The role of spatial phase in texture segmentation and contour integration

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It has been recently argued that the visual system possesses just two phase “detector” mechanisms, namely, +cosine and −cosine (P. C. Huang, F. A. Kingdom, & R. F. Hess, 2006). This suggests rather limited access to the rich distribution of receptive field phase that neurophysiologists tell us are represented in the different response profiles of striate simple cells. Whereas that study has suggested that striate receptive field phase is not directly available to perception for the detection/discrimination of localized stimuli, here we investigate whether such information might be used in more integrative striate or extrastriate functions such as texture segregation or contour integration. Specifically, given that simple cells have different local absolute phase response profiles, we ask whether a network of simple cells with similar phase preferences interact in such a way as to extract textures, contours, or both based on phase alone. Two novel texture segmentation experiments and one contour integration experiment were carried out with the intention of providing an answer to the question of how useful is local absolute spatial phase for texture segmentation and contour integration. The results support the possibility of two phase mechanisms (+cosine) for global texture segmentation, as well as for contour integration, when the elements that make up a given contour are orthogonal to contour paths.

Keywords: spatial phase, texture perception, contour integration, log-Gabor function

General introduction

The use of Fourier analysis in the study of human spatial vision has provided numerous insights regarding how the visual system might encode the spatial information present in real-world environments. Specifically, Fourier theory states that any complex waveform can be represented as the sum of sinusoidal waveforms with different amplitudes, frequencies, orientations, and phases (with orientation conveyed in the 2D Fourier transform). From the Fourier transform of any given 2D waveform (e.g., a real-world scene), one obtains the amplitude spectrum and the phase spectrum. While considerable success in demonstrating how the visual system might encode the amplitudes of complex or “natural” scenes (Atick & Redlich, 1992; Barlow, 1959; Field, 1987; Field & Brady, 1997); little insight has been gained with respect to how (or even if) the visual system encodes the phase spectra. The lack of knowledge regarding phase encoding is compounded by arguments stating that it is the phase relationships that are most important for the representation of complex imagery (e.g., Oppenheim & Lim, 1981). The most common example given is that when a complex image has had its global phase spectrum randomized, all of the coherent structure is destroyed (Doi & Lewicki, 2005; Oppenheim & Lim, 1981; but see Hansen, Essock, Zheng, & DeFord, 2003).

The first insights regarding the possible mechanisms underlying phase encoding were gained from the seminal work conducted by Hubel and Wiesel (1962, 1968), where striate neurons in cat and primate cortex were shown to be selective for the spatial organization of a visual stimulus. The relative organization of “light–dark” sensitivity of a given simple cell’s receptive field or the local absolute spatial phase of that neuron’s receptive field has been illustrated by plotting the neuron’s 1D or 2D “response profile” (e.g., Andrews & Pollen, 1979; Jones & Palmer, 1987a, 1987b; Movshon, Thompson, & Tolhurst, 1978). Since then, a number of neurophysiological studies have documented the distribution of preferred local absolute phase angles of striate neurons (specifically, simple cells) in both cat and primate. By measuring line-weighting functions, it has been shown that the distribution of preferred phase angle of simple cells in cat Visual Area 17 is approximately uniform, ranging from 0 to 360 deg (DeAngelis, Ohzawa, & Freeman, 1993; Field & Tolhurst, 1986; Hamilton, Albrecht, & Geisler, 1989; Jones & Palmer, 1987a, 1987b), with a similar finding in primate V1 (Hamilton et al., 1989). However, a recent investigation conducted by Ringach (2002) in Macaque V1, using a subspace reverse correlation method, reported significant biases (in a sample of 70 cells) toward response profiles exhibiting even or odd symmetry. Specifically, (1) space-time separable neurons that were more finely tuned to spatial frequency and orientation tended to yield response profiles with local absolute phase angle preferences for odd symmetry (i.e., 90 and 270 deg phase angle or ±sine) and (2) the simple cells that were more broadly tuned exhibited
response profiles with local absolute phase angle preferences for even symmetry (i.e., 0 and 180 deg phase angle or $\pm \cosine$; Ringach, 2002).

Alongside the neurophysiological research, a number of psychophysical studies have attempted to determine whether the human visual system is tuned to different stimulus spatial phase angles or spatial phase relationships (Badcock, 1984a, 1984b; Burr, 1980; Burr, Morrone, & Spinelli, 1989; Field & Nachmias, 1984; Holt & Ross, 1980; Lawden, 1983; Morrone, Burr, & Spinelli, 1989; Nachmias & Weber, 1975; Rentschler & Treutwein, 1985; Ross & Johnstone, 1980; Stromeyer & Klein, 1974; Tolhurst, 1972; Tolhurst & Dealy, 1975). The neurophysiological studies mentioned above were primarily focused on measuring the distribution of simple cells with respect to their local absolute phase angle preferences. However, most psychophysical literature to date can be interpreted as investigating (1) whether there exist channels selective for specific phase angles with respect to the local absolute phase angle tuning of the underlying simple cells or (2) whether there exist mechanisms selective for the encoding of the relative phase angle differences of two or more superimposed spatial stimuli. The former can be more closely related to the underlying simple-cell local absolute phase angle preference distribution, whereas the latter seems more related to “pooling” mechanisms farther along the visual processing pathways. Unfortunately, many attempts at measuring relative phase detector mechanisms were often confounded with local contrast (Badcock, 1984a, 1984b) or local spatial cues (Hess & Pointer, 1987) and thus could not provide strong evidence for such encoding mechanisms. Later, studies involving subthreshold detection or suprathreshold discrimination of aligned multicomponent stimuli (e.g., Burr et al., 1989) have provided evidence for local absolute phase detectors or channels at four “cardinal” phases ($\pm \sin cosine$ and $\pm \cosine$), although a more recent study (Huang, Kingdom, & Hess, 2006) has suggested a simpler arrangement (i.e., $\pm \cosine$).

In the recent study mentioned above (Huang et al., 2006), it was argued that the visual system has only two phase mechanisms, namely, $+\cosine$ and $-\cosine$. In other words, increments and decrements form the basis of all other more complex phase judgments. This suggests rather limited access to the rich distribution of receptive field phase that neurophysiologists tell us are represented in the different response profiles of striate neurons and that the phase judgments can be attributed to processes carried out in ON and OFF channels (Schiller, Sandell, & Maunsell, 1986). The evidence for this two-channel model, like its four-channel predecessor, was derived from the detection and discrimination of single localized stimuli. In this study, we wondered whether the phase responses from cells in early visual areas, although recently shown as not being directly available to perception for the detection/discrimination of localized stimuli, might nonetheless be used in more integrative striate or extrastriate functions such as texture segregation or contour integration. Put in another way, given that simple cells have different local absolute phase response profiles, we ask whether a network of simple cells with similar phase preferences interact in such a way as to extract textures, contours, or both based on phase alone. Inspired by the work of Field, Hayes, and Hess (1993, 2000) and Malik and Perona (1990), we set out to examine the role of spatial phase in the segmentation of texture regions and contours. Accordingly, we designed three experiments with the intention of providing an answer to the question of how useful is local absolute spatial phase for texture segmentation and contour integration.

**Experiment 1** involves measuring the ability of human observers to segment a rectangular region made up of random orientation log-Gabor elements (all possessing one of eight different local absolute phase angles—referred to as same-phase elements) embedded in a field of randomly orientated log-Gabor elements that have been randomly assigned a phase angle from the set {0, 45, 90, 135, 180, 225, 270, 315 deg}. **Experiment 2** is similar to **Experiment 1**, except for the fact that instead of limiting same-phase elements to a particular region within a field of elements, they were distributed throughout a field of elements and were assigned one orientation, thereby requiring observers to integrate and segment distributed spatially coextensive elements with respect to local orientation and phase. Additionally, to determine if the ability to integrate and segment different log-Gabor-defined texture patterns, purely based on the phase of the elements, was dependent on spatial frequency, both **Experiments 1** and **2** contained three different spatial frequency conditions. Finally, **Experiment 3** was designed to examine the ability of human observers to integrate same-phase log-Gabor-defined contours of varying curvature and different element-to-path relationships. The contour stimuli were embedded in a field of log-Gabor that were randomly assigned different orientations and phases. The results of the three experiments are discussed in the context of increment/decrement network processes that integrate across different texture regions and contours with respect to their local absolute phase angles, as well as a segmentation process that localizes the different texture regions and contours based on the relative phase angle differences between the background elements and the texture regions/contours.

## General method

### Apparatus

Stimuli were presented with an Intel Pentium IV CPU equipped with a 3.21-GHz processor and a 1-GB RAM. Stimuli were displayed, using a linearized lookup table (generated by calibrating with a UDT S370 Research Optometer) on a 22-in. Mitsubishi Diamond Pro 2070$^{SR}$ CRT...
driven by an ASUS Extreme AX300 Graphics card with an 8-bit grayscale resolution. The maximum luminance was 100 cd/m², the frame rate was 120 Hz, and the resolution was 1600 × 1200 pixels. For Experiments 1 and 2, single pixels subtended 0.019 deg visual angle (i.e., 1.19 arcmin) as viewed from 65 cm. For Experiment 3, single pixels subtended 0.008 deg visual angle (i.e., 0.48 arcmin) as viewed from 1.78 m.

Participants

Two experienced psychophysical observers (one naive to the purpose of the study) and one relatively experienced psychophysical observer (undergraduate that had participated in several psychophysical experiments) participated in all three experiments in this study. For Experiment 2, an additional relatively experienced psychophysical observer was included. All participants had normal (or corrected to normal) vision. The age of the participants ranged between 21 and 30. Informed consent approved by the University’s Research Ethics Board was obtained.

The individual stimulus elements

Marčelja (1980) was the first to provide a mathematical description of the 1D spatial response profile (i.e., orthogonal to the axis of preferred orientation) of simple cells in striate cortex with respect to Dennis Gabor’s elementary signals or “logons” (signals that are maximally localized in both the Fourier and spatial domains), which was later generalized to two dimensions by Daugman (1980, 1985). Since then, the Gabor function has been repeatedly shown to provide a very good fit to the spatial response profile of striate simple cells (e.g., Field & Tolhurst, 1986; Jones & Palmer, 1987a, 1987b). In the spatial domain, 2D Gabor functions can be expressed as

$$g(x, y) = A \cos\left(\frac{2\pi(x-x_{\text{peak}})}{\lambda}\right) - \varphi e^{-\frac{(x-x_{\text{peak}})^2}{\sigma_x^2}} e^{-\frac{(y-y_{\text{peak}})^2}{\sigma_y^2}},$$

(1)

where $A$ represents the amplitude of the function, $x_{\text{peak}}$ and $y_{\text{peak}}$ are the spatial coordinates of the center of the function, $\lambda$ is the period (or wavelength) of sinusoidal modulation, $\varphi$ determines the phase of the function (expressed in terms of a spatial shift, corresponding to a given phase angle, of the sinusoidal component), and finally $\sigma_x$ and $\sigma_y$ represent the standard deviation of the 2D Gaussian in Cartesian coordinates.

However, when constructing 2D Gabors in the spatial domain with identical peak spatial frequencies and Gaussian modulation but with different phase angles, the functions will not have identical amplitude spectra—a difference that is inflated as the spatial frequency bandwidth of the function is increased (Field, 1987, 1993; Field et al., 2000; Kovetsi, 1999). Specifically, as the spatial frequency bandwidth of an even-symmetric Gabor function is increased in the spatial domain, the tails of the filter will encroach on the DC component (refer to Figure 1 for further details). One approach to eliminate this problem would be to construct the Gabors in the Fourier domain. In the Fourier domain, a Gabor filter consists of two 2D Gaussian functions (a real and an imaginary component) and can be expressed as

$$G(u, v) = G_R + G_I = e^{-\frac{1}{2}\left(\frac{u^2}{\sigma_u^2} + \frac{v^2}{\sigma_v^2}\right)} + e^{-\frac{1}{2}\left(\frac{u^2}{\sigma_u^2} + \frac{v^2}{\sigma_v^2}\right)},$$

(2)

where $\sigma_u = 1 / (2\pi\sigma_x)$ and $\sigma_v = 1 / (2\pi\sigma_y)$ represent the standard deviation along two orthogonal directions.

Figure 1. One-dimensional plots of the Fourier amplitude spectra of different “standard” Gabor and log-Gabor functions along the primary orientation of the functions in the spatial domain. Left column: 1D amplitude spectrum plots of standard Gabor filters constructed in the spatial domain (top: even-symmetric local absolute phase angle; bottom: odd-symmetric local absolute phase angle). Right column: 1D amplitude spectrum plots of log-Gabor filters constructed in the Fourier domain (top: even-symmetric local absolute phase angle; bottom: odd-symmetric local absolute phase angle). All insets are examples of the Gabor functions in the spatial domain. Note the difference in the amplitude spectra between the even- and odd-symmetric amplitude spectra near the DC.
(thus determining the width of the Gaussian envelope along the x- and y-axes in the spatial domain), and

\[ u_1 = (u_i - f \cos \theta_1) \cos \theta_1 + (v_j - f \sin \theta_1) \sin \theta_1, \]  
\[ u_2 = (u_i + f \cos \theta_2) \cos \theta_2 + (v_j + f \sin \theta_2) \sin \theta_2, \]  
\[ v_1 = -(u_i - f \cos \theta_1) \cos \theta_1 + (v_j - f \sin \theta_1) \sin \theta_1, \]  
\[ v_2 = -(u_i + f \cos \theta_2) \cos \theta_2 + (v_j + f \sin \theta_2) \sin \theta_2, \]

where \( u_i \) and \( v_j \) are coordinates along the cardinal axes of the polar coordinate system, \( f \) represents the central frequency (in cycles per picture) of the Gabor filter’s pass-band, and \( \theta \) represents its orientation, both expressed with respect to polar coordinates. It is worth noting that the Gabor filters should be constructed with respect to the central position of a given matrix (i.e., \( u = 0; v = 0 \)); thus, if \( \theta_1 = \theta_A \), then \( \theta_2 = \theta_A + 180 \), where \( \theta_A \) is the desired central orientation of the Gabor filter in the Fourier domain (see Figure 2 for an example of the polar coordinate reference map). Unfortunately, this approach still leaves the problem of the tails of the two Gaussians crossing over the DC for lower frequency Gabors. The best solution would be the “log-Gabor” function, proposed by Field (1987), which will always yield a spectrum that approaches zero amplitude toward the DC component, regardless of central frequency of the function or phase angle used in the inverse Fourier transform. In the Fourier domain, the real part of the log-Gabor filter can be expressed as

\[
\text{LG}(r; \theta) = e^{-\frac{\log^2\left(\frac{r}{r_{\text{peak}}}ight)}{2\log^2\left(\frac{\sigma_1}{r_{\text{peak}}}ight)}} e^{-\frac{\phi^2}{2\sigma_2^2}},
\]

where \( r \) and \( \theta \) represent any given position in polar coordinates, \( R \) represents a given radius vector (i.e., the spatial frequency dimension), \( r_{\text{peak}} \) is the central spatial frequency of the log-Gaussian function, \( \sigma_1 \) is the spatial frequency bandwidth of the log-Gaussian function, \( \Phi \) represents a given theta “arc vector” (i.e., the orientation dimension), and \( \sigma_2 \) is the orientation bandwidth of the Gaussian function (refer to Figure 2 for further details).

In all of the experiments in this study, the spatial frequency bandwidth of the log-Gabor elements was 1.6 octaves. In Experiments 1 and 2, three different central frequencies were utilized (2.5, 5.0, and 10.0 cpd). For the 2.5 cpd elements, the period of modulation was equal to 26 pixels; the 5.0 cpd elements had a period of modulation equal to 20 pixels; and the 10.0 cpd elements had a period of modulation equal to 14 pixels. For the three different spatial frequency ranges, different amplitude scalars (for the log-Gabor filters in the Fourier domain) were selected such that all of the spatial elements possessed equal contrast. However, in Experiments 1 and 2, the contrast of any given element was randomly jittered, ranging from 5% to 73%. Experiment 3, on the other hand, utilized only one spatial frequency bandwidth (the 2.5 cpd elements used in Experiments 1 and 2, viewed at 2.74 times the distance), and the contrast of all of the elements was set to 54%.

**Experiment 1**

Malik and Perona (1990) have demonstrated that two adjacent “texture regions” made up of vertically aligned spatial Gabor functions, where one half consisted of Gabor elements assigned with the phase angle, \( \varphi \), and the other half consisted of Gabor elements assigned the phase angle, \( \varphi + 180 \) deg, could be easily segmented when \( \varphi = 0 \) deg, but not when \( \varphi = 90 \) deg (i.e., when the elements were mirror symmetric). This observation was similar to the findings reported by Rentschler, Hubner, and Caelli (1988), where it was shown that texture fields composed of compound Gabor elements that were embedded with a region of mirror-symmetric elements could not be distinguished from regular Gabor textures. Malik and Perona speculated that

Figure 2. An illustration of the different stages of the log-Gabor filter construction process in the Fourier domain. From left to right: 2D polar coordinate reference map depicting the cardinal axes of the polar coordinate system (i.e., \( u \) and \( v \)) and the axes utilized to construct the log-Gabor filter (i.e., the radius or spatial frequency axis, \( r \), and the theta “arc” or orientation axis, \( \theta \)), the radial log-Gaussian filter component, the Gaussian theta component, the combination of the radial log-Gaussian and theta Gaussian components to give the log-Gabor filter, and finally, an example of this filter in the spatial domain that has been assigned an even-symmetric local absolute phase angle. Note that this example only shows the real component.
such results may arise from an underutilization of striate neurons with odd-symmetric phase tuning in texture perception—which they modeled with a modified three-stage filter–rectify–filter algorithm. The above observations are consistent with the conclusions involving the detection and discrimination of localized stimuli (Huang et al., 2006) and suggest that higher levels of visual processing, like their low-level counterparts, receive a relatively impoverished phase input, namely, only ±cosine. However, such an important conclusion should not rest on what was a one-off demo (demonstrated by Malik & Perona, 1990) in which the contrast, spatial frequency, and orientation of the elements were fixed at one value and the spatial positions of those micropatterns were constrained (i.e., regular and aligned). Here, we sought to assess whether the finding of Huang et al. (2006) and Malik and Perona could be generalized to textures possessing elements with different spatial configurations, different orientations, and variable contrasts.

**Method**

**Psychophysical procedure**

The goal of this experiment was to measure the ability of human observers to successfully integrate and segment a texture region from its background purely based on the local absolute phase cues of that texture region. The texture patterns themselves consisted of a log-Gabor “element field” where the contrast and orientation of each element were randomized. Within a given element field, the elements within a rectangular region (i.e., the region to be segmented) of that field were assigned a single phase angle, whereas the elements falling outside of that region were assigned a random-phase angle drawn from the set {0, 45, 90, 135, 180, 225, 270, 315 deg} (see Figure 3 for examples of different log-Gabors possessing one of those phase angles and Figure 4 for stimulus examples). Note that this set contains both ±sine (i.e., odd-symmetric) and ±cosine (i.e., even-symmetric) phase angles, as well as four intermediate or “asymmetric” phase angles. To ensure that the observers successfully integrated and segmented this region from the background elements, they were required to identify the orientation of the rectangular integration region. Accordingly, stimuli were generated such that the rectangular “integration region” was oriented at one of four possible orientations {0, 45, 90, 135 deg}, where 0 deg = vertical.

The psychophysical task consisted of a suprathreshold 4AFC paradigm where, on any given trial, the observers were required to identify the orientation of the rectangular integration region. Because we were interested in the role of local absolute phase (absolute with respect to each local element’s position in the spatial domain) in the ability of observers to “perceptually group” a texture region, eight different local element phase angles were utilized, with one of those eight angles assigned at one time (see Figure 4 for examples of the stimuli).

In addition, three spatial frequency conditions were employed where the log-Gabor texture elements were centered on one of three different spatial frequencies. Each trial sequence involved presenting a 0.46 deg circular fixation (500 ms) followed by the stimulus interval (250 ms), then by a distracter mask (500 ms) that was made up of log-Gabor elements that were assigned random orientations and phase angles drawn from the same set mentioned earlier, and finally by an empty display (set to mean luminance) where the observers were required to make a response via keypress (the duration of the response interval was unlimited). Auditory feedback was provided, and all stimuli were binocularly viewed. There were 320 trials in a given session, which contained 10 element field stimuli possessing

![Figure 3](image)

Figure 3. Examples of the different local absolute phase angles used in the current set of experiments.

![Figure 4](image)

Figure 4. Examples of stimuli used in Experiment 1. The log-Gabor elements used in these examples are from the 2.5 cpd condition for ease of viewing. Left: log-Gabor element field with random-phase background elements and a vertical rectangular integration region where the log-Gabor elements falling in that region have been assigned an even-symmetric local absolute phase angle (i.e., 0 deg). Right: log-Gabor element field with random-phase background elements and a 45 deg oblique rectangular integration region where the log-Gabor elements falling in that region have been assigned an even-symmetric (i.e., 180 deg) local absolute phase angle (outlines of course were not present).
phase-angle-defined integration regions for each of the eight phase angles mentioned above, for each of four different integration region orientations. Sessions were blocked by spatial frequency, and each observer repeated each session four times on separate days—with one session from each of the three spatial frequency conditions being executed per day (in a different random order each day). This resulted in a total of 1,280 trials for each spatial frequency condition, with each of the different phase-angle-defined integration regions being presented 40 times for each orientation of the integration rectangle. All observers were allowed practice sessions to familiarize themselves with the task prior to engaging in the experimental sessions. Estimates of sensitivity ($d'$) were calculated for performance in each session for each of the eight phase angles across integration rectangle orientation, as well as for each integration rectangle orientation (Macmillan & Creelman, 1991)—sensitivity estimates were averaged across the four daily experimental sessions.

**Stimulus construction**

Regardless of the spatial frequency bandwidth of the elements used in this experiment, all stimuli were constructed in an identical fashion with the exception of a couple of parameters that will be made explicit later in this section. As alluded to in the General introduction section, there are a large number of potential spatial cues (other than the local absolute phase of the elements) that could be used to successfully perform the task. Accordingly, a series of parameters were introduced during the construction of the stimuli to reduce the possibility of such cues being utilized by the observers. The following is a general description of the construction of one of the stimulus patterns used in a given condition of this experiment.

The stimuli consisted of a large “field” ($1,024 \times 1,024$ pixels, subtending 20.0 deg visual angle) of pseudorandomly placed log-Gabor elements. The general procedure for constructing the log-Gabor element fields was, in part, based on the methodology employed by Field et al. (1993), which involved dividing the area over which the elements were to be distributed into a grid that was proportional to the desired element spacing (spacing was dependent on the spatial frequency range of the elements). Unfortunately, to maintain the same center-to-center spacing (approximately one period of modulation times 1.2—the value is approximate due to the randomized position jitter—see below) across the three different spatial frequency conditions, the total number of grid cells was not the same. For the 2.5 cpd peak spatial frequency stimulus grids, each grid contained 676 cells: the 5.0 cpd peak spatial frequency stimulus grids contained 1,681 cells; and the 10.0 cpd peak spatial frequency stimulus grids contained 4,096 cells. The orientation of each element in the stimulus was randomly selected from the set {0, 45, 90, 135 deg}, where 0 deg = vertical. The rationale behind using this range of orientations was to eliminate the phase angle—orientation angle confound. Specifically, because this experiment was designed to measure the role of phase in the integration and segmentation of a region of log-Gabor elements possessing a given phase angle from the set {0, 45, 90, 135, 180, 225, 270, 315 deg}, if element orientations greater than or equal to 180 deg were selected, phase angles greater than 180 deg would possess the reverse phase angle. For example, a vertically oriented log-Gabor element with a phase angle of 90 deg would, from left to right, possess a dominant bright subregion followed by a dominant dark subregion. If the same element was oriented at, for example, 45 deg, the left-to-right bright–dark subregion relationship would not change; however, if that same element was oriented at 225 deg, then the left-to-right subregion relationship would be reversed (i.e., although the assigned phase angle was 90 deg, the orientation of that element would cause the phase angle to be 270 deg).

Once the orientation of each cell in the stimulus grid was assigned, the next step was to assign a phase angle to each of the cells. The grid was split into a rectangular integration region oriented at one of four possible orientations and a “background region” made up of all cells in the grid not falling within the rectangular integration region. Regardless of the spatial frequency range of the elements used to create any given stimulus, the size of the integration region was kept constant and subtended 20.0 x 7.3 deg visual angle. For each cell in the background region, a phase angle was randomly selected from the set {0, 45, 90, 135, 180, 225, 270, 315 deg} and assigned to that cell. For all of the cells falling in the integration region, one of the phase angles from the previously mentioned phase angle set was selected and assigned to those cells. The final step in stimulus construction involved constructing a log-Gabor element for each grid cell according to the orientation and phase angle assigned to that cell. To break-up the rigid grid structure of the stimulus, the x and y pixel positions of the central pixel of each element were jittered by a value randomly drawn from the distribution $-4$ to 4 pixels (see Figure 4). The proportion of total field elements assigned to each integration region slightly differed across the three spatial frequency conditions. Specifically, 38%, 36%, and 34% of the total number of elements fell within the integration region for the 2.5, 5.0, and 10.0 cpd element fields, respectively. In addition to creating stimuli consisting of integration and background regions, stimuli that consisted of only a field of background elements were created and used for masking patterns (refer to the Psychophysical procedure section for details). Finally, to ensure that there were no contrast cues that could be used to segment the integration region elements from the background elements, RMS contrast and local mean luminance were assessed for each of the different local absolute phase angle integration regions, as well as for the background element regions. The result of this analysis yielded average RMS and local mean luminance values for the different local absolute phase-angle-defined integration regions that did not differ from those of their respective background elements.
Results and discussion

The results from this experiment are shown in Figures 5A and B. Apparent in Figure 5A is a clear sensitivity bias in favor of integration regions that were assigned even-symmetric (or close to even-symmetric) values, with the poorest sensitivity obtained for integration regions where the local absolute phase angles of the log-Gabor elements were assigned odd-symmetric phase angles. In addition, the same bias was present in all of the three different log-Gabor spatial frequency conditions. Several statistical analyses were carried out to determine which effects were significant. First, a 3 (spatial frequency) × 8 (local absolute phase) two-way repeated measures analysis of variance (ANOVA), using the reasonably conservative Huynh–Feldt correction to adjust the degrees of freedom (Cohen, 2001), was conducted. There was a significant main effect of phase angle, $F(3,7) = 29.1$, $p < .001$, and a nonsignificant Spatial Frequency × Phase interaction, $F(14,28) = 0.663$, $p = .789$. The lack of a significant interaction indicates that there was no effect of log-Gabor spatial frequency for the observers in this study. Individual one-way repeated measures ANOVAs were also conducted (adjusted degrees of freedom) for each of the three spatial frequency conditions. All tests yielded significant main effects of phase; 2.5 cpd: $F(2,4) = 7.1$, $p < .05$; 5.0 cpd: $F(7,14) = 16.22$, $p < .001$; and 10.0 cpd: $F(4,9) = 17.35$, $p < .001$. The results described thus far are very much in line with the predictions of the three-stage preattentive texture segmentation model proposed by Malik and Perona (1990). Specifically, the current set of results argues for an integrated and segmented network process that acts to emphasize local-to-global phase angle differences for a given log-Gabor element-defined texture region possessing even-symmetric phase angles. However, given that the stimuli utilized in this experiment differed from those used in the demo published by Malik and Perona with respect to the implementation of different element spatial frequencies, orientations, contrasts, and relative position, an evaluation of that model with the stimuli employed here would provide a more definitive comparison. We thus set out to evaluate that model with the current set of stimuli and report the results in the Three-stage model simulation section of this study.

Finally, because this experiment required observers to make a response based on the orientation of the rectangular integration region, we were also interested in determining whether the ability to integrate and segment local phase-defined texture regions was dependent on the orientation of the rectangular integration region. As shown in Figure 5B, the same pattern of sensitivity is apparent for all four orientations of the integration region regardless of the spatial frequency of the log-Gabor elements. This was confirmed by examining the main effect of orientation for three separate 1 (spatial frequency) × 4 (orientation) one-way repeated measures ANOVAs (adjusted degrees of freedom) for the three different spatial frequencies; 2.5 cpd: $F(2,4) = 13.1$, $p = .05$; 5.0 cpd: $F(1,3) = 1.7$, $p > .05$; 10.0 cpd: $F(3,5) = .33$, $p > .05$. It should be pointed out that for the 2.5 cpd condition, the sensitivity patterns for the obliquely oriented integration regions are shifted down relative to the cardinal (i.e., horizontal and vertical) sensitivity patterns—an “oblique effect” (Appelle, 1972) in the integration and segmentation of differently oriented 2.5 cpd phase-defined log-Gabor texture regions, a main effect that was barely significant (i.e., $p = .05$). However, in examining individual participant data, this effect is apparent in only one observer’s data.

### Experiment 2

This experiment differs from Experiment 1 in that the “texture” (or target) elements, of which the observers were required to integrate and segment, were spatially coextensive. Specifically, as in Experiment 1, the current set of stimuli consisted of log-Gabor element textures, except that the stimuli were made to contain a given proportion of distributed elements constrained to have one of four possible orientations and one of eight possible local absolute phase angles. By asking participants to make judgments regarding the detection of the orientation of those constrained elements (all of which were assigned the same-phase angle), we were aiming at measuring the extent to which orientationally tuned cortical mechanisms had access to local absolute spatial phase. Put another way, the objective here was to investigate whether global texture segmentation can be “facilitated”

![Figure 5A: Psychophysical data from Experiment 1. Integration region orientation averaged data for the three different spatial frequency conditions. Shown on the ordinate is the suprathreshold sensitivity ($d'$). Shown on the abscissa are the different local absolute phase angles of the elements within the four different integration regions. Error bars are averaged $\pm 1 \ SEM$ of $d'$ across days for each observer. Note the strong dependency of integration region sensitivity on the local absolute phase angle of the elements within the different integration regions, with highest sensitivity for $\pm \cosine$ phase angles.](image-url)
by the relative local absolute phase angle relationships within psychophysical channels tuned to different orientations. Recent primate physiology (i.e., Ringach, 2002) suggests that simple cells with narrower tuning functions have predominately odd-symmetric spatiotemporal receptive field response profiles and that more broadly tuned simple cells predominantly possessed even-symmetric receptive field response profiles. An inspection of the receptive field profiles measured by Ringach (2002) suggests that our micropatterns (bandwidth 1.6 octaves) would be expected to produce significant activation of both populations of simple cells, and thus we would expect to see optimum sensitivity at both \( \pm \)sine and \( \pm \)cosine phases if these cellular responses are available at the perceptual level.

**Method**

**Psychophysical procedure**

The goal of this experiment was to measure the ability of human observers to successfully integrate and segment distributed log-Gabor elements set to one of four possible orientations (i.e., from the set: \{0, 45, 90, 135 deg\}, where 0 deg = vertical), by making use of the local absolute phase angle of those elements (which were assigned one of the possible eight angles \{0, 45, 90, 135, 180, 225, 270, 315 deg\}) relative to the randomly assigned absolute local phase of the other elements in the element field.

The psychophysical task employed in this experiment was a suprathreshold 4AFC paradigm, where, on any given trial, the observers were required to identify the orientation of distributed log-Gabor elements that had been assigned one of four possible orientations and one of eight possible local absolute phase angles embedded in a field of elements randomly assigned different orientations (from the set of four orientations mentioned earlier) and local absolute phase angles (from the set of eight phase angles mentioned earlier)—see Figure 6 for examples of the stimuli. For any given trial, observers were presented with an element field that possessed one of nine different proportions of elements assigned a given orientation, where the phase angles of those elements were all set to one of the eight phase angles mentioned above. As in Experiment 1, three different spatial frequency conditions were employed.

Figure 5B. Psychophysical data from Experiment 1. Integration region data for each of the four different integration region orientations within each of the three different spatial frequency conditions. Shown on the ordinate is the suprathreshold sensitivity (\(d'\)). Shown on the abscissa are the different local absolute phase angles of the elements within the four different integration regions for each spatial frequency condition. Error bars are averaged \(\pm 1\ SEM\) of \(d'\) across days for each observer. Note that there is very little difference in the pattern of sensitivity as a function of local absolute phase angle for the four different integration region orientations.
Figure 6. Examples of some of the stimuli used in Experiment 2. The log-Gabor elements used in these examples are drawn from the 2.5 cpd condition for ease of viewing. Each of the four examples consists of log-Gabor element fields consisting of two types of elements: (1) bias or “target” elements and (2) background or “distractor” elements. The “strength” of the bias in the stimuli used in Experiment 2 was defined by the proportion of total elements that were assigned one local absolute phase angle and one local orientation. The background elements have been assigned different random-phase angles and were assigned one of the three remaining orientations (depending on the orientation of the bias elements). For all four examples shown above, the proportion of bias elements relative to the total number of elements is 0.48. (A) The phase of the bias elements = 0 deg; their orientation = vertical. (B) The phase of the bias elements = 90 deg; their orientation = 45 deg oblique. (C) The phase of the bias elements = 180 deg; their orientation = horizontal. (D) The phase of the bias elements = 270 deg; their orientation = 135 deg oblique.

Each trial sequence involved presenting a circular fixation (500 ms) followed by the stimulus interval (250 ms), then by a distracter-mask (500 ms) which was made up of log-Gabor elements that were assigned random orientations and random-phase angles, and finally, by an empty display (set to mean luminance) where observers were required to make a response via keypress (the duration of the response interval was unlimited). Auditory feedback was provided, and all stimuli were binocularly viewed. There were 1,440 trials in a given session, which contained five element field stimuli possessing the distributed log-Gabor elements with the same orientation and local absolute phase angle for each of the eight phase angles mentioned above, for each of nine different proportions of same orientation and phase log-Gabor elements, and for each of four different orientations mentioned above. Sessions were split in half and blocked by spatial frequency; each observer repeated each halved session four times on separate days—with one session from each of the three spatial frequency conditions being executed per day (in a different random order each day). This resulted in a total of 5,760 trials for each spatial frequency condition, where each of the different phase-biased element distributions was presented 20 times for each orientation bias as well as for each proportion bias. All observers were allowed practice sessions to familiarize themselves with the task prior to engaging in the experimental sessions. Estimates of threshold for detecting the different proportions of distributed biased orientation and phase log-Gabor elements, with respect to the relative proportion (i.e., bias) of those elements present in the log-Gabor texture fields, for each observer (data pooled across days) were obtained using the psychophysical software package “psignifit” (Wichmann & Hill, 2001a, 2001b). Threshold estimates were obtained for each of the eight different phase angles pooled across orientation of the distributed biased elements, as well as for each of the four orientations of the biased elements.

Stimulus construction

The general construction of the stimuli utilized in this experiment was identical to that employed in Experiment 1. In addition, the same spatial frequency ranges employed in Experiment 1 were also utilized in this experiment. The primary differences between the stimuli used in this experiment and those used in Experiment 1 are as follows. (1) Instead of limiting the same local absolute phase log-Gabor elements to a rectangular region, the same-phase (or “target”) elements were uniformly distributed throughout the entire element field. (2) Instead of assigning a random orientation drawn from the set mentioned above, the same-phase elements were all assigned one of the four possible orientations. (3) To obtain a meaningful performance measure for the ability of observers to perform the task described in the preceding section, the relative number of the orientation and same-phase angle elements was varied (hence, different bias “strengths” were introduced by varying the proportion of same-orientation/same-phase elements relative to the total number of elements in the field). Nine different biased element proportions were used in this experiment (which are 0.12, 0.18, 0.24, 0.30, 0.36, 0.42, 0.48, 0.54, and 0.60). (4) Finally, for a given orientation of the biased elements, the remaining “nonbiased” background elements were randomly assigned one of the three remaining orientations (see Figure 6 for examples). To ensure that there were no spatial cues that could be used across stimuli containing different proportions of orientation/phase-biased elements, we assessed RMS contrast and mean luminance for each of the different phase angles used here. Specifically, the analysis was carried out for each of the nine different biased element proportions. The result of this analysis yielded approximately equal average RMS and mean luminance values for the different biased element proportions.
Results and discussion

The results from this experiment are shown in Figures 7A and C. The sensitivity for detecting different proportions of biased orientation and local absolute phase elements is much better when the biased orientation elements were assigned even-symmetric (or close to even-symmetric) values relative to the randomly assigned local phase angle log-Gabor element backgrounds, with poor sensitivity for biased element proportions where the local absolute phase angle of the log-Gabor elements was assigned an odd-symmetric phase (Figure 7A). Several statistical analyses were carried out to determine which effects were significant. First, a 3 (spatial frequency) \times 8 (local absolute phase angle) two-way repeated measures ANOVA, using the same degrees of freedom adjustment as in Experiment 1, was conducted. There was a significant main effect of phase angle, $F(3,9) = 18.6, p < .001$, and a significant Spatial Frequency \times Phase interaction, $F(8,24) = 4.0, p < .01$. However, subsequent analyses revealed that this interaction arises from the last and third-to-the-last (not including 360 deg as it is a copy of 0 deg) points of the 2.5 cpd plot (Figure 7A). Note that although the pattern of sensitivity still peaks at the odd-symmetric phases, it peaks slightly higher for the 225 and 315 deg phase angles, thus causing the interaction. Of course, when those points were removed from the analyses, the interaction fell short of significance, $F(6,18) = 2.43, p = .07$.

The similarity between the three spatial frequency phase sensitivity patterns suggests very minimal, if any, effect of spatial frequency for the observers in this study. Individual one-way repeated measures ANOVAs (adjusted degrees of

Figure 7. Psychophysical data from Experiment 2. (A) Orientation averaged relatively broadband (1.6 octaves) element (or “target” element) bias data for the three different spatial frequency conditions. Shown on the ordinate are the estimated threshold values with respect to the proportion of biased elements. Shown on the abscissa are the different local absolute phase angles of the bias elements. Note the highest thresholds are located at and near the odd-symmetric local absolute phase angles. Error bars are averaged \pm 1 SEM of threshold across days for each observer. (B) Orientation averaged relatively narrowband (0.8 octave) element bias data for two different spatial frequency conditions. The axes are identical to those shown in panel a. Note that threshold sensitivity is approximately equivalent across all of the local absolute phase angles. (C) Data from Experiment 2 (broadband element conditions) collapsed across the three categories of local absolute phase angles, within two bias element orientations: vertical and horizontal (i.e., the cardinal orientations) and 45 and 135 deg oblique. This was carried out for the data within each of the three spatial frequency conditions. Shown on the ordinate are the estimated threshold values with respect to the proportion of biased elements. Shown on the abscissa are the cardinal and oblique orientations for each of the three local absolute phases.
were also conducted for each of the three spatial frequency conditions. All tests yielded significant main effects of phase; 2.5 cpd: \( F(5,15) = 5.8, p < .01 \); 5.0 cpd: \( F(5,15) = 15.1, p < .001 \); and 10.0 cpd: \( F(3,10) = 13.1, p < .01 \). As is apparent in Figure 7A, this pattern of sensitivity (higher thresholds at and near the odd-symmetric phases) is present in all of the three different log-Gabor spatial frequency conditions investigated in this experiment.

The general finding here is very similar to that reported for Experiment 1 in this study. Although the results of Experiment 1 could be predicted by the three-stage model proposed by Malik and Perona, such a model would likely fail to predict the results reported in this experiment simply due to the fact that that model is based on a modified second-order (i.e., filter–rectify–filter) edge detector mechanism. It is possible that the stimuli with higher proportions (i.e., stronger biases) of same local orientation and same-phase elements could form dense same-phase to random-phase element regions that their model might detect. However, it seems much more likely that some other mechanism would be better suited to extract such a signal than the one modeled by Malik and Perona’s three-stage model. Given Ringach’s (2002) results showing a correlation between receptive field tuning and its local absolute phase, we would have expected, based on the bandwidth of our micropatterns, to see the contribution of both odd- and even-symmetric cellular responses. However, the data reported here do not show any significant contribution at odd-symmetric phases. To be absolutely sure, we repeated the experiment with more narrowly tuned micropatterns in an effort to reveal any contribution from odd-symmetric mechanisms. The stimuli were constructed in an identical fashion as described in the Method section of this experiment, except for the fact that the bandwidth of the log-Gabors was limited to 0.8 octave. Because constructing very narrow log-Gabor elements results in elements that cover more area in the spatial domain, the element-to-element spacing had to be doubled. Unfortunately, doubling the element-to-element spacing resulted in a severe decrease in the overall number of elements for the 2.5 and 5.0 cpd element fields. We thus constructed log-Gabor element fields where the elements had a peak central frequency of 10.0 cpd and carried out that condition with one observer at two distances: one where the central frequency was 10.0 cpd (65 cm viewing distance) and one where the central frequency was 5.0 cpd (32.5 cm viewing distance). The data from those conditions are shown in Figure 7B. Unlike the data shown in Figure 7A, the thresholds for detecting different numbers of biased same-phase and same-orientation elements are approximately equivalent across all of the local absolute phase angles investigated here. We could not reveal an odd-symmetric bias in sensitivity for more narrowly tuned micropatterns.

Because this experiment required observers to make a response based on the orientation of the phase-biased elements, we were also interested in determining whether the ability to integrate and segment distributed phase-defined textures was dependent on the orientation bias of those elements. To conduct this analysis, we collapsed the local absolute phase data into four different phase groups, specifically, for each observer, the data from the even-symmetric (0 and 180 deg), odd-symmetric (90 and 270 deg), and the two asymmetric phases (45 and 315 deg and 135 and 225 deg) with respect to the cardinal orientations (vertical—i.e., 0 deg and horizontal) and the oblique orientations (45 and 135 deg oblique) within each of the three different spatial frequency conditions. As shown in Figure 7C, there is a very modest oblique effect (Appelle, 1972) for all of the different local absolute phase-biased elements. However, although this effect is most apparent in the 2.5 and 5.0 cpd conditions, it is extremely small (or nonexistent) for the 10.0 cpd condition. Considering that the behavioral Class 1 oblique effect (Essock, 1980) is typically obtained for relatively high spatial frequency stimuli, it is intriguing that the effect was not observed in the highest frequency condition employed in this experiment. However, over the four repetitions of the three spatial frequency conditions, each element bias orientation (for each bias/proportion level and phase angle) was presented only 20 times; therefore, the orientation sensitivity bias data should be considered with that caveat in mind.

### Experiment 3

There currently exists an extensive body of literature devoted to understanding how the visual system processes contours, either artificially generated (for comprehensive reviews, see Hess & Field, 1999 and Hess, Hayes, & Field, 2003) or modeled after the contour statistics of natural scene imagery (e.g., Geisler, Perry, Super, & Gallogly, 2001; Sigman, Cecchi, Gilbert, & Magne, 1999). However, while the role of phase in the ability to integrate contours has been reported to be somewhat minimal (e.g., Field et al., 1993, 2000), only a handful of parameters have been investigated. Specifically, Field et al. (1993) varied the local absolute phase angle of Gabor elements along contours across different levels of contour curvature and reported very minimal effects of phase. However, their Gabor elements suffered from the confound described in the General method section of this study. To correct this, Field et al. (2000) employed log-Gabor elements for use in their study. The primary experiments in that study consisted of contours constructed with log-Gabor elements that alternated in local absolute phase angle either between 0 and 180 deg (even-symmetric phase angles) or between 90 and 270 deg (odd-symmetric phase angles). In those experiments, the even-symmetric phase alternating contours were embedded in a field of random orientation log-Gabors that were assigned even-symmetric phase angles and the odd-symmetric phase alternating contours were embedded in a field of random orientation log-Gabors that were assigned odd-symmetric phase angles. Again, small phase effects were reported, with a similar phase effect for both types of alternating phase contour elements.
In this experiment, we sought to extend the findings reported in Experiments 1 and 2 by measuring the ability of human observers to integrate and segment log-Gabor-defined contours (where all of the elements along the contour have been assigned either one of four different local absolute phase angles or randomly assigned phase angles) of varying curvature and with different element-to-path relationships embedded in a field of random orientation log-Gabors that were randomly assigned one of four phase angles. We wondered whether contours composed of elements of uniform phase were more detectable and if so, whether some phases were more important in contour integration than others. Because the previous two experiments involved texture segregation, we were particularly interested to know if the same rules applied to a different integrative process, namely, contour integration.

Method

Psychophysical procedure

In this experiment, we were interested in measuring the ability of human observers to integrate artificial contours made up of log-Gabor elements that were either assigned one of four different local absolute phase angles from the set: \{0, 45, 90, 180 deg\} or randomly assigned a local absolute phase angle from the same distribution, which were embedded in a field of log-Gabor elements with random orientation (uniformly drawn from a distribution ranging from 0 to 180 deg) and randomly assigned local absolute phase angles from the same set mentioned above. Aside from the fact that this experiment required observers to integrate contours, this experiment differs from the previous two experiments with respect to the psychophysical task. Specifically, to keep this experiment in line with the methodology utilized in previous contour integration experiments, we chose a 2AFC contour detection paradigm. Thus, the only thing observers had to do was simply detect the presence of a contour and there was no need to identify any other aspects of the contour. The methodology behind the current behavioral paradigm is virtually identical to previous studies (Field et al., 1993, 2000) that investigated the ability of human observers to integrate artificial contours as a function of the local absolute phase angles of the contour elements, with the following exceptions: (1) the phase angle assigned to each log-Gabor element was the same or randomly drawn from the set mentioned above, (2) only six levels of contour curvature were employed, and (3) the element-to-path angle was fixed at one of four possible values from the set: \{0, 22, 45, 90 deg\}, where 0 deg indicates that the elements were aligned with the contour path and 90 deg indicates that the elements were orthogonal to the contour path (refer to Figure 8 for stimulus examples).

The psychophysical paradigm employed here was a 2AFC, where the task of the observer was to identify which of the two stimulus intervals contained a contour. Thus, two stimuli would be presented, both of which consisted of a log-Gabor element fields where the elements were assigned a

![Figure 8](image_url)

**Figure 8.** Examples of some of the stimuli used in Experiment 3. All contours embedded in the examples have been assigned a curvature of 20 deg. In the left column are log-Gabor element “fields” or backgrounds that have been embedded with log-Gabor element-defined contours where the elements are “aligned” with their respective contour path segment (i.e., the axis of orientation of each element is aligned with the local orientation of its path segment). In the right column are log-Gabor element “fields” or backgrounds that have been embedded with contours where the elements are “orthogonal” with their respective contour path segment (i.e., the axis of orientation of each element is rotated 90 deg relative to the local orientation of its path segment). From top to bottom: contours that have had all of their elements assigned a 0 deg phase angle (i.e., even symmetric); contours made up of elements possessing a 90 deg phase angle; and contours that have had all of their elements assigned a random-phase angle (see text for further details).
random orientation and phase, with one of the element fields containing a contour. Each trial sequence involved presenting a circular fixation (500 ms) followed by Stimulus Interval 1 (250 ms), followed by an empty display (set to mean luminance for 1,000 ms), followed by a circular fixation (500 ms), followed by Stimulus Interval 2 (250 ms), followed by an empty display (set to mean luminance) where observers were required to make a response via keypress (the duration of the response interval was unlimited). Auditory feedback was provided and all stimuli were binocularly viewed. For a given session, the local absolute phase angle of the contour elements was either one of four possible values or a random-phase value drawn from a set of four phase values. The curvature of the contour path could have been one of six possible values from the set: {0, 10, 20, 30, 40, 50 deg}. Thus, the trials were interleaved with respect to curvature, and each session was blocked by element-to-path angle. Each session contained 600 trials, with 20 different contours for each of the five phase possibilities, for each level of contour curvature. Each session was repeated three times (run on different days and in a different random order for each day), resulting in a total of 1,800 trials, with 60 repetitions for each path element phase possibility, for each level of path curvature. Before beginning the experiment, all participants were shown examples of the different contours (for each of the five different phase possibilities) at different contour curvature levels and at each element-to-path angle alone, as well as those embedded in a field of background elements. Specific attention was paid to the different element-to-path angle contours because the experimental sessions were blocked by this variable. Observers were then required to run practice sessions for each of the four different blocks with auditory feedback.

**Stimulus construction**

The construction of the stimuli employed in this experiment followed the same rules defined in Field et al. (1993), except for the fact that log-Gabor elements were used. The contour paths themselves were generated using the same algorithm described in Field et al. using the standard rotation equations:

\[
X = D \cos \theta, \tag{5a}
\]

\[
Y = D \sin \theta, \tag{5b}
\]

\[
X_R = X \cos \phi - Y \sin \phi, \tag{5c}
\]

\[
Y_R = X \cos \phi + Y \sin \phi, \tag{5d}
\]

\[
X_N = X + X_R, \tag{5e}
\]

\[
Y_N = Y + Y_R, \tag{5f}
\]

where \(D\) represents the distance (in pixels) of each segment of the contour path (12 segments in total). For this experiment, this distance was 32 pixels (i.e., slightly larger than the modulation period of the log-Gabor elements used in this experiment). With respect to the algorithm used to construct the contour paths, for any given segment of a given contour, \(X\) and \(Y\) represent the current segment end-point position, in a 1,024 \(\times\) 1,024 pixel grid. \(X_R\) and \(Y_R\) represent the rotation as a function of contour curvature; \(X_N\) and \(Y_N\) represent the new location of the following contour path segment. This process was repeated until the full path was generated. The orientation of the contour elements was assigned in the Fourier domain (as opposed to rotating the elements in the spatial domain) and depended on the relative orientation of a given contour segment. As in Field et al., a randomly determined amount of contour curvature jitter was added to each segment's curvature angle that was drawn from a distribution ranging from \(-10\) deg to \(+10\) deg to eliminate the contours with large degrees of path curvature from forming geometric shapes. Also, because we are interested in the detection of contours and not the shapes contours can form, contour paths that looped back on themselves were thrown out and new paths were generated in their place. As mentioned in the preceding section, different contours were generated where each of the 12 path elements were assigned one of four possible phase values from the previously mentioned set or randomly assigned a phase value from the same set (see Figure 8 for examples). The rationale for using a reduced set of possible phase angles for the different contours relates to the element orientation-to-phase angle confound mentioned in the Method section of Experiment 1. Specifically, because the orientation of a given log-Gabor element assigned to a given contour path would change as a function of contour curvature (e.g., a contour that resembles a “U” shape), if the elements are aligned with the contour path (element-to-path angle of 0 deg), elements with a phase angle of 90 deg at one end of the contour would possess their assigned phase angle, whereas elements at the other end would have a phase angle of 270 deg. Accordingly, we decided to use the four different local absolute phase angles described earlier. For the alternative choice element fields (i.e., element fields that did not contain contours), the same methodology was employed in their construction as described in Field et al. However, because the element fields possessed contours with one phase angle assigned to each element along that contour, it is possible that the observers could use this small bias in the total number of elements in the field containing a given phase value as a detection cue. That is, because the observers were aware of the fact that some contours were assigned one phase value, they might unintentionally base their responses on the slight bias in the number of, for example, even-symmetric elements in a given element field. The alternative choice element fields were made to possess the small 12 element phase bias for one of the four different phase angles investigated here to eliminate this possibility. However, a given contour with elements assigned a given local absolute phase angle was not paired with alternative choice element fields containing the same small local phase bias.
Results and discussion

In this experiment, there were two primary questions of interest: (1) Is there any benefit for contour detection for contours with elements having the same phase relative to a random-phase background? (2) If a benefit does exist, is there a performance bias for contours with specific local absolute phases (e.g., is performance with even-symmetric phase contours different from that of odd-symmetric phase contours)?

With respect to the first question, our primary reason for including contours with random-phase elements (i.e., random along the contour) was simply an attempt to provide some basis of comparison for the performance observed with the same-phase element contours. Previous reports have shown contour detection to depend very little on the relative local absolute phase angles of the elements along a given contour, suggesting a phase-insensitive contour integration mechanism. Thus, we needed to compare performance for detecting same-phase contours against random-phase contour detection to determine if the different same-phase contours provided any benefit to a mechanism that has been shown to only slightly rely on local absolute phase. Plotted in Figure 9 are the performance ratios between the three different absolute local phase contours (i.e., even symmetric, odd symmetric, and asymmetric) and the random absolute local phase contours for each of the element-to-path conditions (there were no performance differences observed between 0 and 180 deg phase contours, so that data was combined to form the even-symmetric category). Thus, values above 1.0 indicate higher performance for the same-phase contours; values near or at 1.0 indicate little difference between same-phase and random-phase contours. Given the high level of performance for 0–10 deg curvature contours (refer to Figure 10), it is not surprising that there are very small, if any, phase effects (with the exception of the orthogonal element-to-path condition). The higher ratios seem to generally occur at or beyond 10 deg contour curvature and fall off beyond 30 deg contour curvature as overall performance falls toward chance (refer to Figure 10). The higher same-phase to random-phase contours ratio ranges are highlighted by light gray regions on the graphs depicted in Figure 10.

Regarding the second question, the relative performances for the different same-phase contours for each element-to-path angle condition are shown in Figure 10. For the 0 deg element-to-path contours, performance for all contour phases follows a decreasing monotonic function as a function of increasing path curvature, very much in line with the results reported by previous contour integration experiments. There appears to be very little, if any, effect of phase. For the 22 deg element-to-path contours, performance decreases as a function of path curvature. However, there does appear to be a small effect of phase in that performance for the odd-symmetric phase contours is slightly worse than the contours composed of even-symmetric phase angles. For the 45 deg element-to-path contours, again, performance decreases as a function of path curvature. Here, there is a relatively large effect of phase in that performance for the odd-symmetric local absolute phase angle contours is worse than the contours with even-symmetric phase angles.

Finally, for the 90 deg element-to-path contours, performance decreases as a function of path curvature, and there is a relatively large effect of phase in that performance for the odd-symmetric local absolute phase angle contours is worse than the contours with even-symmetric phase angles.

To statistically verify the observed phase effects described above, we conducted several analyses to determine which element-to-path angle effects were significant. Three different two-way repeated measures ANOVA tests, using the same degrees of freedom adjustment as the other experiments in this study, were carried out (one for each element-to-path angle). As mentioned above, we were only interested in the curvature ranges where the local absolute phase angle assigned to the contours provided a reasonable performance improvement relative to the contour detection performance observed with the random-phase contours. For the element-to-path angles 0 (i.e., elements aligned with the path), 22, and 45 deg, the main effect of phase was not significant: $F(2,4) = 2.03, p = .25; F(2,4) = 0.27, p = .76$; and $F(1,3) = 3.2, p = .20$, respectively. However, there was a significant main effect of phase for the 90 deg element-to-path angle (i.e., elements orthogonal to the path), $F(1,3) = 19.5, p < .05$.

When these data are replotted together (as shown in Figure 11), there is an apparent nonmonotonic trend for the overall performance across the different element-to-path contours. Specifically, overall performance starts out fairly high for the 0 deg element-to-path contours, then bottoms out for the 45 deg element-to-path contours, and then rises for the 90 deg element-to-path contours. The primary independent variable in this experiment was phase, and this trend is consistent with the results reported by Ledgeway, Hess, and Geisler (2005) for static stimuli. It should be pointed out that, in their study, performance for detecting 45 deg element-to-path contours is near chance for most of the contour curvatures they investigated, whereas here, performance is slightly higher for about half of the contour curvatures. This discrepancy could be explained by the role of phase with respect to how the current stimuli were generated. However, a more likely explanation might be due to the fact that this experiment blocked the sessions with respect to element-to-path angle contours, whereas in their study, contour stimuli with different element-to-path angles were interleaved. That is, for a given experimental block, the observers exactly knew what the relationship of the path elements to the contour path was (and had been given practice to do so effectively), which might have eliminated any confusion along those lines.

Three-stage model simulation

As mentioned in Experiment 1, Malik and Perona (1990) have proposed a three-stage model for texture segregation,
which essentially can be conceived of as a modified filter–rectify–filter (or second order) model that was shown to successfully detect the boundary between Gabor element regions with different even-symmetric phase angles but not for Gabor element regions with different odd-symmetric regions. In addition, they also showed that human preattentive texture segmentation performance for discriminating between two texture fields made up of binary texture elements could be accounted for based on the output of this three-stage model. It was suggested that this finding is consistent with the findings reported by Rentschler et al. (1988) and may be related to the fact that striate neurons with odd-symmetric phase tuning may not be utilized in texture perception. Specifically, the first stage of the Malik and Perona model consisted of convolving a given texture pattern with even-symmetric linear filters followed by half-wave rectification. The second stage involved an inhibitory algorithm to reduce “spurious” filter responses (to yield a “postinhibition” response); this process was then followed by a third stage that involved the detection of texture boundaries by computing the texture gradient of the smoothed postinhibition linear filter responses by filtering.

The conclusions made with respect to the results of Experiment 1 in this study involved accounting for human integration and segmentation of global phase relationships where the local elements of a given texture region differed from surrounding elements in terms of local absolute phase angles. The results of that experiment suggested that higher levels of visual processing, like their low-level counterparts, receive a relatively impoverished phase input, namely, only $T \cos$. This conclusion could be predicted by the model proposed by Malik and Perona, however, given that the Gabor element texture patterns used to support the different filter phases used in that model were rigid with respect to local contrast, spatial frequency, orientation, and relative position. We wanted to assess whether their model could be generalized to the stimuli utilized in Experiment 1.

In their model, the authors chose to employ difference of offset differences of Gaussian (DOOG) linear filters; however, several other options were considered and it was noted that the choice was not crucial to their model. Here, we chose to use log-Gabor filters because these were the elements used to construct the integration region stimuli. Having noted that deviation from the original model, we set

![Figure 10](image1.png)

**Figure 10.** Psychophysical data from Experiment 3. Plotted in each graph is the contour detection performance for the three different same-phase contour categories (i.e., even symmetric, asymmetric, and odd symmetric) as a function of contour curvature. Each graph plots the contour detection performance for each of the four different element-to-path angles utilized in Experiment 3 (refer to the text for further details). Shown on the ordinates is the proportion correct. Shown on the abscissas are the six different levels of contour curvature. For each graph, the light-gray regions indicate the range in which contour detection performance was increased or “facilitated” for each of the three different same-phase contours with respect to random element phase contours as a function of contour curvature. For the bottom-left graph, the dark-gray region indicates the range of contour curvature where performance for detecting random element phase contours was better than for the same-phase contours (see text for further details).
to evaluate it with three different stimulus examples from Experiment 1. Specifically, stimuli with vertical integration regions were selected, and the local absolute phase angles of the elements making up the integration regions were even symmetric (0 deg), asymmetric (45 deg), or odd symmetric (90 deg). We then subjected those stimuli to the three-stage model algorithm following the methodology described in Malik and Perona (1990). To quantify the magnitude of the three-stage model output, we followed the method utilized in that study. Specifically, for each post-processed stimulus, the output image (i.e., the responses of the algorithm for a given stimulus) was collapsed onto a single vector by averaging the responses along each vertical pixel column. The averaged vectors obtained for each of the stimuli within the three different stimulus sets were then averaged, yielding a total of three response vectors, one for each of the three phase-defined integration region stimuli. The results of this analysis are shown in Figure 12A. In this figure, the second half of the averaged vectors are plotted; the arrow indicates the location of the right edge of the vertically oriented rectangular integration region (i.e., marks the location of one of the edges between log-Gabor elements that were assigned one phase and the background region where the elements were assigned random phases). Note that the magnitude of the three-stage model responses peaks at this location (with the exception of a slightly skewed peak response for the odd-symmetric case) and that the relative magnitude of those peaks very much follows the psychophysical data reported in Experiment 1. That is, the highest response magnitude was observed for the even-symmetric phase to random-phase element boundaries, intermediate for asymmetric to random-phase element boundaries, and lowest for odd-symmetric to random-phase element boundaries. However, the overall response magnitudes were somewhat small when compared with those shown by Malik and Perona for different textures. One possible explanation for this difference could be due to the fact that our stimuli possessed random local contrast. To verify if this was the case, we repeated the analysis for the

Figure 11. Replotted data from Experiment 3. Here, the performance data from Experiment 3 have been replotted with respect to the element-to-path angle for four different levels of contour curvature (the individual line plots) for the two different same-phase contour categories (i.e., even and odd symmetric) and for the random element phase contour category. Shown on the ordinates is the proportion correct. Shown on the abscissas are the four different element-to-path angles utilized in Experiment 3. Error bars are averaged ±1 SEM of performance across days for each observer. Note that for the even- and odd-symmetric phase-defined contours, there is a nonmonotonic function in performance with respect to the different element-to-path angles for the lower levels of contour curvature. However, this trend is less apparent for contours defined by random-phase elements (refer to the text for further details).
same stimuli, with the only difference being the local contrast of the elements being fixed at 73%. The results are shown in Figure 12B. As expected, the relative response magnitudes were very similar to those shown in Figure 12A; however, the absolute response magnitudes were much higher and more in line with Malik and Perona. The differences in absolute magnitude of the model responses are interesting given that psychophysical sensitivity was quite high (see Figure 5) despite the fact that those stimuli possessed random local contrasts. One possible account for this could be a normalization process that acts to enhance the significant output responses of the integration mechanism. Whether such a normalization process takes place, it is worth noting that the three-stage model still provides a plausible account for the results reported in Experiment 1.

General discussion

This set of experiments demonstrated significant performance and sensitivity effects due to the local absolute phase angle of the target elements. Specifically, performance for integrating and segmenting same-phase-defined rectangular regions or distributed local orientation and phase-biased log-Gabor elements favored even-symmetric phases and was typically poor for odd-symmetric phases. In addition, this local absolute phase effect did not depend (if at all, depended very little) on spatial frequency. Likewise, the contour experiment demonstrated a significant phase effect; however, this effect was dependent on the element-to-path angle. Specifically, for contour elements that were orthogonal to the contour paths, there was a significant difference in performance, which favored the even-symmetric phase contours relative to the odd-symmetric phase contours. Thus, across the three psychophysical experiments presented in this paper, an advantage was found for even-symmetric phase and no advantage was found for odd-symmetric phases. This suggests that texture and contour processing of the sort investigated here have access to no more than increments and decrements in the luminance profiles of visual stimuli. A similar conclusion was arrived at by a recent study on the detection and discrimination of localized spatial stimuli (Huang et al., 2006). In that study, the role that local phase played in the threshold detection and discrimination of both narrowband and broadband stimuli was assessed. They, like us, found no evidence for anything other than a bias that could be attributed to increment and decrement processing and, in doing so, provided evidence against the current proposal that there are four cardinal phase processes in human vision (Burr et al., 1989; Field & Nachmias, 1984). The results of this study add further weight to this argument by showing that the four-cardinal-phase proposal is also not relevant at the later stage of visual processing where the information from localized regions of the visual field are either segmented to extract textures or integrated to extract contours.

The first experiment was inspired by the demonstration of Malik and Perona (1990) in which a texture composed of

![Figure 12](image)
even-symmetric elements but differing in polarity between two regions perceptually segmented, whereas a similar texture comprising odd-symmetric elements did not. Here, we have taken this a step further by measuring the strength of the segregation while ensuring that local contrast, orientation, spatial frequency, and element alignment did not provide secondary cues. The basic result stands, but it is not strong enough to be classified as “pop-out,” being only an approximately 35% difference with respect to percentage correct. The question at hand is whether this effect is sufficient to support Malik and Perona’s three-stage model of texture perception. Specifically, would their model predict the magnitude differences observed in Experiment 1 for similar stimuli (i.e., with randomized local contrast, orientation, and position)? These issues were addressed in the Three-stage model simulation section of this study. In general, the results of the simulations discussed in that section did support their model (i.e., ±cosine channels for texture perception), and the relative magnitudes were proportionally similar, with the predicted magnitudes being somewhat larger than the psychophysical relative performance difference. However, it is the relative differences that are the key component here, which were indeed predicted by their model. Because the relative outputs of the three-stage model simulations carried out here were similar, it is possible that, following the third stage, a normalization process might take place.

The second experiment assessed the role of phase in log-Gabor-defined textures embedded with elements possessing the same local orientation and local absolute phase. The reason for doing this was twofold. First, it has been recently shown (Ringach, 2002) that the receptive fields of space-time separable primate simple cells that are more narrowly tuned (bandpass for orientation and spatial frequency) predominantly possess odd-symmetric response profiles, whereas those that are more broadly tuned predominantly possess even-symmetric response profiles. Thus, given that the bandwidth of our stimuli would have activated both classes of simple cell, we were curious whether integrative performance might now show optimal performance for local elements whose phase was not only ±cosine but also ±sine. However, this did not turn out to be the case. Furthermore, using even more narrowly tuned micropatterns did not bias sensitivity to ±sine phase, as might have been anticipated from the recent neurophysiological data. Secondly, the results of this experiment show that the ±cosine advantage demonstrated in the first experiment was not due to randomization of local orientation. The results of Experiment 2 show significant phase effects within separate orientation bands (defined by the local orientations of the same-phase elements). Thus, phase-dependent processes must be able to operate between (Experiment 1) as well as within (Experiment 2) orientation bands.

In the third experiment, we employed a contour integration task, which can be viewed as complimentary to the tasks utilized in Experiments 1 and 2, and asked whether there is any advantage of contours being composed of elements of a particular phase compared with background elements of random phase. Although the stimuli in Experiment 3 involved quite different local spatial element position manipulations, when compared with the two preceding experiments, the results are quite comparable, namely, the phase effects support a ±cosine bias for contours with the elements orthogonally aligned to the contour path.

The general conclusion is that whether local (Huang et al., 2006) or global (present experiments) processing are involved; at the perceptual level, the visual system has limited access to the rich collection of phase-dependent neurons that we know are present at earlier levels of visual processing (e.g., DeAngelis et al., 1993; Field & Tolhurst, 1986; Hamilton et al., 1989; Jones & Palmer, 1987a, 1987b; Ringach, 2002). It seems that perception only has access to increments and decrements but nothing more in terms of “phase encoding.” The segmentation and integration performance reported here may relate to the ON and OFF neuronal responses first reported by Hubel and Wiesel in cortical simple cells, which we know from the studies of Schiller (1982) and Schiller et al. (1986) result in selective perceptual impairment when the retinal ON component is silenced. Should such processes be involved, the mechanisms involved in the integration of textures and contours might operate via a network process that integrates across different texture regions and contours with respect to their local absolute phase angles (i.e., extracting or pooling increments and decrement activity) and a segmentation process that localizes the different texture regions and contours based on the relative phase angle differences (i.e., differentiating increment- and decrement-induced cortical activity) between the background elements and the texture regions/countours. Thus, texture regions (or contours) inducing larger increment or decrement responses would be extracted when in a background where the generalized increment/decrement activity is approximately equivalent (as would be expected from backgrounds consisting of micropatterns of random local absolute phase). Finally, although the data reported here argue against perceptual access to the broad distribution of simple-cell phases known to exist in striate cortex, it does not mean that the position sensitivity of simple cells is not utilized. For example, it is most likely that such information is utilized by cells receiving input from a number of space-time separable simple cells for motion processing (e.g., Adelson & Bergen, 1985).

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There have been a number of studies that have employed tasks that are more directly related to determine if the human visual system possesses channels that are tuned to the local absolute phase alignment within a given stimulus and hence are more suited to provide a psychophysical correlate of the physiological data regarding the spatial phase tuning of striate simple cells. Specifically, such studies have addressed two aspects regarding local absolute phase tuning. The first aspect is concerned with whether there exist channels selective to different local phase angle alignment, and the second aspect is concerned with whether a performance bias can be observed with respect to those channels. The psychophysical approaches that have been employed to help provide answers to the abovementioned issues have typically involved using broadband spatial frequency stimuli consisting of a localized sharp edge flanked by light–dark or dark–light regions, as well as broadband stimuli constructed in the Fourier domain to yield a single localized sharp edge or line (in the spatial domain) by aligning the phases along a given orientation at 0 or 180 deg (i.e., localized line in the spatial domain) or at 90 deg (i.e., a localized edge in the spatial domain) or some other asymmetric phase value (Burr et al., 1989; Morrone et al., 1989; Tolhurst, 1972; Tolhurst & Dealy, 1975). The tasks themselves involved a number of approaches, including (1) measuring the detectability of edges of different polarity following adaptation to an edge of a given polarity (Tolhurst, 1972), (2) the discrimination of edge or line polarity at detection threshold (Tolhurst & Dealy, 1975), and (3) the discrimination thresholds for broadband stimuli possessing phase alignment along a given orientation in the phase spectrum (Burr et al., 1989; Morrone et al., 1989). The primary assumption with such stimuli is that because they possess maximum energy localized at one specific spatial location (Morrone & Burr, 1988; Morrone & Owens, 1987), the relative activity among the similarly local absolute phase-tuned neurons would be greatest at that location, thus providing the basis for the behavioral response (which may or may not depend on the phase angles used to construct the stimuli). The general consensus of those studies support the idea that there exist up to four local phase alignment-selective channels in the human visual system, which are selective for even (0 or 180 deg) or odd (90 or 270 deg) spatial phase symmetry.

Within the psychophysical literature, there are a large number of studies that have employed compound gratings, typically consisting of two component sinusoids (f and 3f—but other configurations have been investigated), where the relative phase angle difference between the two components served as the independent variable. These studies employed a number of different approaches that have been grouped into two fundamental paradigms (Hess & Pointer, 1987; Lawton, 1984). The first set of approaches typically involved varying the relative phase angle difference between f and 3f until observers could just discriminate that difference from an aligned compound grating. In addition, the contrast of the 3f component was usually equal to or greater than the f component (Badcock, 1984a, 1984b; Burr, 1980; Holt & Ross, 1980; Rentschler & Treutwein, 1985; Ross & Johnstone, 1980). The second set of approaches involved the discrimination of compound sinusoids, where one stimulus consisted of a compound with f and 3f aligned with respect to one phase angle, Φ, and the other stimulus consisted of a compound grating with the component sinusoids aligned at Φ + 180 deg (also referred to as “phase reversal discrimination”). The ability to discriminate between such stimuli was typically measured for a range of fixed contrasts of one of the components, and the contrast of the other component would be varied until the two stimuli could just be discriminated (Field & Nachmias, 1984; Lawden, 1983; Nachmias & Weber, 1975; Stromeyer & Klein, 1974). The former approach has yielded minimum relative phase angle difference discrimination angles from 10 to 30 deg (Badcock, 1984a; Burr, 1980). The results from both approaches support the existence of one, two, or four relative phase angle difference detector mechanisms, with the four-mechanism result being the most favored. Specifically, based on the observed data, the four mechanisms have been proposed to be tuned to ±cosine and ±sine relative phase-aligned compound stimuli (Field & Nachmias, 1984).

The ±cosine and ±sine channels described in Footnote 1 are not the same as the ±cosine and ±sine mechanisms discussed above. The fundamental discrepancy is related to the nature of the stimuli utilized in the studies described in Footnote 1 and those described here (i.e., the f and 3f compound sinusoidal gratings). Specifically, because the two component gratings typically differ by more than one octave and are easily discriminable from each other when presented separately, it can be assumed that they are being encoded by two different narrowband mechanisms, sensitive to different ranges of spatial frequencies. Because more than one cycle of the f component was visible in those tasks (with three times as many visible for the 3f component), the stimuli cannot be considered spatially limited. What this means is that, at the level of activation of the local absolute phase-tuned simple cells, the entire population of different local absolute phase-tuned simple cells (selective for either the f or 3f component spatial frequency) would be activated (i.e., any given location on the stimulus will selectively activate neurons tuned to different phases). With both of the entire f and 3f selective populations activated, there would be no way for the visual system to make the discrimination unless there existed mechanisms that responded to the relative phase differences between pairs of neurons, each selective for a different component spatial frequency.

Finally, it should be noted that it has been argued by a number of vision scientists that the abovementioned approaches are confounded by the presence of a number of spatial cues (other than the relative phase differences) that can successfully explain the results briefly described above (e.g., Badcock, 1984a, 1984b; Hess & Pointer, 1987). Specifically, it has been shown that when the f component is of
considerably high contrast, performance can be explained by edge blur (or luminance gradient), whereas when the 3/f component is of relatively high contrast, performance can be explained by observers employing local contrast discrimination (Hess & Pointer, 1987).

References


