Local and global contributions to shape discrimination

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Abstract

Humans are remarkably sensitive in detecting small deviations from circularity. In tasks involving discrimination between closed contours, either circular in shape or defined by sinusoidal modulations of the circle radius, human performance has been shown to be limited by global processing. We assessed the amount of global pooling for different pattern shapes (different radial modulation frequencies, RF) when circular deformation was restricted to a fraction of the contour. The results show that the improvement in performance depends on the modulation frequency (the pattern shape) when increasing the number of cycles of an RF pattern. Global processing only extends up to modulation frequencies between 5 and 10. For higher frequencies, performance can be predicted by probability summation. Position uncertainty cannot explain these effects.

In a circumstance where global pooling exceeds probability summation (RF = 5), we split the pattern up into five identical segments conserving the total amount of information presented. Thresholds are significantly affected by different global arrangements of these segments: (a) Occluding small parts of the pattern shows a significant effect on the position of occluders with performance lowest when gaps are placed at the points of maximum curvature. (b) Shifting segments away from the pattern centre (exploded condition) or displaying them out of concentric context (spiral condition) shuts down global processing. (c) Jittering segments radially disrupts both global and local processing. We conclude that RF patterns in the global processing range are analysed by detecting the points of maximum curvature and that, in this range, the visual system can only reliably process up to about 5 local curvature extrema.

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1. Introduction

Shape identification and form discrimination are fundamental to almost any visual task (for an excellent review see Regan, 2000). Consequently, they have attracted much attention both in psychophysics (recent publications include: Cavanagh, 1987, 1988; Hess, Wang, & Dakin, 1999; Keeble & Hess, 1999; Levi & Klein, 2000; Regan & Hamstra, 1992; Wilkinson, Wilson, & Habak, 1998; Wilson, Wilkinson, & Asaad, 1997; Wilson & Wilkinson, 1998) as well as in neurophysiology (Gallant, Braun, & Van Essen, 1993; Gallant, Connor, Rakshit, Lewis, & Van Essen, 1996; Hegde & Van Essen, 2000; Pasupathy & Connor, 1999; Missal, Vogels, Li, & Orban, 1999).

In recent years particular focus has been directed towards a hierarchical framework for pattern vision. It is widely agreed that visual information is initially encoded by discrete localised filters which are sensitive to orientation, spatial and temporal frequency (e.g. DeVlois & DeVlois, 1988). It is clear, however, that the computation of more complex shapes requires the combination of these local filter responses. Gallant and colleagues (Gallant et al., 1993; Gallant et al., 1996) recently provided insight into potential mechanisms. They found neurons in V4 which respond preferentially to radial and concentric gratings and suggested that such units may form an intermediate stage of a pattern vision pathway.

Properties of such intermediate mechanisms have been measured in a variety of psychophysical experiments employing circular stimuli. Results show that humans are remarkably sensitive to judging deviations from perfect symmetry of circles and squares (Regan & Hamstra, 1992). Further studies (Levi & Klein, 2000;
Keeble & Hess, 1999) substituted the closed circular contours with circles constructed of individual samples matching the properties of early neuronal mechanisms. In this way, it could be shown that one crucial factor is the separation between samples. Collinearity of individual samples is only important when inter-sample separations are small.

Wilkinson et al. (1998) introduced radial frequency (RF) patterns to measure the amount of deformation required for observers to discriminate between two closed contours: a perfect circle and a deformed version of it. Applying a sinusoidal modulation to the pattern radius creates such patterns where the amount of deformation is determined by the sinusoidal amplitude and the number of lobes by its RF. Discrimination thresholds for a wide range of RFs are in the hyperacuity range. Hess et al. (1999) used these patterns subsequently to address the question of whether the visual system relied on local or global strategies in such tasks and found evidence for global pooling. Independent evidence for global pooling in intermediate form vision comes from Wilson et al. (1997) and Wilson and Wilkinson (1998). Detection thresholds were measured for Glass patterns (Glass, 1969), which are characterised by a sinusoidal modulation of the radius from Eq. (1a) (Wilkinson et al., 1998):

$$D4(r) = C \left(1 - \frac{4}{3} \left(1 - \frac{r - r_{\text{mean}}}{\sigma} \right)^2 \right) \left(1 - \frac{4}{3} \left(1 - \frac{r - r_{\text{mean}}}{\sigma} \right)^4 \right) e^{-\left((r - r_{\text{mean}})/\sigma\right)^2}$$

where $r$ is the radius from Eqs. (1)–(3) (see below), $\sigma$ determines the peak spatial frequency, and $C$ denotes the contour contrast. The full spatial frequency bandwidth for such a D4 profile is 1.24 octaves at half amplitude and its peak spatial frequency was set to 8 cpd. The mean radius ($r_{\text{mean}}$) for all stimuli was 0.5°. Pattern contrast was set to its maximum value (99%).

We also measured thresholds when the radial deformation was restricted to a fraction of the contour leaving the remainder circular. Deformation was applied to 0.5, 1, or 3 cycles of the patterns for the lower radial

2. General methods

2.1. Stimuli

The closed contours in this study were created according to the following equation (Wilkinson et al., 1998):

$$r(\theta) = r_{\text{mean}}(1 + A \sin(\omega \theta + \varphi))$$

where $r$ and $\theta$ (in radians) are the polar coordinates of the contour, $r_{\text{mean}}$ is its mean radius, $A$, $\omega$, $\varphi$ are the amplitude, RF, and phase of the pattern respectively. To ensure that the contours are closed and do not cross themselves, the amplitude ($A$) has to be restricted to values between 0 and 1 and the frequency ($\omega$) always set to an integer value. The resulting RF patterns are characterised by a sinusoidal modulation of the radius ($r_{\text{mean}}$) of a circle. The frequency determines the number of lobes of the stimulus. Frequencies of $\omega = 3, 5, 10, \text{ and } 24$ (Fig. 2, insets) were used in this study. With the exception of the second experiment, patterns were always presented with random phases ($\varphi$) rendering it impossible for the subjects to predict the exact location of the lobes from trial to trial.

The task in all experiments was to discriminate a perfectly circular shape from patterns, which deviated from circularity by certain amounts. The independent variable for the test patterns was the modulation amplitude ($A$). Setting $A = 0$ in (1) defined the comparison circle. As the amplitude increases the pattern appears progressively to differ from a circle.

The cross-sectional luminance profile of the patterns was defined by a D4 (Wilkinson et al., 1998):

$$D4(r) = C \left(1 - \frac{4}{3} \left(1 - \frac{r - r_{\text{mean}}}{\sigma} \right)^2 \right) \left(1 - \frac{4}{3} \left(1 - \frac{r - r_{\text{mean}}}{\sigma} \right)^4 \right) e^{-\left((r - r_{\text{mean}})/\sigma\right)^2}$$

A second aim of this study was to reveal some of the properties of the mechanisms involved in shape processing. By splitting patterns into individual segments and presenting them in certain ways, we show that performance depends strongly on the configuration of otherwise identical information. Comparison of different conditions suggests that RF patterns are analysed by detecting the points of maximum curvature. Moreover, certain arrangements (avoiding coherent context) appear to disrupt global processing while others (radially jittering segments) affect both global and local processing.
frequencies \((\omega = 3, 5)\) and also to 5 and 7 cycles for radial frequencies of 10 and 24. In all cases, the non-circular part of the pattern was presented in a continuous stretch. The otherwise sharp transition between deformation and circular remainder was smoothed by a D1 (first derivative of a Gaussian) that was fitted to the transitional part of the sinusoidal modulation. Mathematically, patterns where the deformation was applied to only a fraction of the contour, were defined as:

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

\[
\text{for } \theta_{\text{centre}} - \frac{N - 1}{\omega} \pi \leq \theta \leq \theta_{\text{centre}} + \frac{N - 1}{\omega} \pi
\]

\[
R(\theta) = r_{\text{mean}} \left(1 + B \frac{\theta'}{\sigma} e^{-\theta'^2/\sigma^2}\right)
\]

\[
\text{for } \theta_{\text{centre}} + \frac{\omega - 1}{\omega} \pi \leq \theta \leq \theta_{\text{centre}} + \frac{\omega - 1}{\omega} \pi
\]

\[
r(\theta) = r_{\text{mean}} \text{ elsewhere}
\]

where \(\theta_{\text{centre}}\) corresponds to the central location of the deformed region and \(N\) to the number of cycles. \(B\) and \(\sigma\) are the two free parameters of the D1 which were set to match the sine wave's maximum (and minimum) deviation from the base circle and its maximum slope. Note that the above equation is defined for odd number of cycles and the angular phases for the D1s is:

\[
\theta' = \theta - \left(\theta_{\text{centre}} \pm \frac{N - 1}{\omega} \pi\right)
\]

Moreover, the phase of the pattern \((\phi)\) was always set to give a zero-crossing at the central location \(\theta_{\text{centre}}\) (sine phase):

\[
\phi = \omega' \theta_{\text{centre}}
\]

Patterns with half a cycle of deformation were created by either raising or lowering the radius of the appropriate part of the pattern in a way given by a raised (or lowered) cosine function:

\[
r(\theta) = r_{\text{mean}} \left(1 \pm \frac{A}{2} \left(1 + \cos(\omega \theta + \phi)\right)\right)
\]

\[
\text{for } \theta_{\text{centre}} - \frac{\pi}{\omega} \leq \theta \leq \theta_{\text{centre}} + \frac{\pi}{\omega}
\]

\[
r(\theta) = r_{\text{mean}} \text{ elsewhere}
\]

where the positive sign represents a convex bump and the negative sign a concave bump (Fig. 1, left insets). Note that for the amplitude \((A)\) to describe the same maximum radial deviation from a circle as in Eqs. (1) and (2), the value had to be reduced by a factor of two.

2.2. Observers

Three experienced psychophysical observers participated in these experiments, one of whom was naïve with respect to the purpose of the study. All had normal or corrected-to-normal vision. No feedback was given either during practice or when data were taken.

2.3. Apparatus

Stimuli were presented on an Apple iMac. The spatial resolution of the monitor was set to 1024 × 768 pixels (37.24 pixels per cm). The software lookup table was defined to maximise contrast linearity using 150 equally spaced grey levels. Pattern luminance was modulated about a mean of 85.4 cd/m². Subjects viewed the stimuli under dim room illumination and a chin and forehead rest was used to maintain a constant viewing distance of 131 cm. At this distance each pixel subtended 0.012°. Viewing was always binocular. The program controlling the experiments included routines from Pelli’s Video-Toolbox (Pelli, 1997).

2.4. Procedure

The method of constant stimuli in a temporal two-alternative forced choice paradigm was employed. Subjects indicated which interval showed the deformed RF pattern (i.e. which interval did not contain a perfect circle) by pressing one of two keys. The screen

![Fig. 1. Dependence of modulation detection thresholds on the number of cycles of deformation (abscissa) for three individual subjects (open symbols) and their average fitted by the solid line. Thresholds (minimum modulation amplitude) for a RF 5 pattern are expressed in visual angle (right ordinate) and as the Weber fraction between the mean radius of the pattern and the modulation amplitude (left ordinate). Average performance improves with increasing number of cycles and is fit well by a power–law function (exponent = −0.69, solid line). The dashed line gives the prediction of probability summation over locally independent detectors arbitrarily anchored at one-half cycle. Probability summation clearly underestimates the increase in performance. Here and throughout error bars represent standard errors of the mean.](image)
background was set to a mean grey luminance. Each trial was initiated by pressing a key on the keyboard which was followed by two, temporally separated stimuli. The presentation time for each stimulus was 160 ms to preclude eye-movements and multiple fixations. The patterns were presented at a random location within ±25% of the pattern mean radius around the centre of the screen. The time delay between pressing a key and onset of the first interval (as well as the inter-interval delay) was 300 ms. Within an experimental run, patterns with four varying degrees of radial deformation (\(A\)) on a linear scale were presented randomly. Each of these four amplitudes was presented 30 times, giving a total of 120 repetitions. The resulting data were fitted individually by a Quick (1974) function, using a maximum likelihood procedure. Thresholds were defined at the point where subjects were correct at 75% of the trials. Subjects typically completed three repetitions of each experimental condition, on different days. Separate threshold estimates were then averaged.

3. Experiments

Two sets of experiments were conducted. The first set was designed to investigate observer ability to integrate shape information across entire contours. The second aimed to determine which factors are crucial in such a shape discrimination task.

3.1. Experiment 1: Dependence of the degree of information pooling on pattern shape

In order to measure the ability of observers to integrate information across entire contours, thresholds were compared when the radial deformation was restricted to different fractions of the contour. Fig. 1 plots the result for one of the pattern shapes used (RF 5, suggestive of a pentagon). The thresholds for each of the three subjects (open symbols) are shown as Weber fractions, defined as the ratio between the mean radius of the pattern and the modulation amplitude at threshold. Alternatively, the right hand ordinate gives corresponding values expressed in visual angle (sec of arc). The number of cycles within which the deformation was contained is plotted along the abscissa and is symbolised by the top insets. In this case, we measured discrimination thresholds for the unrestricted RF pattern (5 cycles) as well as for 3, 1, and 0.5 cycles. Here and in all subsequent experiments, there was no significant difference between a convex half-cycle deformation and a concave depression. Consequently, the data were averaged for these two conditions.

The results show that thresholds decrease substantially (sensitivity increases) as the radial deformation is applied to an increasing part of the pattern. Averaged across subjects, performance improves almost by a factor of five when comparing the half-cycle condition with the unrestricted RF pattern. Averaged data fall along a straight line in these log-log coordinates indicating a power-law relationship between cycles and threshold, and the exponent of the best fit (the slope of the black solid line) is \(-0.69\). This value is slightly lower than that expected if the visual system pooled information across the entire pattern in a perfect linear fashion. Linear summation would result in an exponent of \(-1\). The observed exponent of \(-0.69\) is, however, a clear indication for global pooling. If discrimination was based purely on local mechanisms, we should expect flat curves, i.e. sensitivity independent of the number of cycles containing the deformation. Even under the assumption of probability summation over local, independent mechanisms, a slope as steep as \(-0.69\) would not be predicted. In our experiments, probability summation would predict a much shallower slope of \(-0.33\) (Fig. 1, dashed line). \(^1\)

We repeated this experiment for three other radial frequencies (\(\omega = 3, 10, \) and 24). The results are summarised in Fig. 2. Comparing the data, it becomes obvious that there is a vertical shift of thresholds for the different RF conditions. This indicates that, in absolute terms and across the entire range of cycles, a RF of 3 (Fig. 2, top left) is harder to discriminate from a circle than RF 5 (Fig. 2, top right) or RF 24 (Fig. 2, bottom right) and RF 10 (Fig. 2, bottom left) is the easiest (the differences between radial frequencies 3, 5, and 10 for 0.5, 1, and 3 cycles are statistically significant; \(p < 0.001\)). Small differences in absolute thresholds for unrestricted RF patterns has been reported previously (Wilkinson et al., 1998). More relevant for the current study, the data show a different dependency on the number of cycles. Comparing the slopes for the three lower frequency conditions (RF 3: \(-0.86\); RF 5: \(-0.69\); RF 10 \(-0.64\)) reveals considerable similarities. The higher exponent for RF 3 may suggest that there is slightly more global summation than in the other two cases. In contrast, the slope of the best fitting curve for RF 24 is significantly shallower (\(-0.31\)) and close to the predictions of probability summation.

\(^1\) This slope of \(-0.33\) was calculated as follows: If deformation was computed on a local basis by independent detectors then the increase in performance when increasing the number of cycles may be predicted by probability summation over these independent detectors (Graham & Robson, 1987). According to this assumption, the relationship between number of cycles and threshold would be given by \(Th = cN^{-0.33}\), where Th is threshold, \(c\) a constant, \(N\) the number of cycles, and \(k\) the slope of the psychometric function. To derive an estimate for \(k\), we averaged the slopes of the psychometric functions across experiments and observers. The resulting value of 3.0 corresponds to a slope of \(-0.33\) for the prediction of probability summation.
It is also evident that for the intermediate frequency (RF 10), the best fitting curve to data points below 3–5 cycles (solid line) would considerably underestimate the thresholds for the entire pattern. The data for this condition is much better described by a two-line fit. Performance between 0.5 and about 3–5 cycles improves more dramatically (slope of $0.64$) than above 3–5 cycles (slope of $0.38$). While the former slope suggests global processing, the latter would be expected from an array of locally independent mechanisms, where the rate of performance increase is given by their probability summation.

In summary, it appears that sensitivity to circular deformation improves with the number of cycles but the rate of this improvement depends on frequency of the circular deformation and the number of cycles. For small and intermediate radial frequencies only about 5 cycles appear to be integrated in a global process. When more cycles are available or when the pattern frequency is high, improvements in performance can be predicted purely by probability summation over local mechanisms. Where global pooling is evident, performance improves slightly less than would be expected from perfect linear summation and there is evidence towards more pooling for lower RF patterns.

3.2. Experiment 2: The role of spatial uncertainty

Up to now the orientation (the phase) of the patterns was always varied randomly from trial to trial. This rendered it impossible for the subjects to predict the exact locations at which maximum and minimum radial deviations would occur. This condition of spatial uncertainty was chosen for the main experiments because one of the goals of this study was to investigate the ability to integrate information across entire patterns. Spatial certainty risks that the subject’s attention is localised to a fraction of the contour and more global shape aspects are disregarded. However, as was argued by a reviewer, spatial (un-)certainty has the potential to explain the main effect presented so far: relatively poor performance at low number of cycles and low modulation frequencies. So can the large threshold elevations, when deformation is restricted to a fraction of the contour, be explained by spatial uncertainty? To investigate this, we repeated the above experiments but removed the uncertainty.

Fig. 3 shows averaged data for three different radial frequencies (3, 5, and 24) in the absence (open circles connected by dashed lines) and presence (filled circles connected by solid lines) of spatial certainty. Spatial
certainty was introduced by fixing the orientation (the phase) of the patterns so that one of the lobes was always pointing upwards. In general, thresholds decrease when subjects are aware of the orientation of the patterns. In the case of the lowest modulation frequency (RF 3, Fig. 3 top left), introducing spatial certainty only marginally lowers thresholds. Most importantly, thresholds are affected equally, independent of the number of cycles and hence the slope of the best-fitting line is unchanged. For the RF 5 pattern (Fig. 3, top right), spatial certainty improves performance somewhat more for one cycle than for the full pattern, thus causing a modest decrease in the slope. While this suggests that some of the large threshold elevations in the first experiment are due to spatial uncertainty, it is clear that introducing spatial certainty for one cycle does not cause thresholds to drop to values as low as those observed for the whole pattern. Furthermore, the improvement in performance when increasing the number of cycles is still stronger (slope of −0.57) than the prediction from probability summation (−0.33), even when spatial uncertainty is corrected for. For the highest RF (24), providing certainty has no effect for the full pattern (24 cycles) but lowers thresholds for 1 cycle. The slope for both conditions (with and without certainty) are close to the predictions of probability summation (thin dashed line).

Consequently, all observations (differences in slopes for different pattern shapes and the failure of probability summation to explain the data for low and intermediate modulation frequencies) made under conditions of spatial uncertainty remain unchanged when introducing certainty. Position uncertainty cannot explain our results. Instead the effects are a consequence of global shape processing.

3.3. Experiment 3: How do contour closure and contour continuation affect sensitivity?

The second experiment aimed to isolate the influence of different factors on the ability to detect circular de-
formation. In all the conditions here, the amount of information presented is identical to that of the unrestricted pattern in the first experiment. Only the way this information is displayed differs between conditions. Hence, a perfect observer who could base a decision on the total amount of information available, regardless of how this information was provided, ought to perform equally well in all conditions. This may not, however, be a reasonable expectation, particularly in the presence of global processing observed in the first experiment. Instead, it is likely that such global mechanisms require information to be presented in a certain fashion. Consequently, such mechanisms would be expected to show a strong dependency on how information is distributed. For example, it has been proposed previously that closed contours are of critical importance in object recognition (Kovacs & Julesz, 1993). If this was the case, one might expect sensitivity to deteriorate when contour closure is broken. In addition, we also tested for the impact of the smoothness of contour continuation and out-of-context segment arrangement as described below.

3.3.1. Methods
RF 5 patterns were split notionally into five identical one-cycle segments. This particular pattern was chosen because we wanted to assess the impact of segment arrangements on global pooling, and global processing was evident for this pattern in the first experiment.

In a first condition (“gap”), contour closure was disturbed by occluding small parts of the pattern (Fig. 4a). Neighbouring segments were separated by small pie-shaped occluders (each 7.2° of polar angle, equivalent to an occluder width of 3.8 arc min of visual angle) set to the background luminance and hence invisible. Any differential impact of the location of these occluders was assessed by centring them either at the points where maximum curvature occurred (corresponding to the corners of the suggestive pentagon; left inset in Fig. 5), minimum curvature (at the sides; right inset in Fig. 5), or zero curvature (halfway between the sides and the corners; central inset in Fig. 5).

In a second condition (“exploded”), the five one-cycle segments were shifted by an equal distance (10% of the pattern’s base radius) away from the pattern centre as if the pattern was exploding (Fig. 4b). In this and all subsequent conditions, the location at which individual segments were separated from each other was located at the zero-crossings (i.e. at points where Eq. (1) takes the value of \( r_{\text{mean}} \)). In a third condition (“jitter”), individual segments were alternately shifted by different amounts. Three out of the five segments were shifted away from the pattern centre while the remaining two appeared at their original position.

Fig. 4. Patterns used in the second experiment. Both the comparison circle (top) and the RF 5 pattern (bottom) were split into five identical one-cycle segments (separated at zero-crossings) and arranged in four different ways: (a) with small gaps occluding parts of the pattern, (b) where individual segments were shifted away from the pattern centre by equal amounts, (c) where individual segments were shifted radially by different amounts, and (d) where they were arranged in a spiral fashion.
(Fig. 4c). In a final arrangement ("spiral"), the five one-cycle segments were positioned in a spiral fashion (Fig. 4d). Here, the central point on each contour segment was fixed at its original position and each segment rotated around this point by 45°. To render the discrimination task non-trivial, the split-up RF 5 patterns were always compared with a corresponding split-up version of a perfect circle (see top half of Fig. 4), resulting in e.g. five circular segments in a spiral array (Fig. 4d, top). Patterns were presented randomly oriented (spatial uncertainty) throughout this second set of experiments.

3.3.2. Results
All thresholds are given as elevations relative to the original condition in experiment 1, where the RF 5 pattern was presented with random phase. Compared to this baseline condition (corresponding to a threshold elevation of 1), thresholds were elevated when contour closure was broken (Fig. 5). Thresholds were raised by an average factor of 1.2, 1.7, or 2.5 when the occluders were placed at the points of minimum curvature (grey bars), zero curvature (hatched bars), and maximum curvature (black bars) respectively. Note that
these points correspond to the sides, between corner and side, and the corners of the suggestive pentagon shape. Consequently, not only do thresholds depend on contour closure, they also vary depending on where the gaps are and increase with increasing curvature of the occluded part of the contour. These differences were assessed statistically using a two-way, repeated measures ANOVA (subject by gap position). A significant effect of gap position \( (F_{2,18} = 13.2; \ p < 0.002) \) was found. Post-hoc analysis (Fisher’s PLSD) shows that all three gap conditions (maximum, minimum, and zero curvature) differ significantly \( (p < 0.05) \) from each other.

The results for the remaining conditions are shown in Fig. 6. To allow comparisons, the data for the gaps located at the points of zero curvature are re-plotted in Fig. 6 (grey bars) since this was the position where the segments were split up to create the exploded, jittered, and spiral patterns. The exploded condition (Fig. 6, bars hatched obliquely from bottom left to top right) shows average thresholds elevated by a factor of two \( (3.5 \text{ versus } 1.7) \) compared to this gap condition. Given their obvious similarity (compare Fig. 4a and b) this is a surprisingly large difference. While they can both be seen as similar, partly occluded contours, there is one obvious difference: their size. Individual segments in the exploded condition have been shifted away from the centre of the pattern by 10\% of its mean radius. In a previous study, thresholds on identical shapes have been found to be a constant fraction of the pattern’s mean radius over a four-octave range of radii, including the radius tested here (Wilkinson et al., 1998). Consequently, if the overall size of the pattern was responsible for differential behaviour, a change in radius of 10\% should affect absolute thresholds in the range of 10\%, which cannot explain the large differences observed here.

In contrast to the first two conditions, the third condition of jittered individual segments (Fig. 4c) provides an example of a disconnected contour, where smooth continuation between individual segments is violated. Thresholds (Fig. 6, black bars) are elevated further than for the exploded condition, rising by an average factor of 5.5 compared to the unrestricted RF 5 pattern and by 1.6 compared to the exploded version.

To our surprise, performance did not deteriorate further when individual segments were arranged in a spiral fashion (Fig. 4d). Rather, it improved compared to the jittered condition. In such a spiral arrangement, (bars hatched obliquely from bottom right to top left) there is obviously no continuation between individual segments but thresholds were not higher than in the exploded condition \( (3.5 \text{ times that of the baseline}) \). In summary, all modifications (gap, exploded, jittered, and spiral) significantly affect our ability to discriminate between a circle and a RF pattern. Implications for shape processing mechanisms are discussed below.

4. Discussion

4.1. Global pooling only extends over about five lobes of RF patterns

The first aim of the study was to determine the amount of global information pooling in a task where subjects had to discriminate circular from non-circular shapes. Evidence for global processing is considered to be present if the increase in sensitivity with increasing number of cycles of RF patterns exceeds those predicted by simple probability summation over local detectors. The results isolate two regimes depending on the frequency of the RF patterns (shape) as well as on their number of cycles. Global pooling only extends up to about RF 5. Probability summation on the other hand is a successful predictor for patterns with higher frequencies. For one intermediate frequency (RF 10), a switch between global and local processing is evident. The visual system outperforms local computations only up to about 3–5 cycles of the RF 10 pattern. Increasing the number of cycles further improves performance only marginally, in accordance with probability summation of local information.

Although evidence for global strategies in shape perception exists (Hess et al., 1999; Levi & Klein, 2000; Regan & Hamstra, 1992; Wilson et al., 1997; Wilson & Wilkinson, 1998), its dependence on the pattern details is new. In a related study, Hess et al. (1999) also investigated the effect of the number of cycles of RF patterns on performance but only tested two low frequency patterns (RF 4 and 8). In agreement with our findings, performance was underestimated by probability summation for both patterns in their study. There are, however, subtle differences between model predictions and data in the two studies. While Hess et al.’s data suggest a close correspondence with probability summation for all but the point of complete circle modulation, our data for low RFs deviate already from predictions at intermediate numbers of cycles (see Figs. 1 and 2). A number of explanations could account for the apparent differences between prediction and data in the two studies. One possibility is the somewhat different experimental parameters: different presentation times \( (160 \text{ ms versus } 500 \text{ ms}) \) with the possibility of multiple fixations for the longer duration, different radial modulation frequencies and different transition region designs. While we smoothed the transition between the area comprising circular deviation and the circular remainder of the patterns, their radial modulation was abruptly terminated at points of zero-crossings. Such a transition results in a salient feature, which may explain why their thresholds were less dependent on the number of cycles than ours. A second possibility lies in the fact that in both studies model predictions were anchored at the lowest number of cycles tested \( (1/2 \text{ in our study}) \).
versus 1 cycle in Hess et al.). This causes our data to deviate from the theoretical prediction at a lower number of cycles.

In any case, there is agreement that the visual system possesses special, global mechanisms for closed shapes which sum information along entire contours in a way that exceeds the (probabilistic) summation over independent local detectors. However, as our results show, such mechanisms do not appear to exist for all patterns but instead are restricted to a certain range of shapes (modulation frequencies and number of cycles) which are identified by our experiments. Therefore, our results go beyond those of Hess et al. in that they allow the nature of the mechanisms computing different closed contour shapes to be inferred. Firstly, the fact that evidence for global processing is present only for relatively low modulation frequencies and number of cycles argues against a fixed, stimulus independent computational strategy. The visual system appears to be able to take advantage of the entire contour only for certain shapes. Only in this range is the whole pattern more than the sum of its parts. Secondly, the different slopes for different pattern shapes argue in favour of at least three different mechanisms.

- One, that shows very strong global pooling and is selective to low radial frequencies (e.g. RF 3). Note that such strong global pooling (slope = \(-0.86\)) is not significantly different from global summation observed for concentric Glass patterns (slope = \(-0.91\); Wilson et al., 1997). Moreover, in experiments on deforming RF patterns, a combination of two low frequencies (RF 2 and 3) also showed the strongest global pooling (Loffler & Wilson, 2001) providing further evidence for specific mechanisms for low RF patterns.
- A second that exhibits pooling in excess of probability summation and computes intermediate frequencies and number of cycles (e.g. RF 5 and up to about 5 cycles of RF 10).
- And a third mechanism, which simply adds up local signals resulting in a probabilistic behaviour for high modulation frequencies and number of cycles (e.g. RF 24 and above about 5 cycles of RF 10).

Neither of these conclusion could have been drawn from Hess et al.’s results.  

Why is global processing observed for some pattern types but not for others? Considering the results of a study concerned with the identification of RF patterns (Wilkinson et al., 1998) may be instructive. Although observers were equally sensitive in discriminating RF patterns from circles if the RF was above two, a clear difference in observer ability to recognise patterns was found. Only few-sided patterns up to a RF of about six could easily be identified; performance was at chance for many-sided patterns. Based on this observation, Wilkinson et al. (1998) proposed that the source of these limitations lies in the nature of hypothetical units which sum concentric contour information. The existence of such mechanisms, restricted to a small range of radial frequencies (up to six in their case) finds support from our data. Global processing does not extend beyond between RF 5 and 10. In this global processing range the visual system appears capable of reliably processing only about 5 cycles of RF patterns. Exceeding this number forces the visual system to revert to local processing where sensitivity does not further improve according to global pooling. Instead, in these circumstances, performance includes global pooling of up to about 5 cycles and some local processing adequately described by probability summation. In contrast to this, for sufficiently high frequencies (e.g. RF 24) where neighbouring lobes become increasingly close, there is no evidence of specialised global processes: over the entire range of cycles, performance is limited by probability summation. It is important to stress that we find evidence showing that these effects cannot be explained by position uncertainty.

4.2. Implications for mechanisms involved in shape discrimination

The third experiment aimed to isolate the differential effects of presenting the same total information in various global arrangements. For a pattern for which the visual system exhibits global processing (RF 5), it can then be tested which arrangements shut down global computations and force the visual system to revert to local processing.

Two conditions served as baselines: performance for the original RF 5 pattern (global processing, threshold elevation of 1 in Fig. 6) and for the case where deformation was restricted to within one-cycle of a closed contour (local processing; bars densely hatched from bottom right to top left in Fig. 6). This latter condition seems an appropriate comparison because in all arrangements here, multiple continuous single cycles were always present. As pointed out by one reviewer, it could be argued that a one-cycle intact pattern is not the best comparison for broken-up patterns. To examine this, a second baseline condition for local computation was included: a single, isolated cycle (bars densely hatched from bottom left to top right in Fig. 6). Across two subjects, performance was not statistically different for
these two conditions \((p = 0.62)\) suggesting that either one could be used as a baseline for local computation.

The condition where individual segments were displayed completely out of their original, annular context (spiral condition) provides a landmark. If such an arrangement disrupted global, concentric pooling mechanisms, performance would be expected to be determined by local computations and no better than for a single cycle of a continuous pattern. This is exactly what happens. Performance for the spiral condition and for one cycle of a RF 5 are essentially identical (Fig. 6). This lack of difference was confirmed statistically using a two-way, repeated measures ANOVA (subject by condition). There are significant differences between some of the conditions \(F_{2,36} = 2.0; p < 0.05\) but not between the spiral and the one cycle \((p = 0.45, \text{ Fisher’s PLSD}).\)

In addition to this out-of-context condition we also tested other global arrangements, where the annular nature of individual segments was explicitly conserved. Occluding small parts of the contours deteriorates performance but the amount of loss in sensitivity depends on the exact position of the occluders. These positions were found to correspond to contour curvature: in order of their increasing effect on elevating thresholds, they were at the points of minimum, zero, and maximum curvature respectively. Thus, while observers can judge whether a presented pattern is perfectly circular or not, regardless of where the contours are broken, their sensitivity suffers significantly more when patterns are occluded at the point of maximum curvature. When occluding these points of maximum curvature, performance drops almost to that for one cycle, indicating that global processes are severely impaired. This in turn suggests that RF patterns are analysed by detecting the points of local maximum curvature. Such an important role for local curvature extrema in visual perception was first pointed out by Attneave (1954) and subsequently confirmed by others (Richards, Dawson, & Whittington, 1986). In combination with our results from the first experiment, it indicates that the visual system cannot reliably combine the information of significantly more than about 5 such local curvature maxima.

Our finding that the regions of maximum curvature rather than those of minimum curvature provide the most important information for discrimination of RF patterns disagrees with inferences in an earlier study (Hess et al., 1999). Their conclusion was based on indirect masking evidence showing that thresholds were elevated most when one-dimensional noise components of the mask (two or three orientations were superimposed) were oriented parallel to the sides of RF 4 or RF 6. In all cases, however, the angles formed by the intersections of their noise components were also oriented in the same way as the “corners” of the RF pattern to be discriminated. Thus, we feel that their masking data are moot concerning the locus of information used to discriminate RF patterns, and we believe that our occlusion results in Fig. 5 provide a clear resolution of the issue.

Further evidence for the important role of curvature in this shape discrimination task comes from the exploded condition. At first sight, the gap and the exploded condition are identical up to a magnification factor and may therefore be expected to yield similar results. This is most evidently not the case \((p < 0.0001)\) and is another example where the visual system appears to revert to local processes: there is no significant difference \((p = 0.47)\) between the exploded and the one cycle condition. What is different between the gap and the exploded condition that could cause such dramatic effects? In contrast to the gap condition, a smooth continuation of the exploded contour at the points of occlusion would result in a dent. This is a consequence of individual segments falling on an annulus but their curvature differing from that of the annulus as can be best appreciated by considering the comparison circle (Fig. 4b, top). Perceptually, this manifests as a less circular appearance for the exploded condition (Fig. 4b, top) than for the gap condition (Fig. 4a, top). What kind of mechanisms would be influenced by these subtle differences? The most obvious choice is that of a mechanism which is sensitive to the average curvature throughout the closed contour under analysis.

The final condition of jittered segments is probably the most striking because thresholds are even more elevated than when segments are displayed in an incoherent context (spiral condition) or in the one cycle condition \((p < 0.0001 \text{ for both comparisons})\). One may argue that it is not particular surprising that a stimulus manipulation which mimics the very cue to which the observer is attending (‘bump’ detection) has a significant effect upon performance. However, the most important observation is not the fact that performance deteriorates in the jittered condition but that it drops below that of a single cycle (isolated or as part of an intact contour). Under the assumption that an observer can only rely on local information in the case of an isolated one-cycle segment, this result indicates not only that global processing is absent but moreover that local computations are disturbed. This suggests that there are global manipulations where performance for the whole (i.e. preserved amount of information) drops beyond that of a single of its parts.

Why does the jittered condition result in the worst performance? One argument could be made on the basis of mechanisms linking individual contours. Linking in contour integration has been reported to depend strongly on local orientation: elements with similar orientation are linked but not those with markedly different orientations (Field, Hayes, & Hess, 1993). Using sampled circles, Levi and Klein (2000) found alignment to enhance performance for sufficiently small inter-sample separation in shape discrimination tasks. Due to the rather small gaps in our experiment, it might be argued
that part of the threshold elevation for the jittered condition is attributable to a mismatch in alignment. Close inspection reveals, however, that the difference in orientation on either side of the split is very small compared to the 90° orientation differences in Levi and Klein’s study. In any case, as Levi and Klein find an effect of about 30–60%, this is clearly not sufficient to explain the huge detrimental effect observed here (550%). It appears more likely that the radial offset between neighbouring segments is critical in effectively abolishing smooth continuation. Another explanation for these counter-intuitive results can be made on the basis of masking effects. It is conceivable that while the jittered configuration masked the global processing of a closed contour, such masking is not present when individual segments are presented out of context, as in the spiral arrangement.

The results of the third experiment allow speculation about the nature of mechanisms underlying closed contour discrimination. Evidently, these mechanisms are very sensitive to the way information is presented. The global mechanisms are affected by non-concentric organisation (a task which includes the computation and comparison of curvature) and by disruption of smooth continuation. The most crucial parameter appears to be that individual segments have to fall into a narrow concentric annulus with a radius determined by averaging across segments. We believe that these observations are compatible with a global computation integrating shape information along entire contours within an annulus determined by the average contour curvature. These processes are not dramatically affected by occlusion, except near points of maximum curvature.

In summary, global processing in shape discrimination only extends up to between RF 5 and 10. RF patterns in this global processing range are analysed by detecting the points of maximum curvature and the visual system can only reliably encode up to about 5 such local curvature extrema. Presenting individual pattern segments in an out-of-context way (spiral condition) shuts down global processing and forces the visual system to revert to local processing. This is also the case when segments are displayed in an exploded fashion. In contrast, jittering elements seems to disrupt both global and local processing.

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### References


