inversion, will introduce perceptual structure orthogonal to the true transformation (Dakin, 1997b). This is consistent with observers' reports of the presence of a "petal-like" radial structure in these patterns.

There is indirect evidence that the filtering operations underlying local grouping are tuned to a narrow range of spatial frequencies. Oriented structure in Glass patterns (composed of dots) is contained within a relatively narrow range of spatial frequencies, so that a broadly spatially tuned filter would be swamped by noise from adjacent frequency bands (Dakin, 1997a). Indeed, observers' precision at judging the orientation of translational Glass patterns is consistent with these local filtering operations being selective for both local orientation and local spatial frequency (Dakin, 1997a).

A smaller amount of research has examined how local orientation estimates are combined in Glass patterns to form the global percept of structure. Wilson and coworkers (Wilson, Wilkinson, & Asaad, 1997; Wilson & Wilkinson, 1998) have reported that a subject's ability to see structure in high-density Glass patterns depends to a great extent on the type of global organization. Specifically, they found that signal-to-noise detection thresholds are lowest for circular, and highest for 90° translational, Glass patterns. These authors interpret their findings as evidence for a contribution to the detection of rotational structure from cells in cortical area V4 that have been shown, in the macaque, to be sensitive to circular structure (Gallant, Braun, & Van Essen, 1993). Poor performance with translational patterns is attributed to a lack of global integrators for translational structure, so that subjects have to rely on local grouping mechanisms, which integrate over smaller regions of space. Recently, however, we questioned the generality of the results by Wilson et al by demonstrating that this "circular advantage" seems to be at least partially contingent on the stimulus window being round (Dakin & Bex, in press). We have suggested that the "rotational advantage" could be attributable to the presence of edge artefacts caused by the presence of unmatched elements at the edge of translational, but not rotational, patterns. Contrary to Wilson et al, we also reported broadly similar integration performance for rotations and translations, the latter of which are supposedly subserved by grouping mechanisms operating over a more limited locale. Equal performance of the majority of our subjects at detecting rotational and translational structure does not serve to delineate the operation of local and global grouping mechanisms.

Spatial frequency tuning for texture segmentation is known to be band-pass (Kingdom & Keeble, 2000), but no previous studies have examined spatial frequency tuning of global grouping processes in Glass patterns. However, because it seems reasonable to suppose that the perception of structure in Glass patterns involves the detection of extended contourlike structure, evidence that pertains to the grouping processes underlying contour detection may be relevant. The paradigm for examining contour detection developed by Field, Hayes, and Hess (1993) involves the detection of a string of discrete oriented patches, whose orientations and positions are consistent with the presence of a contour, embedded in a field of randomly oriented distractor elements. Using this task, it has been established that the global grouping mechanism responsible for contour linking is tuned for local orientation (Field et al, 1993), but not for the local contrast (Hess, Dakin, & Field, 1998) and only weakly for the local phase of elements (Field, Hayes, & Hess, 2000). Dakin and Hess, (1998) estimated the spatial-frequency tuning of the contour linking process by measuring the disruptive effect of switching between two spatial frequencies along alternate elements of the path. This study showed contour linking to be spatially band-pass in its sensitivity with the bandwidth showing an inverse dependence on the curvature of the contour. Detection of straight contours is less sensitive to local spatial frequency variation than the detection of curved contours.

The purpose of this paper is to estimate the spatial frequency tuning of local and global grouping processes in the perception of Glass pattern structure.

General Methods

Equipment

Stimuli were generated on an Apple Macintosh G3 computer, fitted with a Mac Picasso 850 graphics card (VillageTronic Ltd, Hanover, Germany), and presented on a 19-inch Sony Multiscan 400PS colour monitor. The screen had a resolution of 1280 × 1024 pixels and the vertical blanking rate was 85 Hz. Stimuli were displayed with pseudo 12-bit contrast accuracy (ie, 256 grey levels could be displayed from a possible range of 4096), which was achieved by electronically combining the RGB outputs from the graphics card using a video attenuator (Pelli and Zhang, 1991). A monochrome signal was generated by amplifying and sending the same attenuated signal to all three guns. The output luminance was linearized using a look-up table. The programs for running the experiment were written in the Matlab environment (MathWorks Inc., Natick, MA) using code from the Psychophysics Toolbox (Brainard, 1997) and the Videotoolbox (Pelli, 1997) packages. The screen was viewed binocularly at a distance of 147 cm, so that 1 pixel on the screen subtended 0.57 arcmin^2. The display had a background luminance of 48 d/m^2.

Subjects

The authors served as subjects in the experiments. Both are experienced psychophysical subjects with considerable experience at this and similar tasks. S.C.D. is a corrected myope.

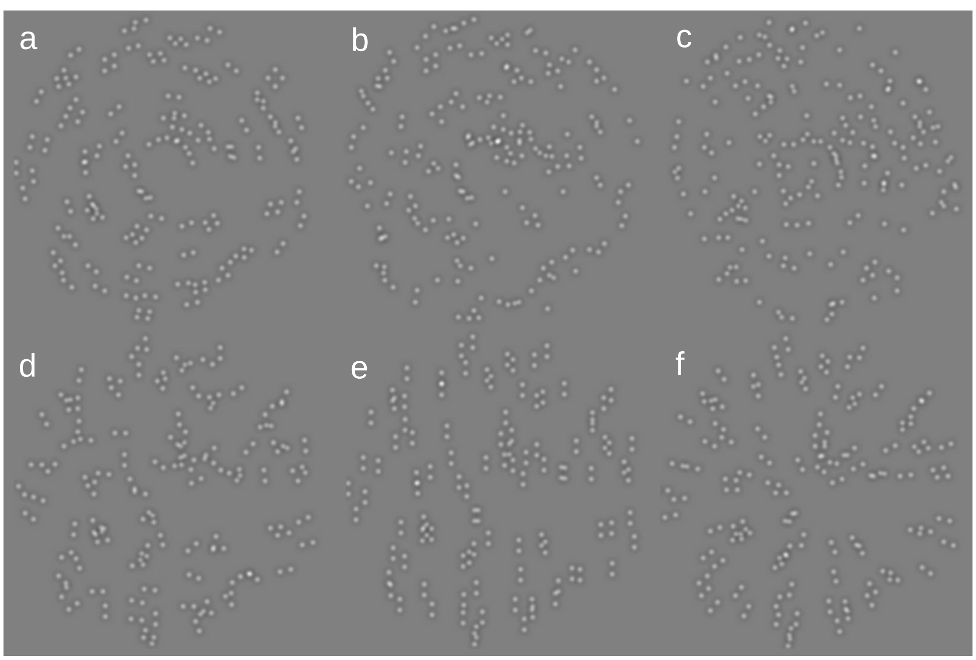

Figure 2. Examples of the stimuli used. Rotational Glass pattern containing 100% (a), 50% (b), and 25% (c) signal dots; the remainder of elements have been randomly positioned. Subjects perform a discrimination between structured patterns, such as “a,” and random patterns, such as “d,” to determine the minimum proportion of structured dipoles that supports discrimination. Experiments were performed with three global organizations: rotations (a), 90° translations (e), and expansions (f). Note that these global transformations are used to determine only the orientation of dipoles. Dipole length is constant throughout the pattern (whereas a true rotation, for example, would lead to elements being closer to one another at the stimulus center).

Stimuli

Stimuli were 512 pixel (24.0 degrees) square images containing a texture composed of a mixture of element-pairs and randomly positioned elements. All elements were two-dimensional Laplacian-of-Gaussians:

$$\nabla^2 G(x,y,\sigma) = \left(1 - \frac{x^2+y^2}{2\sigma^2}\right) e^{-(x^2+y^2)/2\sigma^2}$$

Elements were pregenerated, stored within a region of size ±4σ at floating-point accuracy, and presented at 50% contrast. Overlaps were added, and values producing overflow were clipped at the maximum displayable grey level. All Glass patterns contained exactly 200 elements. Dipoles were constrained to fall in a circular region with radius 10.0°. Elements falling outside the circular region were not plotted. Three transformations were used to generate dipole orientations: rotations, vertical translations, and expansions (examples of each are shown in Figure 2a, 2e, and 2f, respectively). Note that the transformations were used to generate only dipole orientation and not length; dipole elements were separated (center-to-center) by a constant distance of 48 arcmin for all pattern organizations.

Procedure

Subjects performed a two-interval, two-alternative forced-choice task. Two patterns were presented sequentially, each for 145 milliseconds, separated by a 500-millisecond interstimulus interval (ISI). One interval contained a Glass pattern, the other a noise texture, and the subject indicated which interval contained the Glass pattern. The independent variable was the proportion of correctly oriented dipoles in the Glass pattern (the signal-to-noise ratio), where the remaining dots were randomly positioned. Examples of various mixtures of signal and noise elements are shown in Figure 2a-2c. The noise interval contained a stimulus composed of randomly oriented dipoles (interspersed with the same proportion of randomly oriented position elements; Figure 2d shows a pattern composed exclusively of randomly oriented dipoles). QUEST (Watson & Pelli, 1983), an adaptive psychophysical method, sampled a range of signal-to-noise ratios and attempted to converge on the ratio of signal-to-noise dots that elicited 83% correct performance. Runs consisted of blocks of 45 trials and at least three runs were undertaken for each data point plotted. Runs were not interleaved; subjects always knew for which organization they were looking. Data were pooled across all runs performed with a particular stimulus configuration; error bars show the estimated SE.

Table 1. Stimulus parameters for the 13 interleaved conditions comprising each experiment

	Local conditions					*Global conditions*				*Control conditions*			
	1	2	3	4	5	6	7	8	9	10	11	12	13
N_s	200	200	200	200	200	100	100	100	100	100	100	100	100
N_m	0	0	0	0	0	100	100	100	100	100	100	100	100
Settings for spatial-frequency varying experiments (Experiments 1 and 2; reference sf = 2.0 c/deg)													
Sf_{s1}	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.0	1.4	2.8	4.0
Sf_{s2}	1.0	1.4	2.0	2.8	4.0	2.0	2.0	2.0	2.0	1.0	1.4	2.8	4.0
Sf_m	-	-	-	-	-	1.0	1.4	2.8	4.0	2.0	2.0	2.0	2.0
Settings for contrast varying experiments (Experiments 2 and 3; reference contrast = 0.5)													
C_{s1}	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.25	0.35	0.5	0.71
C_{s2}	0.25	0.35	0.5	0.71	1.0	0.5	0.5	0.5	0.5	0.25	0.35	0.5	0.71
C_m	-	-	-	-	-	0.25	0.35	0.71	1.0	0.5	0.5	0.5	0.5

N_s is the number of paired or cued dots in the stimulus (ie, twice the number of dipoles), and N_m is the number of randomly positioned singleton elements comprising the mask. Sf_{s1} and Sf_{s2} refer to the spatial frequencies (in c/deg) of the two components of each dipole, and Sf_m refers to the spatial frequency of the masking pattern. C_{s1}, C_{s2}, and C_m refer to the Michelson contrast of the two dipole components and the masking pattern, respectively. Each experiment consisted of five local conditions, where spatial frequency and/or contrast varied (around some reference value) within a dipole, four global conditions, where spatial frequency/contrast was fixed within a dipole but stimuli were added to a mask at various spatial frequency/contrasts, and four control conditions, where various consistent dipole spatial frequency/contrast combinations were tested in the presence of a mask at the reference contrast/spatial frequency. This procedure forced subjects to attend to all spatial frequency/contrast bands, any of which could contain the target or mask.

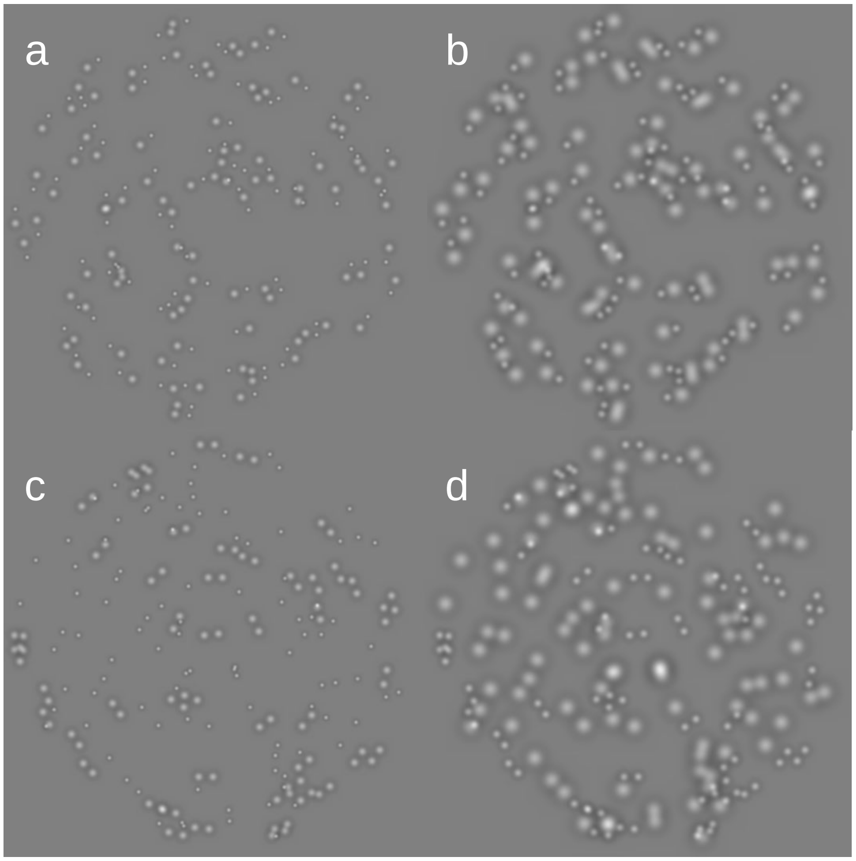

Figure 3. Examples of the stimuli from Experiment 1 local (a,b) and global (c,d) conditions. Dipoles are composed of elements at 2.0 and 4.0 c/deg (a) and 2.0 and 1.0 c/deg (b). Dipoles are exclusively composed of 2.0 c/deg elements and have been intermixed with randomly positioned masking dots at 4.0 c/deg (c) and 1.0 c/deg (d).

We attempted to separate the effects of spatial frequency and contrast variation in three experiments. Experiment 1 examined spatial frequency with fixed Michelson contrast (ie, variable root mean square [RMS] contrast/visibility). Experiment 2 examined spatial frequency with fixed RMS contrast/visibility (ie, variable Michelson contrast), and Experiment 3 looked at the effects of Michelson/RMS contrast for a fixed spatial frequency.

Experiment 1. Spatial Frequency Tuning With Matched Michelson Contrast

The first experiment examined the effect of spatial frequency variation on local and global grouping with elements at a fixed Michelson contrast (C = 0.5). Each session consisted of 13 interleaved runs, probing 5 local, 4 global, and 4 control conditions (Table 1 summarizes relevant stimulus parameters). In the local conditions (1-5), one (randomly selected) element of each dipole was fixed at 2.0 c/deg, and the spatial frequency of the other was varied according to condition from 1.0-4.0 c/deg, in half octave steps. Examples of stimuli from the local condition are shown in Figure 3a and 3b. As the signal-to-noise ratio was lowered, dipoles were replaced with randomly positioned dots at the same spatial frequencies as the dipole elements. The threshold signal-to-noise ratio was defined as the level supporting 83% discrimination from a noise pattern composed of randomly oriented dipoles (with matched spatial frequency structure). In the global conditions (6-9), dipole elements were always both fixed at 2.0 c/deg, but dipole elements were intermixed with a mask composed of the same number of randomly positioned elements at a single, different spatial frequency (1.0, 1.4, 2.8, or 4.0 c/deg). Examples of stimuli from the global condition are shown in Figure 3a and 3d. The signal-to-noise ratio of the dipole population was then varied as in the local conditions. The control conditions (10-13) were the converse of the global conditions; dipoles now contained a single spatial frequency (1.0, 1.4, 2.8, or 4.0 c/deg) and were intermixed with a mask composed of an equal number (ie, 2× the number of dipoles) of randomly positioned elements at 2.0 c/deg. Control conditions ensured that subjects could not perform the task by attending only to 2.0 c/deg but instead had to distribute their attention across spatial frequencies.

Results

Results from the local grouping condition, for the three global transformations tested, are graphed in Figure 4a and 4b. Sensitivity (the reciprocal of threshold) is plotted as a function of the spatial frequency interleaved with the 2.0 c/deg element. Neither subject shows a consistent advantage for any one transformation, but both show slightly poorer sensitivity to radial structure. Both subjects are decreasingly sensitive to Glass pattern structure as the difference between the spatial frequency of dipole elements increases. Because this task encourages subjects to integrate over as wide a range of spatial frequencies as possible, this pattern of band-pass sensitivity should reflect the spatial tuning of the mechanism underlying detection of local structure in these patterns. Spatially band-pass tuning is consistent with the notion that local grouping is performed by oriented filtering mechanisms. This in turn is consistent with previous theoretical (eg, Zucker, 1985), and psychophysical (Dakin, 1997a) observations, as well as the notion that filters are instantiated by the receptive fields of V1 neurones, which are band-pass tuned for spatial frequency.

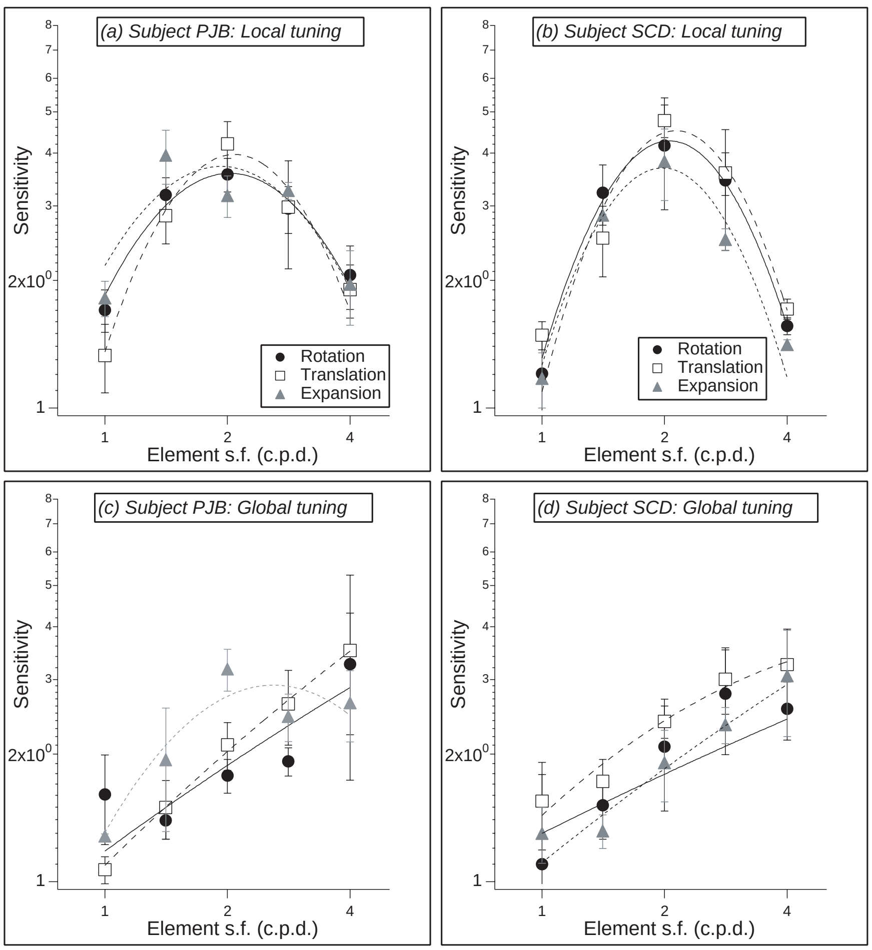

Figure 4. Spatial frequency tuning of local and global grouping for subjects P.J.B. (a,c) and S.C.D. (b,d). (a,b) Local sensitivity (the reciprocal of the signal-to-noise ratio at threshold) is plotted as a function of the spatial frequency of the element paired with a 2 c/deg dipole element. In “a” and “b,” data directly reflect the sensitivity of the underlying mechanism (because the task requires subjects to integrate over as wide a range of spatial frequencies as possible) so that the higher sensitivity at middle frequencies indicates that the local grouping mechanism is band-pass tuned. (c,d) Global sensitivity is plotted as a function of the spatial frequency of the masking stimulus. Here, sensitivity inversely relates to the sensitivity of the underlying mechanism (because the task requires subjects to operate over as narrow a range of spatial frequencies as possible); ie, the observed higher sensitivity at higher masking frequencies indicates that the global grouping mechanism is low-pass tuned (which allows it to ignore high spatial frequencies).

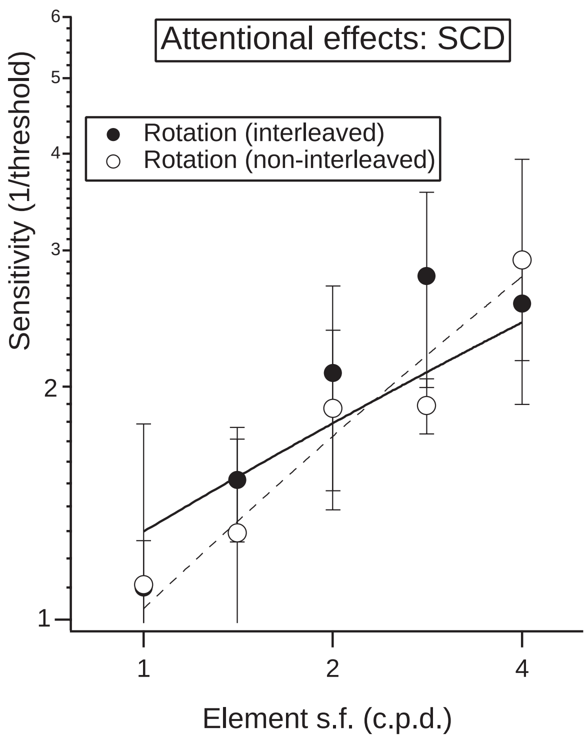

Figure 5. The effect of visual attention on global tuning. S.C.D. was required to detect rotational structure in the presence of masking elements; however, conditions were not interleaved so that the subject always knew which spatial frequencies defined the target. Results (open circles) are similar to data from Experiment 1 (filled circles; replotted from Figure 3).

Results from the conditions probing global grouping are presented in Figure 4c and 4d. In contrast to the local condition, the global task discouraged subjects from integrating over a wide range of scales. In order to discount the presence of noise, subjects should attempt to utilize information only at the spatial frequency of the dipole elements. Therefore, poor performance on this task (ie, low sensitivity) at a particular spatial frequency indicates higher sensitivity of the underlying mechanism to structure at that scale. Tuning of the underlying mechanism will, therefore, be the inverse of the pattern of tuning shown in Figure 4c and 4d, which demonstrates that both subjects show lower sensitivity to structure when Glass patterns were intermixed with noise elements at lower spatial frequencies. This means that global grouping mechanisms are decreasingly able to ignore structure at decreasingly lower frequencies (ie, they are spatially low-pass in their tuning).

A general point to note from Figure 4 is that, contrary to Wilson et al (Wilson et al, 1997; Wilson & Wilkinson, 1998), we observe no consistent advantage for any one transformation over another. This seems likely to be due to the relatively low density of our patterns, which do not support the type of edge cues that may be responsible for the reported advantage in dense patterns (Dakin & Bex, in press).

Control Experiment: Attentional Modulation of Global Tuning

In Experiment 1, all conditions were interleaved to prevent subjects from attending to structure within any one spatial frequency band. However, we were concerned that the demands we placed on subjects, who were required to monitor a series of spatial frequencies/contrasts simultaneously, may have influenced the tuning observed. To test this we reran the global conditions from Experiment 1 (using rotational patterns) but did not interleave them, so that the subject knew in advance which spatial frequencies defined the target. Somewhat to our surprise, results remained similar (Figure 5) with the observer showing clear low-pass tuning for detection. There appears to be little influence of top-down factors on this task.

Experiments 2-3. Tuning for Spatial Frequency or Contrast?

Manipulating local spatial frequency, in the manner described above, also affects the visibility of elements. It is therefore possible that the observed low-pass tuning for global grouping results from a simple inverse relationship between the visibility of elements and their spatial frequency (although visibility clearly cannot explain the local band-pass tuning result). Indeed, the high-pass elements in Figure 3a and 3c do appear less conspicuous, and so might be expected to have a less disruptive effect on detection of the target pattern.

We ran two experiments to examine this question. Experiment 2 employed a methodology similar to the first experiment but equated the RMS contrast of all elements. This amounts to lowering the Michelson contrast of the low-frequency elements, and raising the Michelson contrast of the high-frequency elements. Experimental parameters are given in Table 1 and examples of the stimuli are shown in Figure 6. Notice that on casual inspection, elements at all spatial frequencies now appear equally visible, and it is the case that RMS contrast has been shown to be a good predictor of apparent contrast in two dimensional noise patterns (Moulden, Kingdom, & Gatley, 1990). If it is either the changes in RMS contrast or, to a reasonable approximation, the visibility of the elements that determines the tuning we observed in Experiment 1, then we should observe no spatial frequency tuning in Experiment 2.

If tuning is observed in both Experiments 1 and 2, then that would suggest that it is the spatial frequency and not the contrast that determines the tuning observed in Experiment 1. However, one cannot rule out the possibility that the system is tuned for both contrast and spatial frequency without looking at the effect of contrast with spatial frequency held constant. Experiment 3 measured this and was analogous to Experiment 1 but employed changes in contrast, rather than spatial frequency. Thus, there were 5 local conditions with elements varying in contrast within each dipole, and 4 global conditions with targets at a fixed mid-contrast and masks at lower and higher contrasts. All targets were rotational Glass patterns composed of 2 c/deg elements. (Because findings from Experiment 1 and from a pilot version of Experiment 2 indicate that performance is ostensibly similar across all transformations, we will consider only the detection of rotational Glass patterns in Experiments 2-3.) Again, Table 1 gives the values of the relevant experimental parameters, and note that the ranges of local/global contrasts used were identical to those used in Experiment 2 to allow comparison across experiments. Casual inspection of the examples shown in Figure 7 suggests that we are tolerant of quite a wide range of contrast variation within dipoles (Figure 7a and 7b) but are more able to ignore the low-contrast masks (Figure 7d) than the high (Figure 7c).

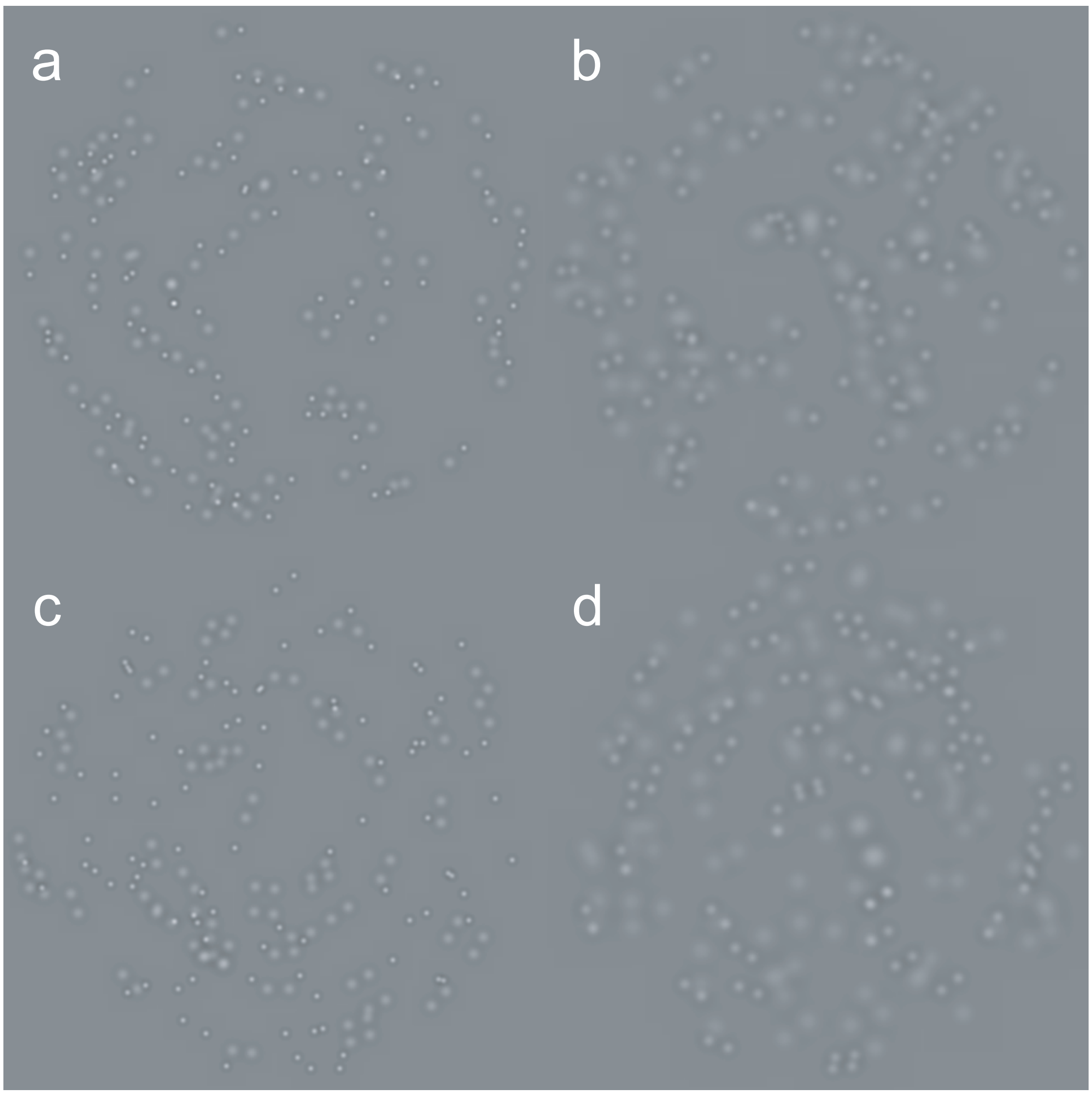

Figure 6. Examples of the stimuli from Experiment 2. Elements varied in spatial frequency but were equated for RMS contrast. Local grouping condition: dipoles are composed of 2.0 & 4.0 c/deg (a) and 2.0 & 1.0 c/deg (b), where elements have been matched for RMS contrast. Global grouping conditions: patterns consist of 2.0 c/deg dipoles intermixed with masking dots at 4.0 c/deg (c) and 1.0 c/deg (d).

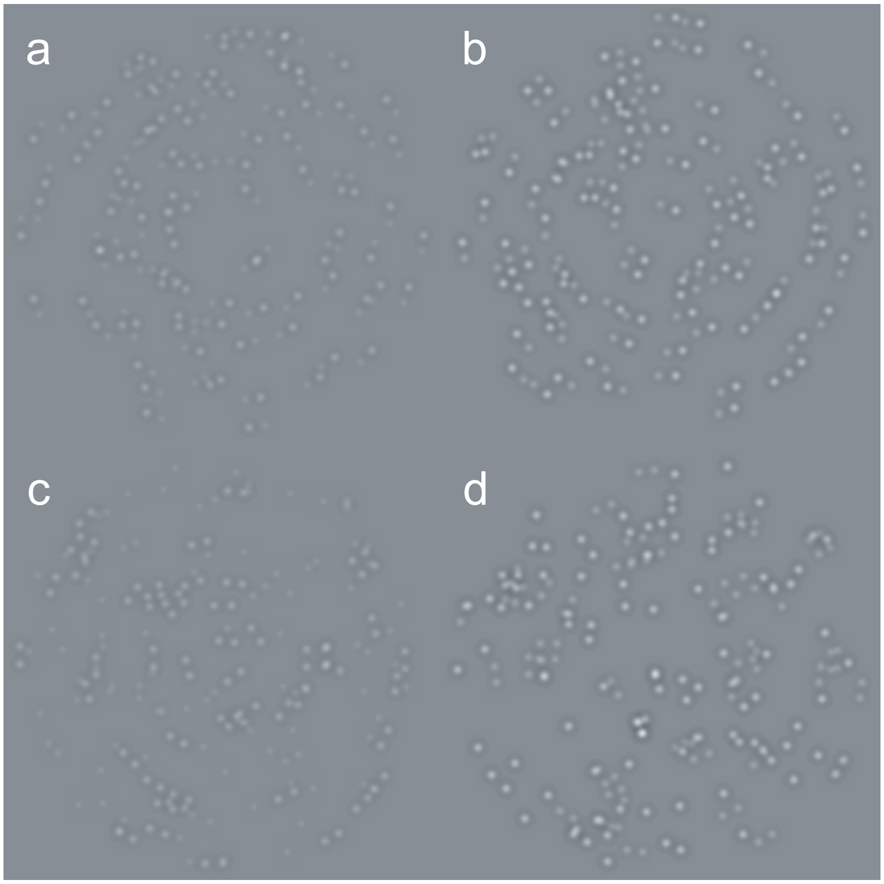

Figure 7. Examples of the stimuli from Experiment 3. Elements varied in RMS/Michelson contrast but were matched in spatial frequency (2 c/deg). (a,b) Local grouping condition; dipoles are composed of elements with contrasts of 50% and 25% (a) and 50% and 100% (b). (c,d) Global grouping conditions; patterns consist of 50% contrast dipoles intermixed with masking dots at 25% (c) and 100% (d).

Results

Figure 8 summarizes data from Experiments 1-3 for the detection of rotational Glass patterns. Local tuning (Figure 8a and 8b) is clearly tuned for RMS contrast-matched spatial frequency variation (grey squares) but only weakly tuned for pure contrast changes with 2 c/deg elements (open triangles). This is consistent with local structure being grouped using a simple filtering scheme where it is spatial frequency similarity that primarily determines strength of grouping. In the context of a local filtering scheme, there are two reasons why changes in local spatial frequency might be more disruptive than local contrast variation. The first is that the image undergoes some form of early contrast gain control prior to filtering. However, this account predicts broad tuning for both local and global tuning when we do not observe the former (Figure 8c and 8d). The second explanation, which we favor, involves filter selection. If it were the case that our spatial filters perfectly integrated contrast energy, then based on the principle of univariance, the spatial frequency and contrast changes we examined should be equivalent. However, assuming that the visual system has spatial frequency selective receptive fields that are well modeled by oriented filters such as Gabors, then the spatial frequency difference between the dipole elements force the visual system to use nonoptimally tuned filters (presumably operating at spatial frequencies midway between the two elements). This reduces their efficacy at integrating contrast energy. Changes in contrast will not force this compromise in tuning because the optimal spatial frequency of the filter will simply be at or close to the spatial frequency of the two elements. This predicts more efficient integration of contrast (rather than spatial frequency) varying dipoles, and thus a broader tuning in the latter case than in the former.

Results from the global grouping condition (Figure 8c and 8d) indicate that subjects still show clear low-pass tuning for RMS matched stimuli (grey squares); they are unable to ignore low-frequency masks even though they are now at a substantially lower Michelson contrast than the target structure. This shows that visibility cannot account for the low-pass tuning observed for global grouping in Experiment 1. Tuning for pure contrast changes at a fixed spatial frequency (open triangles) is somewhat more ambiguous but suggests that the global grouping system is selective for both contrast and spatial frequency. Subjects show a degree of contrast-tuning in that both are more affected by the presence of a high-contrast than a low-contrast mask, but data from subject P.J.B. show a weaker dependence on mask contrast. Such differences are likely to arise from subtle differences in the observers' strategies for performing this task.

This result is contrary to some recent evidence bearing on contrast tuning for Glass patterns. Earle (1999) presented subjects with Glass patterns composed of L-shaped dot triples that contained ambiguous horizontal and vertical structure. The salience of horizontal and vertical structure was measured as a function of the relative contrast of the dots. When two of the elements are low contrast and the third is high contrast, energy models based on simple filters predict that apparent structure will be dominated by the structure with highest overall contrast (ie, between elements of dissimilar contrast). However, the most salient structure was actually determined by contrast similarity, even between low-contrast elements. Grouping by contrast-similarity predicts that we should find band-pass contrast tuning for global grouping rather than the low-pass tuning we observe in Figure 8c and 8d. We conjecture that grouping by contrast similarity may be possible only under quite specific conditions and may depend critically on local spatial configuration (spacing/density, "clustering" of low-high elements) and/or the spatial frequency structure of dots.

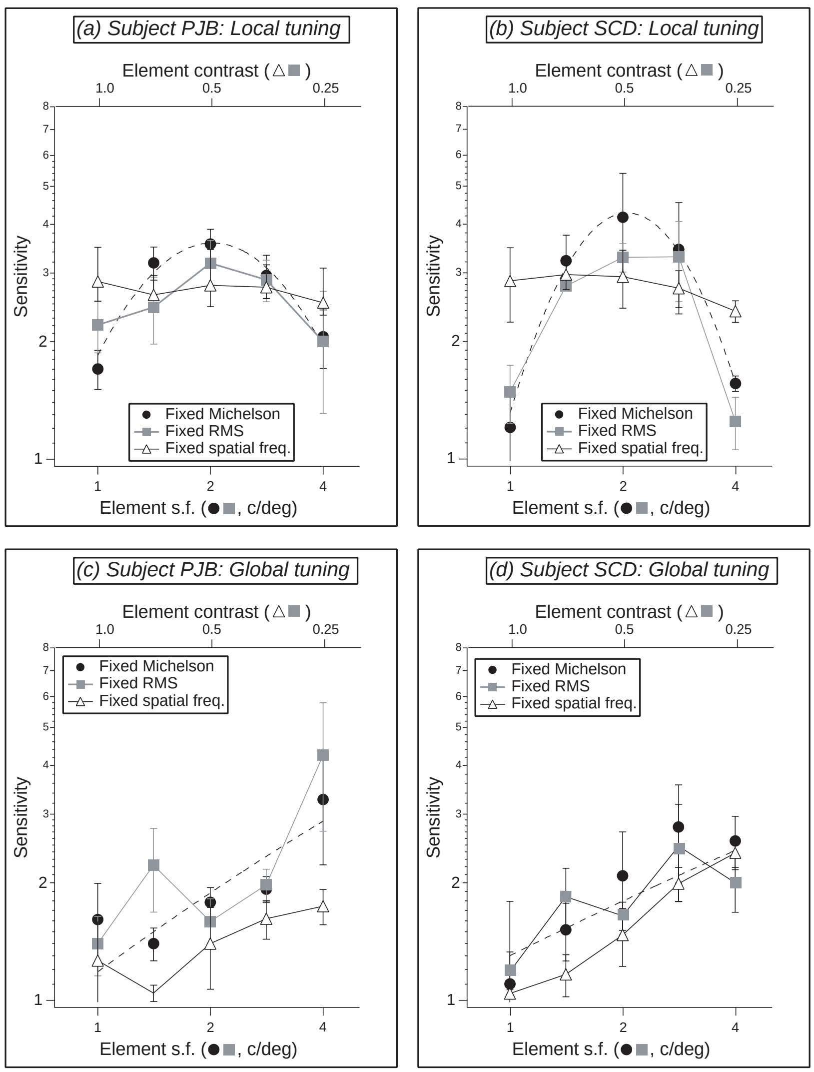

Figure 8. Comparison of the tuning of local and global grouping for spatial frequency (filled circles), RMS-matched spatial frequency (grey squares), and contrast (open triangles). Note the dual abscissas: the lower is for data from the fixed Michelson (variable spatial frequency) condition; the upper is for the fixed spatial frequency (variable RMS contrast) condition; and both apply to data collected with fixed RMS (covarying Michelson contrast/spatial frequency). (a,b) Local grouping is tuned for spatial frequency irrespective of contrast and is weakly tuned for pure contrast changes. (c,d) Global grouping shows dependence on both contrast and spatial frequency.

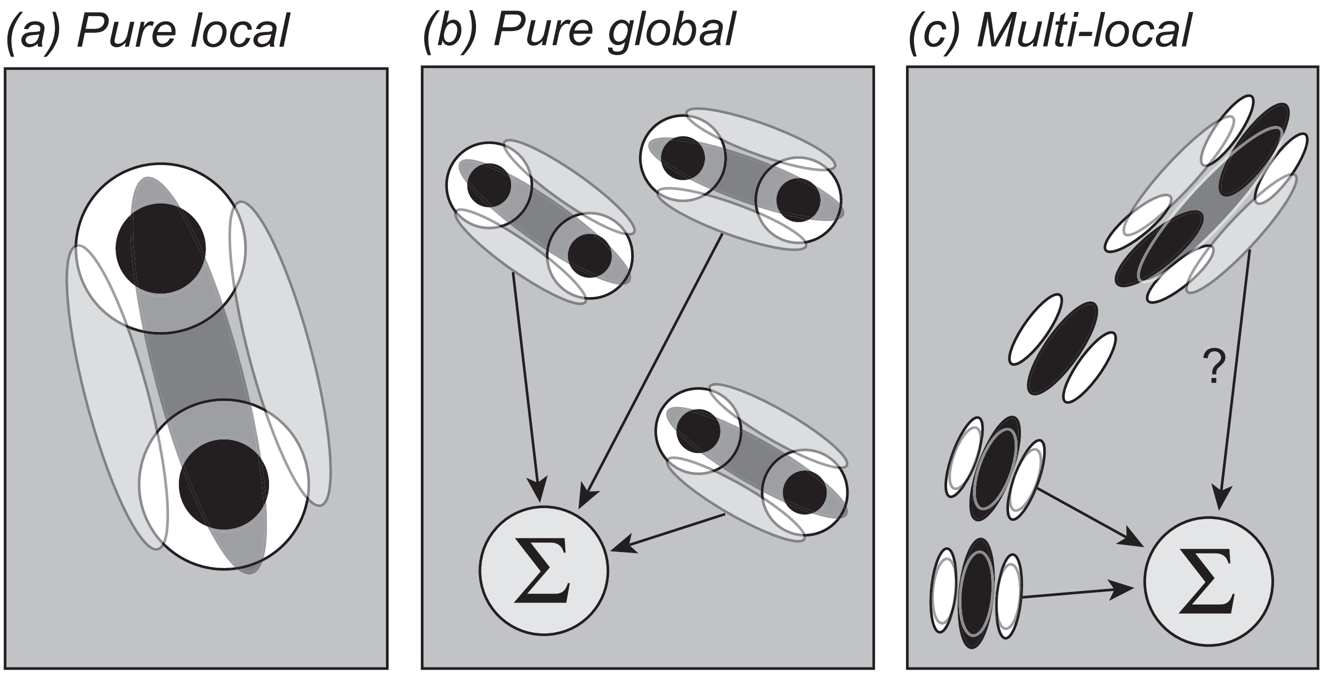

Figure 9. (a) Center-surround Laplacian-of-Gaussian elements uniquely stimulate local grouping mechanisms such as oriented filters (shown as a translucent overlay) when presented in pairs, but not in isolation. We refer to this as "pure" local grouping. (b) Larger groupings across space are unlikely to be detected by such local filtering, since pairings are randomly distributed throughout the image, implying that a more global grouping mechanism must be used. (c) Although contour stimuli presumably exploit a similar global grouping mechanism to (b), pair-wise coalignment of oriented features might also be signaled to some degree by local grouping mechanisms. The "multi-local" groupings might also feed into the global grouping mechanism.

Reduction of element contrast is not the only way that the global energy of low- and high-frequency masks can be equated; one can also alter their densities, and it is possible that low-frequency masks are more effective not because of their spatial frequency but because their elements are larger and have a greater "coverage" of the stimulus. (We are grateful to an anonymous reviewer for this information.) To examine this possibility, we conducted a control experiment. Subjects were presented with rotational Glass patterns composed of 100 elements at 2.0 c/deg embedded in random-dipole masks composed of 25, 100, or 400 elements at either 1.0, 2.0, or 4.0 c/deg. The coverage of these conditions is now matched and under these conditions we do indeed observe equal performance for both subjects [S.C.D.: mean threshold of 0.35 (SE = 0.05), 0.33 (0.02), and 0.38 (0.03); P.B.: 0.38 (0.02), 0.36 (0.08), and 0.36 (0.07)]. These findings are not incompatible with a global integration mechanism with low-pass tuning, which would predict that changing the density/energy of the mask would change performance. Note also that this finding is only *suggestive* that the coverage of the mask is an important parameter; because we also varied the number of elements in the mask, we cannot be certain that this is the case without systematically covarying mask density, extent, and numerosity (Dakin, 2001). By conducting this procedure at a series of mask spatial frequencies we are presently attempting to disentangle spatial frequency, density, number, and spatial extent to determine which parameters determine global masking in these displays.

Discussion

To summarize, we have demonstrated a substantial qualitative difference between local and global grouping processes in visual texture perception; the former are narrowly tuned for spatial frequency structure, and the latter show broader, low-pass tuning. Performance on local grouping is consistent with previous modeling of detection psychophysics, indicating that subjects must be using a relatively narrow range of filters to process Glass patterns; otherwise, they would be swamped by noise from adjacent bands (Dakin, 1997a). That local grouping is spatially band-pass is consistent with the notion that cells in area V1 implement the filters responsible. The global grouping experiments shed some light on how the visual system might then combine together these filter outputs. The global grouping mechanism shows clear low-pass spatial frequency selectivity (because we observe low-pass tuning even with RMS–matched elements) but our data would also appear to indicate a greater degree of tuning for the contrast of the mask than shown by the local grouping mechanism. Thus the global grouping mechanism may combine various attributes of local features and could be characterized as being tuned to something more akin to "visibility."

In the "Introduction," we alluded to previous findings that spatial frequency tuning observed for texture segmentation (Kingdom & Keeble, 2000) and contour detection is band-pass (Dakin & Hess, 1998). Given that both contour integration and the global Glass pattern task require subjects to integrate orientation information across space, these results would appear to be contradictory. Figure 9 illustrates a possible explanation for the difference; it shows schematic diagrams illustrating the distinction between local and global grouping, in the context of a local grouping mechanism based on oriented filters. In the former case, individual features are isotropic and, although they individually do not selectively stimulate any one filter orientation, pairs of features that are close enough together, do. Thus, local grouping cares about the relative position of input features. In the global case, provided that feature pairings are relatively sparse, an oriented filtering mechanism continues to give useful information only about local groupings. Larger, more complex assemblies must be signaled by a mechanism combining responses across space. This is what has traditionally been thought of as a "texture" process in that global grouping cares little about the relative position of input features. Figure 9c shows what we term the "multi-local" case. While both contour and Glass pattern stimuli require orientation integration across space, only in the contour case is the stimulus arranged in such a way as to facilitate interactions between orientation signals; features are densely packed and positioned so that their local orientations are coaligned along an imaginary underlying "backbone." While we know that the conditions under which a whole multi-element contour can be signaled by large filters are quite limited (Hess & Dakin, 1997), that is not to say that the response of large filters to pair-wise groupings in the contour might not be important for binding these elements across space. Contour linking seems to straddle our definitions of local and global grouping. In isolation, local features do stimulate oriented filters; thus their grouping must in some sense be a global linking task. However, like a local grouping task, contour linking must care about position. Moreover adjacent contour elements can mutually stimulate oriented filters operating at a coarser scale so that the contribution of the relative position of contour elements to grouping may ultimately be linked to the degree to which adjacent contour elements mutually stimulate local grouping mechanisms. If one hypothesizes that these pair-wise or multi-local groupings contribute to contour linking (the link marked with a '?' in Figure 9c), then because local grouping is primary (in that global grouping cannot proceed without it), one can see how contour detection might exhibit spatial frequency tuning properties more akin to local grouping. Although the details of the feasibility of pair-wise contour linking is beyond the scope of this paper, we are presently investigating the role of interactions between adjacent elements in contour linking.

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