The role of orientation and position in shape perception

Mhairi Day
Department of Vision Sciences, Glasgow Caledonian University,
Glasgow, Scotland, UK

Gunter Loffler
Department of Vision Sciences, Glasgow Caledonian University,
Glasgow, Scotland, UK

This study investigates the contributions of position versus orientation information in shape perception by putting the two in conflict. Sampling the orientation of, e.g., a rounded pentagon and positioning the samples on a circle creates a stimulus in which element positions are consistent with a circle but element orientations with a pentagon. Whether orientation or position dominates the percept depends on a number of factors. First, perceived shape shows a band-pass relationship with respect to number of samples. Element orientation captures element position unless elements are widely separated or very closely spaced. This effect is scale invariant. Second, increasing element envelope size or decreasing carrier wavelength strengthens the influence of element orientation, while other parameters such as the phase and polarity of the carrier or the scale of the Gabor are irrelevant. Third, the overall shape of the contour modulates the effect. The strength of the positional signal rises as the orientation difference between adjacent elements increases. Consequently, the computation underlying contour shape relies on a weighted combination of element orientation and position with weights, not fixed, but dependent on stimulus details. When orientation is dominant, its signal is strong enough to alter positional information, giving rise to the illusion of, e.g., a pentagon despite elements being on a circle.

Keywords: shape and contour, object recognition, space and scene perception, perceptual organization


Introduction

Individual neurons in the early stages of visual processing are responsive only to stimulation from within a small part of the visual field (Hubel & Wiesel, 1968). Such discrete and localized sampling presents the visual system with a serious computational problem: objects extend over space and are rarely confined to a small part of a scene. The visual system must therefore combine information across space (Wallach, 1935). The obvious solution is to pool information from cells responding to nearby points in the visual field. However, in the presence of occlusion or abrupt changes in edge orientation (e.g., corners), sophisticated processes are required to decide which signals to include in the representation of an object and which to exclude. Simple proximity rules are not sufficient and more complex computations are required.

Experimental work on spatial facilitation between adjacent elements has confirmed that collinearity is a key parameter in this process (Polat & Sagi, 1993, 1994). According to this, strong facilitation for contrast detection occurs if the orientation of flanking elements is the same as that of a central target and the flankers are positioned along the axis given by the target’s orientation (collinear). Neither orientation alignment (iso-orientation) nor position alignment (same axis but non-matching orientations) are sufficient to produce maximum facilitation alone (Polat & Sagi, 1994).

The dominant role of collinearity in linking elements has also been demonstrated in a task where observers have to detect a smooth, sampled contour embedded in noise (e.g., Barlow & Reeves, 1979; Beck, Rosenfeld, & Ivry, 1989; Field, Hayes, & Hess, 1993; Smits, Vos, & van Oeffelen, 1985). Field et al. (1993) coined the term “association field” to describe the geometric relationships between neurons that result in linkage. The association is strong along the axis given by a cell’s orientation. Along each side of its main axis, the cell has connections with other cells whose orientations are aligned (tangential) to that path. The association field therefore depends on a combination of position and orientation. A recent study (Watt, Ledegway, & Dakin, 2008) has questioned the significant role of element orientations when linking elements into a contour chain. A model based on spatial adjacency, without consideration of element orientations can be successfully applied to some human data on contour integration. However, while spatial adjacency on its own appears to go some way to explain contour detection, it is insufficient to capture the fact that varying the orientation of elements of a path has a significant effect on path detection (e.g., when elements oriented at 45° to the path, the path is undetectable; Ledegway, Hess, & Geisler, 2005).

The relative contributions of element position and orientation in shape processing have been investigated. Orientation alignment can be facilitative in many circumstances (Caelli & Bevan, 1982; Caelli & Dodwell, 1984; Saarinen, Levi, & Shen, 1997), but it does not always
enhance performance. Judgments of whether Gabor patches are aligned (Keeble & Hess, 1998) and detection of positional jitter in a curved path (Keeble & Hess, 1999) show little or no benefit when orientations are aligned. Orientation alignment can enhance performance when detecting small perturbations in the position of elements on a circle but only when the separation between elements is small (Keeble & Hess, 1999; Levi & Klein, 2000). This has prompted the suggestion that element position is more important than its orientation. However, positional dominance over orientation is not seen universally. Wang and Hess (2005) tested observers’ ability to discriminate between sampled shapes and found that orientation information yields performance that is twice as good as position information but neither is as effective a cue as when they are combined.

In this study, we used a novel method to assess the relative role of position versus orientation, using patterns where these two features represent different shapes. Subjects judged the overall appearance of a sampled contour (Figure 1). The orientations of the samples are consistent with one shape (e.g., a rounded pentagon), but their positions are consistent with another (e.g., a circle). If the positional information dominates the percept, the stimulus should be perceived as elements of quasi-random orientation on a circle (jagged circle). This percept would be expected if individual samples were grouped into shapes as in Marr’s (1982) full primal sketch. According to this idea, shape is the consequence of the spatial arrangement of tokens, independent of token properties such as their orientations (Marr, 1982). The overall Gestalt is determined by the position of the tokens. In support of this notion, Marr shows an example of a set of small line segments with random orientations, which results in the percept of a circle when the elements are positioned on a circle’s circumference (Marr, 1982, p. 92; see also Figure 3, right). In contradiction to this, we show that under certain circumstances element orientations, when grouped globally, can determine shape appearance. Observers see a pentagon shape, with elements at its sides perceived as closer to the center than elements at the corners, even though elements are physically equidistant from the center point.

**Methods**

**Stimuli**

The shapes in this study are part of a set of radial frequency (RF) patterns, which are generated by applying...
a sinusoidal modulation to the radius of a circle in polar coordinates (Wilkinson, Wilson, & Habak, 1998):

\[ r(\theta) = r_{\text{mean}} \cdot (1 + A \cdot \sin(\omega \cdot \theta + \phi)). \] (1)

In Equation 1, \( r \) and \( \theta \) (in radians) are the polar coordinates of the contour, \( r_{\text{mean}} \) is its mean radius (size), \( A, \omega, \phi \) are the amplitude, radial frequency, and phase of the pattern, respectively. Different pattern shapes are generated by varying the radial frequency (the number of lobes), the amplitude (affecting the sharpness of each lobe), or the phase (pattern orientation). Zero amplitude describes a circle. Amplitudes are presented throughout this paper relative to the mean radius of the contour in percent.

Theses shapes were either presented as continuous contours or were sampled by oriented 2-dimensional Gabor elements:

\[ \text{Gabor}(x, y, \phi) = e^{-\frac{[x^2 + y^2]}{2\sigma^2}} \cdot \cos(2\pi \omega(x \cos \phi + y \sin \phi) + \delta). \] (2)

Gabor position is given by \((x, y)\), Gabor orientation by \(\phi\), \(\omega\) describes its carrier peak spatial frequency and \(\delta\) its phase. The standard deviation of the circular Gaussian envelope is given by \(\sigma\). Unless stated otherwise, the Gabor’s peak spatial frequency was 6 c. deg.\(^{-1}\), phase was 0 (i.e., cosine phase) and standard deviation was 0.1\(^{\circ}\). The profile of the Gabors was set to match the cross-sectional profile of the continuous contours. The contrast of all patterns (continuous or sampled) was 98\%.

Sampled contours consisted of a variable number of Gabor elements, evenly spaced around the pattern circumference. Two types of sampled patterns were used, differing by the position of the Gabor elements. For the “consistent” type, Gabors were sampled from an RF shape: their position was given by the radius of the RF contour and their orientation by the tangent to the contour at that point (first derivative of Equation 1). For the “conflicting” case, Gabor orientations were sampled from an RF contour (identical to the consistent case), but they were positioned on the circumference of a circle. Therefore, their positions are consistent with a circle but their orientations with a non-circular shape (Figure 2).

To preclude observers from comparing absolute positions of parts of two stimuli (e.g., which contour extends more upward), patterns were presented at the center of the screen with a small amount of random positional jitter (±0.36°). Moreover, to force observers to base their decision on the shape of the pattern rather than on a linear measurement (e.g., the diameter of the pattern), the size \((r_{\text{mean}})\) of each stimulus (which was typically 3.58°) was varied randomly by up to ±0.1°. Pattern phases were fixed so that one lobe always pointed upward. This does not affect the general outcome of the experiments. In a control condition (not shown), randomizing pattern orientations produced the same band-pass relationship between PSEs and number of elements (see Figure 4) with a slight increase in the overall magnitude of PSEs. This suggests that fixing the phase and thereby the orientation of the contours produces a conservative estimate of the capturing effect of orientation on position.

**Procedure**

In order to investigate how orientation and position influenced perception, we measured points of subjective equality (PSE) for “consistent” versus “conflicting” stimuli. The method of constant stimuli was employed in a temporal two-alternative forced choice paradigm. During any given trial, two stimuli, a reference and a test, were sequentially presented in random order. Reference stimuli had “consistent” elements. Test stimuli were consistent RF contours, either continuous or sampled (see Figure 3).

The subjects had to judge the shape of the reference stimulus by comparing it to the test. Their task was to determine which of the two shapes in a trial contained more radial deformation, i.e., which of the two shapes appeared less circular. Responses were made by pressing one of two keys on the computer keyboard. Each trial was initiated by pressing a key and there was a pause of 200 ms before the first stimulus appeared. Stimulus presentation time was 200 ms and the two stimuli were separated by a 200-ms blank. A fixation mark was present on the center of the screen and subjects were encouraged to maintain fixation.

A single experimental run contained one “conflicting” reference stimulus and 7 “consistent” test stimuli of the same radial frequency as the reference but with varying amplitudes. The experimental measure was the percentage of trials in which the test stimulus was judged as less...
circular than the reference for each of the 7 test amplitudes. Different test amplitudes were presented randomly in different trials. Each of the tests was presented 25 times, giving a total of 175 trials per experimental run. The resulting data from each trial sequence were fitted with a Quick function (Quick, 1974), using a maximum likelihood procedure. The PSE (50% point) was determined from each psychometric function. The PSE is therefore the amplitude of the “consistent” test pattern, which produces a perceptually equivalent deviation from the circle as the “conflicting” reference. For each condition, each observer carried out at least two experimental runs on different days and separate threshold estimates were averaged.

**Observers**

The two authors, both experienced psychophysical observers, and four naive subjects (2 males and 2 females) participated in the first experiment, which was designed to quantify the main effect. Subsequent experiments, which aimed to investigate the influence of various stimulus parameters, used a smaller number of observers, specified in the figure legend for each condition. All observers had normal or “corrected-to-normal” vision and viewing was always binocular. No feedback was given to the observers regarding their performance.

**Apparatus**

Stimuli were presented on a LaCie “electron22blue” high-resolution monitor controlled by an Apple Power-Mac G4 computer. The frame refresh rate of the monitor was set to 85 Hz and the spatial resolution was set to $1024 \times 768$ pixels. The software lookup table was defined to maximize contrast linearity using 151 equally spaced gray levels. Pattern luminance was modulated about a mean of 61 cd/m$^2$. Subjects viewed the stimuli.
under dim room illumination and chin and forehead rests were used to maintain a constant viewing distance, which was typically 120 cm. At this distance each pixel subtended 0.018°. To avoid reference cues, the monitor frame was covered with a white cardboard mask with a circular aperture subtending 12° in diameter. Individual patterns were calculated prior to the experiments and displayed using the MATLAB programming environment and routines from the VideoToolbox (Pelli, 1997).

Results

Experiment 1: Position versus orientation

The question addressed here is how position versus orientation information is used by observers when judging shapes. In the first experiment, the orientations of the reference stimuli were derived from an RF pattern with a radial frequency of 5 (pentagon shape) and an amplitude of 5%. This amplitude is approximately 15 times the threshold for discriminating a continuous RF pattern from a circle (Wilkinson et al., 1998) and therefore perceptually clearly distinguishable from a circle.

When comparing the “conflicting” reference with “consistent” tests of varying amplitudes, one might expect a match when the test amplitude is close to zero, consistent with the notion that the position of elements determines the overall Gestalt of the shape. In other words, if observers based their judgment primarily on element position, the “conflicting” pattern should be perceived as a jagged circle with no radial deformation. To provide a quantitative baseline, we determined PSEs for a pattern composed of randomly oriented elements positioned on a circle (Figure 3, sample stimulus shown on the right). This yields a PSE that is close to, but significantly above zero (A = 1.05%; p < 0.05; dotted line). The fact that this value is greater than zero suggests that randomly oriented elements placed on a circle produce—perceptually—a small amount of circular distortion. This could be due to some of the elements having orientations that are consistent with local distortions, i.e., local humps or dents and the shape therefore not appearing perfectly circular. On the other end of the spectrum, a PSE of A = 5% would indicate that appearance was determined entirely by element orientation, with the “conflicting” pattern perceived as the pentagon from which element orientations were sampled (dashed line).

The PSE indicates the best match when the amplitude of the test was A = 3.2% (Figure 3, left): the conflicting stimulus appears to have the shape of a pentagon. The PSE is significantly above the baseline (paired t-test, p < 0.03). Hence, orientation dominates the percept and captures the position of the elements. Positional information exerts a surprisingly small influence on the overall appearance but is not completely ignored. The PSE is lower than what would be expected (A = 5%) if orientation was the sole determinant.

In addition to continuous shapes, we repeated the basic experiment with two additional test patterns to investigate the effect of continuous versus sampled contours and the effect of explicit orientation information in the test pattern. In the first condition, the test was composed of oriented Gabors, identical to those used in the conflicting pattern (Figure 3, center). If a continuous pattern appears to contain more radial deformation than a sampled pattern, this might explain part of the data. Contrary to this, data are independent of the type of test stimulus: continuous or sampled tests yield essentially the same PSEs.

In a second condition, we removed element orientation from the test, by replacing oriented Gabors with circularly symmetric elements (luminance profile given by a D4, the fourth derivative of a Gaussian). In this case, observers cannot base their judgment on a comparison of element orientations between test and reference. Instead, they are forced to base their judgment on the perceived amount of radial variation. This also leaves PSEs unaffected (Figure 3, right). A two-way (subject and condition) analysis of variance (ANOVA) showed that neither of these differences were statistically significant (F(2,12) = 0.426, p = 0.69).

In the remainder of this paper, we investigate how the orientation capture effect depends on the number and details of the Gabor elements and on the overall pattern shape. Given that the type of test stimulus does not affect the data, all subsequent experiments were carried out with continuous tests.

Experiment 2: Varying number of elements

We next investigated how this effect depends on the number of elements and consequently the inter-element separation. Data in Figure 4 show PSEs for various numbers of Gabor elements sampled from an RF 5 shape (pattern radius = 3.58 cm; carrier SF = 6 c. deg.−1; envelope size = 0.1 cm; viewing distance = 1.2 m). There is a significant effect of the number of elements (ANOVA, F(5,18, = 14.384, p < 0.001): data show a band-pass relationship with PSEs highest for about 30 elements (inter-element separations s = 4.5λ, where λ is carrier wavelength) and significantly reduced for few (N = 15, s = 9λ) and many elements (N = 60; s = 2.25λ; Scheffe post hoc, p < 0.01 for all comparisons). PSEs for 60 elements do not significantly differ from the baseline condition in which elements have random orientations (p = 0.587), indicating that sampling densely causes element position to capture the percept.

The number of elements was not reduced below 15 for a radial frequency of 5 in order to allow the shape to be sampled by at least 3 elements per modulation cycle. Although the theoretical limit (Nyquist) is lower for a “consistent” stimulus (2 elements/cycle), this does not
apply to conflicting patterns. For conflicting conditions, fixing the position of the elements on a circle and sampling the orientation of a pentagon with 2 samples per cycle (i.e., 10 elements) result in a stimulus that can be indistinguishable with respect to both position and orientation, from a sampled circle (e.g., the samples are taken from the pentagon’s maximum and minimum radial positions).

Hence, we have shown that perception can be driven by element position or orientation, but it does not allow us to identify which of several factors might be responsible for the switch. Two obvious candidates that might account for the band-pass nature of the data are the number of elements and the separation between elements. The next set of experiments was designed to differentiate between these possibilities.

Experiment 3: Scaling

We first investigated the effect of absolute inter-element separation by varying viewing distance. Figure 5 shows PSEs as a function of number of elements for each of three viewing distances (0.6 m, 1.2 m, and 2.4 m). PSEs for two further distances (3.3 m, 4.2 m) were also measured for 30 elements. Data exhibit scale invariance over this seven-fold range of viewing distance. Two patterns that appear the same (as measure by PSEs) when viewed at one distance also appear the same when viewed at a different distance.

Note that data, here and elsewhere, are not plotted as absolute values. PSEs are presented relative to the radius of the stimuli (as a fraction of the radius in percent). Therefore, a PSE of 3% indicates that a consistent contour containing a radial variation (RF amplitude) of 3% is perceptually matched to a conflicting pattern with orientations sampled from an RF contour with a 5% amplitude (5% was the standard amplitude used for the conflicting stimuli). This means that the absolute amplitude (when expressed in degrees of visual angle) of the PSE increases when pattern radius is increased (by decreasing viewing distance), but the relative amplitude remains unchanged, i.e., scale invariance.

Manipulating viewing distance causes a concomitant scaling of several stimulus parameters (Gabor envelope size, carrier wavelength, inter-element separation, pattern size). Therefore, the inter-element separation, relative to the size and the wavelength of the elements, stayed constant in the preceding experiment. Given the scale invariance in Figure 5, absolute inter-element separation (in degrees of visual angle) can be ruled out as a critical parameter, leaving relative separation (e.g., multiples of carrier wavelength) and/or number of elements as possible factors.

Experiment 4: Carrier wavelength

We first investigated the effect of carrier wavelength. If performance depended solely on the number of elements, the PSE should be unaffected when varying the carrier
wavelength. Contrary to this prediction, the data show a clear dependence on carrier wavelength (Figure 6). Results are for three carrier frequencies (4.5, 6, and 9 c. deg\(^{-1}\), corresponding to carrier wavelengths of \(\lambda = 0.22\)\(^{\circ}\), 0.167\(^{\circ}\), and 0.11\(^{\circ}\)). Gabor envelopes were fixed at 0.1\(^{\circ}\), the RF was 5, the radius was 3.58\(^{\circ}\), and the viewing distance was 1.2 m.

Increasing carrier frequency has two obvious effects. First, the maximum number of elements for which orientation dominance can be seen increases with increasing frequency (decreasing wavelength). The three curves differ most dramatically on the right-hand side where, for example, PSEs show no reduction for 60 elements when carrier frequency is 9 c. deg\(^{-1}\). In contrast, PSEs return to baseline when carrier frequency is 6 c. deg\(^{-1}\) or below. Hence, the higher the carrier frequency, the closer elements can be without diminishing the capturing effect of orientation. Note, however, that 60 elements is the highest number that could be used without adjacent elements starting to overlap for Gabor envelopes of 0.1\(^{\circ}\).

Second, carrier frequency has a modulating effect. The strength of the effect increases with increasing frequency. Note also that there is likely to be a ceiling effect. For all conditions we tested, the highest PSE was approximately 3.5%. This suggests that a perceptual difference remains between consistent and conflicting patterns so that a consistent pattern with an amplitude of 5% always appears to contain more radial deformation than a conflicting pattern with the same amplitude. This argues that the two factors, orientation and position, are combined, rather than the stronger cue exclusively determining performance.

This suggests that the fall-off of PSEs for high number of elements may depend on carrier wavelength rather than the number of elements and suggests that the effect is driven by the inter-element separation expressed relative to carrier wavelength: the higher the carrier frequency, the closer elements can be. To complete the investigation into element separation, we modified the size of the envelope.

### Experiment 5: Envelope size

We increased the overall pattern size (radius of 5.0 deg) to allow elements of increased size without overlap. Carrier frequency was fixed at 6 c. deg\(^{-1}\), RF was 5, and viewing distance was 1.2 m. Modulating the size of the Gabor envelope would not be expected to affect data if the relative separation (center-to-center distance) between adjacent elements was the sole parameter since it is independent of Gabor size. Alternatively, it is conceivable that the relative gap between elements (distance between successive envelop edges) is important, in which case...
PSEs should decrease with increasing envelope size. Neither of these two predictions captures the data.

Similar to increasing carrier spatial frequency, increasing the size of the Gabor envelope increases the strength of orientation. Note that the larger the Gabor envelope, the smaller the maximum number of elements that can be tested without allowing Gabor to overlap (Figure 7).

In summary, increasing Gabor envelope or increasing carrier frequency independently increase PSEs. Given scale invariance—whereby increasing envelope size and concomitantly decreasing carrier frequency results in an undiminished effect (see Figure 5)—this indicates that the two Gabor parameters (size and wavelength) interact.

A likely explanation for the modulating effect of both carrier wavelength and envelope size is their effect on the orientation signal carried by a Gabor. Both increasing spatial frequency and increasing the size of the envelope narrows the range of orientations contained in the Fourier description of a Gabor and hence increases the precision with which its orientation is defined. Therefore, one might expect that an illusion, which is a manifestation of orientation information capturing positional information, is increased when the bandwidth of the orientation content is decreased. However, unlike many other cases, the separation between elements expressed as multiples of carrier wavelength is not the sole determining parameter. The size of the Gabor’s envelope has a major impact.

**Experiment 6: Gabor scale, carrier phase, and polarity**

Randomizing certain parameters, including phase and contrast polarity of the carrier, have been shown to influence a variety of illusions. The motivation behind ascertaining if randomizing such parameters has a detrimental effect is that, if observed, they can be used to suggest that the effect arises from certain cortical processing channels (e.g., channels restricted to one contrast polarity). We also aimed to investigate the possibility that our effect might strongly depend on interactions within a spatial frequency channel by randomizing the scale of the Gabor elements (i.e., corresponding changes of envelope size and carrier wavelength). Data are for 30 elements, where we observed the strongest effect.

The results are surprisingly robust when Gabor parameters are varied (Figure 8): PSEs are not significantly affected (ANOVA, $F_{3,16} = 0.203, p = 0.89$) by randomizing element phase, contrast polarity, or element scale (within a four-fold range). The results suggest that the mechanism underlyng shape computation in these cases largely ignores characteristics such as element scale, phase, and polarity, indicating that it is likely that the effect is not due to interactions at the early stages of visual processing.

**Experiment 7: Varying contour shape**

So far, the only shape used was that of a rounded pentagon (RF 5). We next investigated the generality of the effect by studying different shapes. In the first part of this experiment, two further shapes (RF 3 and RF 8) were tested. If the shape of the contour had an effect, because, for example, the number of samples per modulation cycle changes, data showing PSEs versus number of elements might exhibit a horizontal shift with peaks depending on the radial frequency. The data do not support this hypothesis. Data for all three shapes exhibit the same band-pass relationship with peaks occurring for about 30 elements. There is a small difference in the overall strength of the effect for the three shapes tested. Note that the minimum number of elements was fixed at 3 samples per modulation cycle, i.e., 9, 15, and 24 elements for RFs 3, 5, and 8, respectively (Figure 9).

This suggests that the effect is not driven by the number of elements per cycle of contour deformation. Rather, the
strong similarities of the curves for different radial frequencies suggest similar processing underlying computations of triangular, pentagonal, and octagonal contour shapes.

In the second part of this experiment, we determined PSEs for a wider range of shape frequencies but restricted the investigation to the number of elements, for which the effect appears to be strongest ($N = 30$). The amplitude of all shape frequencies was set to 5% and the frequency of the two patterns to be compared (reference and test) always matched. Although PSEs are highest for intermediate shape frequencies and lower at the top and bottom ends of the range tested, differences between conditions are not statistically significant (Figure 10; ANOVA, $F_{9,20} = 0.822, p = 0.61$). Due to the increased variability between subjects for high pattern frequencies, some conditions are not significantly different from baseline (RF 9: $p = 0.20$; RF 10: $p = 0.26$; RF 12: $p = 0.40$). Modulation frequencies higher than 12 were not tested to avoid the sampling limit mentioned above.

In addition to modulation frequency, manipulating modulation amplitude can also modify pattern shape as shown in the third part of this experiment. PSEs for comparing “consistent” with “conflicting” stimuli depend on pattern amplitude for an RF 5 shape (Figure 11, ANOVA, $F_{6,14} = 36.261, p < 0.001$). For low reference amplitudes (≤0.075), the PSE increases with increasing amplitude. In this range, the PSE is always >60% of the amplitude from which the orientation was sampled (dashed line). Further increasing the reference amplitude causes a reduction in the PSE. Data approach the baseline for high amplitudes (paired $t$-test between baseline and $A = 0.25, p = 0.587$) suggesting that these “conflicting” patterns are perceptually similar to a circle sampled by randomly oriented elements. The icons above Figure 11 show this trend: the appearance of a pentagon increases and then diminishes as the amplitude of the conflicting shape is enlarged from left to right.

Figure 8. Gabor scale, carrier phase, and contrast polarity. Data are for 30 elements of an RF 5 with 3.58° radius, viewed at 1.2 m. PSEs ($N = 3$) show little dependence on these parameters. Randomizing the scale of the Gabors (by concurrently changing carrier wavelength and envelope size from 3 c. deg. to 12 c. deg., second column), carrier phases (across 0–360°, third column), or contrast polarity (+ or −98%, right column) has no measurable effect on the data compared to the condition ($N = 6$) when these parameters are fixed (left column, replotted from Figure 3).

Figure 9. PSEs ($N = 3$) for three different shapes (RF 3, RF 5, and RF 8) relative to the number of elements. Pattern radius was 3.58°, viewing distance was 1.2 m, pattern amplitude was 5%, carrier frequency was 6 c. deg. , and envelope size was 0.1°. Data for the three shapes exhibit largely identical band-pass relationships with peaks occurring for about 30 elements, suggesting that the effect is not dependent on the shape and not driven by the number of elements per cycle of contour deformation.
Figure 10. Effect of global shape assessed by altering the modulation frequency thereby modifying the number of lobes. The stimuli above the graph show conflicting shapes with radial frequencies of 2, 4, 5, 6, 8, and 12. The amplitude of the conflicting references was the same for all shapes ($A = 5\%$). PSEs ($N = 2$) are highest for intermediate shape frequencies and lower at the top and bottom ends of the range tested. Due to the increased inter-subject variability for high RF frequencies, the data for RF 9, RF 10, and RF 12 are not significantly different from the baseline (dotted line).

Figure 11. Effect of global shape assessed by altering modulation amplitude. Increasing modulation amplitude of RF patterns increases the sharpness of each lobe by dragging the shape corners outward (its sides inward). The stimuli above the figure show examples of conflicting patterns with amplitudes increasing from left to right. PSEs ($N = 2$) increase with increasing amplitude of the reference up to about $A = 7.5\%$ and decrease for $A > 10\%$. The diagonal dashed line shows the amplitude of the global shape from which element orientations were sampled. The magnitude of the effect, relative to this amplitude, decreases with increasing amplitude. For high amplitudes ($A = 25\%$), the PSEs approach the baseline (dotted line) suggesting that these “conflicting” patterns are perceptually similar to a circle sampled by randomly oriented elements.
Experiment 8: Rectilinear versus closed contours

We finally ascertained whether the perceptual shift of element position by element orientation is limited to closed contour shapes. In order to investigate the generality of the effect, we constructed “rectilinear” versions of the stimuli. References were composed of Gabor patches with positions centered on a vertical straight line and orientations sampled from a sinusoid.

To allow a direct comparison with Experiments 1 and 6, the number of samples (30) and the frequency and amplitude of the sinusoid were selected to match the parameters used in those experiments. To match the eccentricity of the elements, half were placed to the right of fixation and the other half to the left, with a distance of 3.58° between them (Figure 12). The conflicting reference contours were compared with consistent test stimuli, which were continuous sinusoids. The amplitude of the tests was varied to obtain PSEs as before. Overall orientation of the pattern was always vertical.

The rectilinear version shows an effect, which is qualitatively similar to that for the closed contours: reference stimuli appear to have sinusoidal undulations although their elements fall on a straight line (Figure 12). However, the PSE for the rectilinear version is significantly lower (by about 30%) than for the closed shapes ($p < 0.035$). The dotted line in Figure 12 shows the average PSE for the closed shape condition from the first experiment. As in the case of closed contours, the PSE for rectilinear patterns is unaffected by randomizing Gabor scale, carrier phase, and contrast polarity (ANOVA, $F_{3,12} = 0.203, p = 0.89$).

Discussion

By putting two cues into conflict, our results detail the relative weight that orientation and positional information exert when determining the appearance of a sampled shape. Both cues exert an influence on perception and their weighting depends on a number of factors. In the circumstances where orientation is dominant, its effect is strong enough to alter perceived position such that elements placed on a circle appear to be on, e.g., a pentagon. This is observed in spite of randomizing element scale, contrast polarity, or phase, suggesting that the interactions where orientation is involved in determining perceived shape are beyond the early stages of visual processing. However, the capturing effect by orientation of position is incomplete since the perceived shape can be strongly biased toward but is never identical to that from which the orientations were sampled, suggesting that the percept is determined by a weighted combination of orientation and position.
That orientation can alter position is an unexpected finding given that the overall shape of broken contours is generally considered to be the result of combining the position of elements or tokens independent of characteristics such as their orientations (e.g., Marr). In other words, you expect to see the contour of a hedge despite individual leaves sticking out at different angles and disrupting the smooth continuation of the hedge’s contour. Our results show that this is not universally the case. Under specific circumstances, the visual system favors orientation signals and overrides positional information so that elements are seen to be somewhere else than where they actually are.

Orientation dominance is reduced if patterns are sampled with too few elements. When many elements are used, the switch from orientation to position depends on carrier frequency. The higher the frequency the larger the number of elements and, consequently, the smaller the relative inter-element separation before position becomes dominant. Both increasing carrier frequency and increasing envelope size increase orientation dominance. This suggests that the two interact, since the overall observation is scale invariant: decreasing frequency and simultaneously increasing envelope size leaves results unaffected. The relationship between the orientations of adjacent elements is a further parameter. Element position dominates when adjacent orientations differ substantially (e.g., high RF amplitude or high RF frequency). For high RF amplitudes, the positions where elements actually are (on a circle) are substantially different from where they should be according to the shape from which orientations are sampled.

We will presently argue that this effect probably arises from global shape detection mechanisms rather than local contour completion mechanism. First, we will review the relevant parameters in our experiments and compare them to previous studies.

Relationship to previous studies

The perceived orientation and position of Gabor elements can be influenced in a number of ways. For example, the perceived orientations of a Gabor’s carrier and its envelope are dependent upon each other (Dakin, Williams, & Hess, 1999; Morgan, Mason, & Baldassi, 2000; Skillen, Whitaker, Popple, & McGraw, 2002); the orientation of the envelope attracts the perceived orientation of the carrier, while the orientation of the carrier can either attract or repulse the perceived orientation of the envelope depending on their relative orientations. These interactions between first-order (Gabor carrier) and second-order (envelope orientation) information have been linked to two well-known visual illusions, the Fraser and Zöllner illusions (Dakin et al., 1999; Morgan & Moulden, 1986; Tyler & Nakayama, 1984). In the case of the Fraser (Münsterberg or twisted cord) illusion (Fraser, 1908; Münsterberg, 1897), when a line is made up of tilted elements, its orientation is perceptually biased toward the orientation of the elements. In the case of the Zöllner illusion (Zöllner, 1862), when a line is intersected by oblique elements its orientation is biased away from the orientation of the elements. The relationship between the orientations of the line and those of the elements can explain these opposite illusions (Dakin et al., 1999; Morgan & Moulden, 1986; Tyler & Nakayama, 1984).

Skillen et al. (2002) investigated the effect of spatial scale on the Fraser and Zöllner illusions. Their results indicate that the attraction (Fraser) and repulsion (Zöllner) effects between the orientation of the envelope and that of the carrier depend on the relationship between the spatial scales of the carrier and envelope. Largely independent of the orientation difference between the carrier and envelope, if the spatial scales of the carrier and envelope are similar, attraction is seen; if the spatial scales are very different, primarily repulsion results. There is no agreement about scale invariance of these effects. Skillen et al. (2002) observed scale invariance while Dakin et al. (1999) did not. We see scale invariance and a dependence on carrier wavelength, suggesting that our effect, like those reported by Skillen et al. (2002), depend on relative rather than absolute spatial scale. However our experiments differ in a critical point from those above. Biases in the earlier studies depend on the interaction between two orientation signals, that of the carrier and that of the envelope. In our experiments, only the carrier had a dominant orientation since the Gabor envelope was circular. The perceived orientation of individual Gabors can therefore only be determined by the carrier orientation. As a result, we would not expect biases of carrier orientation on envelope orientation, or vice versa, to affect our results. Rather, we see a perceptual shift of the location of the second-order envelope by the carrier orientation of neighboring elements.

Cases where the presence of surrounding elements can shift the perceived position of a central Gabor have also been reported (Keeble & Hess, 1998; Popple & Sagi, 2000; Whitaker, McGraw, Keeble, & Skillen, 2004). These might be broadly divided into effects elicited by carrier phase or carrier orientation. As an example of the first class, observers perceive a string of vertically oriented Gabors placed directly above each other as if they were positioned on a tilted line if the carrier phases of successive Gabors are gradually shifted (Popple & Levi, 2000; Popple & Sagi, 2000). Phase has also an effect on positional judgments of Gabors. Whitaker et al. (2004) showed that positional judgments of first- (carrier) and second-order (envelope position) information are dependent upon each other. Relative to surrounding elements, the envelope of a Gabor can bias the perceived phase of its carrier and the phase of the carrier can bias the perceived position of the envelope. This effect depends on the separation between elements and their phase relationship. While element separation is also relevant for the data presented here, phase shows little effect on our illusion.
Levi, Li, and Klein (2003) also studied the effect of element phase on element position for a string of five Gabors arranged on a straight line or a curved arc. Their study is a conceptual analogue to ours, both investigating the interactions between carrier and envelope information in shape perception. While Levi et al. studied the effect of carrier phase on envelope position, we measured the effect of carrier orientation on envelope position. The phase of adjacent elements can capture perceived position of a central target with the strongest capturing effect at small inter-element separations (Levi et al., 2003). Our results show that orientation too can capture position but we see the strongest effect of the carrier (in our case orientation) for intermediate separations and no effect for small separations (where position is dominant). Moreover, Levi et al. reported a linear, monotonic relationship between separation and perceived position rather than our non-monotonic dependence. In spite of these differences, it is clear that, in the process of shape computation, positional information can be subjected to adjustments by phase as well as orientation. It is clear from our study that the effect of orientation on position is independent of any effect that carrier phase might have since randomizing the phase of elements has no detrimental effect on our results. Hence, while there are interesting similarities between other studies concerned with phase versus position and ours on orientation versus position, they are independent.

Concerning the effect of orientation on position, Keeble and Hess (1998) showed that the perceived position of a central element could be shifted by the carrier orientation of adjacent Gabors. When 3 Gabors are positioned vertically above one another, the position of a central element is biased toward the right if the orientation of the peripheral Gabors are consistent with a rightward curved contour (i.e., the orientation of the upper Gabor is “\("\) and that of the lower is “/”). Although this illusionary bias was not seen for each observer (one showed an opposite bias), the general trend is in the direction of the illusion reported here. However, the magnitude of the shift in the earlier study is considerably smaller than what we find. Keeble and Hess (1998) report a shift that is “relatively small compared with the shift required to actually put the central Gabor on the contour.” The measured shift was only about 10% of the total shift needed if the element was actually on the contour. The differences in the magnitude of the effect between the earlier study and ours might be due to the different number of elements (Keeble and Hess used only 3 elements) or the comparatively larger difference between element orientations (orientations differed by 45° in the study of Keeble and Hess). The capturing effect of orientation on position in our study shows a clear dependence on relative orientation and essentially disappears if the orientation difference between adjacent elements exceeds a certain limit.

Prins, Kingdom, and Hayes (2007) did use more elements with smaller orientation differences than Keeble and Hess. They sampled sinusoidal lines to determine which component, position, or orientation is critical when discriminating a straight contour from one that is sinusoidally modulated. In contrast to our results on “rectilinear” contours, they found element position to be dominant, at least for low sinusoidal frequencies. For high frequency sinusoids, both features contributed equally to discrimination. What makes a direct comparison between studies difficult is the fact that it is not clear that the computations involved in contour discrimination and those involved in contour appearance are the same. Connected to this, it is conceivable that different task requirements (detecting a deviation from a straight line versus discrimination between two closed contour shapes) may dictate which source of information is primarily utilized by the observer (position versus orientation). In addition, different mechanisms might process different curved contours. Prins et al. (2007) tested curvature detection against a straight line. We concentrated on sinusoids with amplitudes considerably above threshold (by at least an order of magnitude). Evidence suggests that curvature discrimination is subserved by different mechanisms depending on the magnitude of curvature (Whitaker & McGraw, 1998; Wilson & Richards, 1989). In any case, the effect seen with rectilinear stimuli is significantly smaller (by 30%) than with the closed contours, which was the main focus of our study, and it is therefore not clear that the two are the consequence of the same mechanism.

The role of orientation versus position has also been studied for discrimination thresholds with circular and quasi-circular shapes. Levi and Klein (2000) measured detection thresholds for perturbation of the positions of oriented Gabor elements placed on the circumference of a circle. When element orientations are tangential to the circle (collinear), performance is slightly better than when they are not. This modulating effect of orientation is, however, only evident when the inter-element separation is small (Keeble & Hess, 1999; Levi & Klein, 2000) contrary to our findings where orientation shows the strongest effect for intermediate rather than small separations. On the basis of the small effect of collinearity, Keeble and Hess (1999) argue that when detecting small perturbations in the position of elements on a circle, the element location (Gabor envelope) is more important than their orientation (carrier). Note that, contrary to our results, Keeble and Hess found that randomizing dimensions such as patch size and wavelength degrades performance in their shape task.

The positional dominance over orientation seen by Keeble and Hess for circular contours has not been seen in other cases. Wang and Hess (2005) tested observers’ ability to discriminate between sampled RF shapes and circles. Depending on sampling location, the shapes to be discriminated differed either only by position (when sampling from the “corners” and “sides” of RF patterns), only by orientation (when sampling from the “zero-crossings” of RF patterns), or both. Shape discrimination
is twice as good with orientation cues than with position cues but neither yields as good a performance as when they are combined. Apart from the fact that Wang and Hess (2005) measured shape discrimination at threshold, there is another critical difference between their and our stimulus design: both element position and orientation in their study were always consistent with a sampled RF pattern. In contrast, in our experiments, element orientation was always consistent with one shape, while element position was consistent with another.

In summary, evidence is mixed with respect to whether orientation or position information is more important for contour perception. It appears that many parameters, including element orientation, position as well as phase can be important and their relative weights depend on the task and stimulus details. Our study, where the two sources of information are in conflict, offers an example in which perception of contour shape shifts from being dominated by orientation to being dominated by position depending, presumably, on the weight of each or these two cues.

Implications for contour shape processing—relation to contour integration and global shape mechanisms

Much work has focussed on how signals are integrated to form spatially extended contours (for a review see Loffler, 2008). The accumulated evidence is in support of element collinearity as a key parameter. Collinearity requires neighboring elements along a contour to have a specific relationship with respect to both their relative positions and orientations—their orientations need to be tangent to the contour they are positioned on. Interestingly, however, in our study, observers perceive a smooth contour despite the fact that strict collinearity is violated. Only close inspection shows that elements in the “conflicting” case are not collinear. This suggests that element orientation influences perceived position in such a way that it produces a perception of a string of collinear elements.

The perception of a smooth curve in the absence of strict collinearity leads to the speculation that the mechanism underlying our illusion might not be the same as that observed in contour integration tasks. The insensitivity of our results to element phase, contrast polarity, and Gabor size adds support to this notion. Contour integration can be sensitive to element phase, although the extent of this seems to depend on the study (Field et al., 1993; Field, Hayes, & Hess, 2000; cf. Chen & Tyler, 1999; Wehrhahn & Dresp, 1998; Yu & Levi, 1997; Zenger & Sagi, 1996), and is generally limited to operate within spatial scales (Dakin & Hess, 1998, 1999).

There appears to be a considerable amount of discrepancy between studies with respect to scale invariance and the role of absolute versus relative inter-element separation. For contour integration, data have been presented in support of relative separations (Dakin & Hess, 1998) as well as absolute separations (May & Hess, 2008). Similarly, shape illusions (Fraser and Zöllner) exhibit scale invariance according to some (Skillen et al., 2002) but not others (Dakin et al., 1999). As for the effect of orientation on position here, we see scale invariance and an effect of carrier wavelength, pointing toward relative separation as an important parameter. However, we also observe an effect of envelope size, ruling out relative separation as the sole determinant.

In addition to scale invariance, our results are unaffected when element phases, contrast polarities, or Gabor sizes are randomized, all pointing toward operations at a site beyond the early stages of visual processing and suggesting a mechanism, which integrates information broadly across space and across scale and is insensitive to element phase and contrast polarity. This mechanism shares its insensitivity to these Gabor parameters with one that has been described for concentric texture detection (Achtman, Hess, & Wang, 2003).

Evidence from other studies favors global computations processing the type of shapes employed here. It has been shown that the spatial information pooling for RF patterns operates along the entire circumference of the contours and beyond that seen between adjacent elements (Hess, Wang, & Dakin, 1999; Jeffrey, Wang, & Birch, 2002; Loffler, Wilson, & Wilkinson, 2003). Recently Loffler, Bennett, and Gordon (2007) showed that observers can detect an RF shape embedded in a noise field even when “signal” contour elements are not adjacent and separated by several “noise” elements. This ability suggests the presence of shape-specific global mechanisms that have access to information along the entire contour and can sum signal information across space, even in the presence of interspersed noise. Local inter-element interactions cannot account for these results. Therefore, it seems unlikely that mechanisms observed in contour integration studies are the sole limiting factor for the computation of contours such as the RF patterns used here. Rather, global mechanisms must be considered. The global nature of the mechanism responsible for the illusion is also evident from the fact that the effect is significantly diminished for a rectilinear arrangement.

This argues that orientation and position cues are being combined by a globally pooling mechanism in the process of building a contour shape. Rather than one of the two cues enjoying the casting vote, each contributes. This is evidenced by the fact that we never see complete capture of position by orientation. Our data are consistent with a weighted cue combination, whereby the two cues of orientation and position contribute, depending upon how reliable each signal is. If the orientation signal is made more reliable (e.g., by increasing carrier frequency or envelope size), it receives more weight than when it is not. Both increasing spatial frequency and increasing size of the envelope narrow the orientation bandwidth of the elements and hence increase the precision with which its orientation is defined. On the other hand, if the orientation
signal is unreliable (e.g., decreasing carrier frequency or envelope size), the relative weight of the positional signal increases.

With respect to the non-monotonic effect of the number of elements, if elements are sampled too coarsely, local carrier orientations are largely irrelevant since they help little to determine the overall shape. If samples are very close, their relative positions can be derived accurately. In both cases, the strength of the positional signal is high and dominates over orientation. However, for intermediate separations, relative to the wavelength of the carrier, orientation dominates over position.

Which of the two cues dominates also depends on the relative orientations of adjacent elements. If these are very different, as in the case of a five-cornered star represented by a high modulation amplitude or in the case of a multi-cornered polygon, orientation is ignored in favor of position. Only when position and orientation are broadly consistent with the same shape (i.e., when orientation is roughly collinear) can orientation dominate and alter position. In other words, the radial distance between the positions where elements are in the conflicting case (i.e., on a circle) and where they should be if it was a consistent shape (i.e., on a pentagon) must not exceed a critical limit. If local orientations are consistent with one shape but positions with a very different shape, substantial misrepresentations would result if position was ignored in favor of orientation. Hence, the positional weight increases (or orientation weight decreases) when orientation varies drastically from element to element.

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Corresponding author: Gunter Loffler.
Email: g.loffler@gcal.ac.uk.
Address: Department of Vision Sciences, Glasgow Caledonian University, Cowcaddens Road, Glasgow, G4 0BA, Scotland, UK.

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