Modulated textures with shape structures implied by a closed flow are processed globally

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Radial frequency (RF) patterns, shapes deformed from circular by a sinusoidal modulation of radius, have been used to demonstrate global integration of shape information around a closed path by showing that the modulation depth required to detect shape deformation decreases rapidly as larger segments of the contour are modulated. In this psychophysical study we use a field of Gabor patches to examine integration of shape information in sampled RF patterns either alone or placed within an orientation-noise background and show that orientation-noise can be disregarded during the integration of modulation information. We also examine integration in modulated textures with local orientations that flow parallel or perpendicular to an underlying RF shape-structure. In using modulated textures comprising of elements with a random radial position but with orientation modulated such that it conforms to the local orientation of an RF pattern (RF texture) we demonstrate integration around texture patterns that imply shape. Texture patterns with element orientations locally orthogonal (RFO textures) to those of RF textures, however, exhibit a rate of decrease in modulation threshold, which is substantially reduced. When the textures are scrambled by permuting the polar positions of the patches the rate of decrease in threshold with increasing number of patches modulated in orientation is reduced for RF textures but not RFO textures. Detection of modulation in both scrambled textures is shown to be consistent with the detection of local cues. We conclude that implied closure in a modulated flow appears to be critical for global integration of textures.

Introduction

In order to interact with objects in the environment appropriately they first have to be identified. This requires the extraction of contour information from natural backgrounds and has been long recognized as a complex task (Marr & Hildreth, 1980). The visual system first needs to detect the local elements of contour information and thereafter combine this with the correct subset of neighboring elements to form the boundary contour of an object (Loffler, 2008). There is evidence to suggest that early stages of visual processing highlight and facilitate the detection of properties of contour fragments that continue smoothly across the scene (Field, Hayes, & Hess, 1993; Kapadia, Westheimer, & Gilbert, 2000; Li & Gilbert, 2002). Thus the salience of the boundary is enhanced. A recent study has also highlighted the influence of the texture contained by the boundary on the detectability of the object as a whole. Machilsen and Wagemans (2011) showed that the probability of detection of objects embedded within noise was predicted by the integration of information provided by the boundary cue and a contained texture cue. Specifically, information provided by a path of Gabor patches aligned tangentially to a shape boundary and a texture cue provided by a contained area of parallel Gabor patches combined to allow performance in detection that could not be predicted by a probabilistic treatment of the performance using the two cues independently.
Once an object is rendered visible analysis of the shape of the object is possible. Evidence exists for processes that actively combine (or globally integrate) properties of the contour fragments around a bounding contour to facilitate subtle discrimination between different shapes (e.g., Dickinson, Han, Bell, & Badcock, 2010; Hess & Field, 1999; Loffler, Wilson, & Wilkinson, 2003).

Global integration of shape has been frequently demonstrated with the use of radial frequency (RF) patterns (Dickinson et al., 2010; Loffler et al., 2003; Tan, Dickinson, & Badcock, 2013). RF patterns are contours created by sinusoidally modulating the radius of a circle. In order to determine threshold amplitudes for discrimination observers are usually asked to discriminate an RF pattern from an unmodulated base pattern (i.e., a circle). Thresholds are determined for a range of numbers of modulation cycles of a particular pattern (i.e., a circle). In order to determine threshold amplitudes for discrimination observers are usually asked to discriminate an RF pattern from an unmodulated base pattern (i.e., a circle). Thresholds are determined for a range of numbers of modulation cycles of a particular frequency (cycles required to complete 360°). As larger sectors of modulation deform the RF pattern discrimination thresholds decrease. This might be expected when more local deformed sectors are presented due to probability summation (PS) of near threshold signals. Probability summation here is defined as the increased probability of detecting local deformation from circularity as more cycles of modulation (CoM) are progressively introduced.

Although some have argued that thresholds for discriminations of RF patterns fall at the rate of probability summation for an incomplete RF pattern (one with fewer cycles than is required to fill 360°) and that thresholds then drop steeply once the entire (whole) pattern is modulated (Schmidtmann, Kennedy, Orbach, & Loffler, 2012), our prior data and those of others typically show a smooth decrease in threshold with increasing numbers of cycles (Dickinson et al., 2010; Dickinson, McGinty, Webster, & Badcock, 2012; Loffler et al., 2003; Tan et al., 2013). Schmidtmann et al. (2012) did however extend the investigation of detection of modulation in RF patterns to the detection of an increment in amplitude of modulation. Global integration/pooling of local components is invoked as an explanation for this superior performance. The presence of integration, the improvement in threshold in excess of that predicted by probability summation, has led to the suggestion that a specialized process exists in the human visual system for the detection of the shape of bounding contours (Kempgens, Loffler, & Orbach, 2013; Poirier & Wilson, 2006). The probability summation prediction used in this study is derived from the fitted parameter $Q$ of the Quick function (see Equation 3). Specifically the rate of decrease of threshold is predicted to fall according to a power function with an index of $-1/Q$. This is the method conventionally applied in studies examining integration of shape information in RF patterns (Bell & Badcock, 2008; Dickinson et al., 2010; Dickinson et al., 2012; Loffler et al., 2003; Schmidtmann et al., 2012; Tan et al., 2013). The method makes the assumption that the threshold for each detector is sufficiently high that a false positive detection result cannot be caused by random physiological noise—a High Threshold Theory assumption. It has been pointed out that other formulations of probability summation can give different predictions under certain experimental circumstances (Meese & Summers, 2012; Pelli, 1985; Tyler & Chen, 2000) and that under such circumstances a Signal Detection Theory treatment might be preferred (Laming, 2013; Meese & Summers, 2012; Nachmias, 1981). A second common assumption of High Threshold Theory is that of a linear transduction of signal. The Quick (1974) function, however, employs an accelerating non-linearity at low contrast and Wilson (1980) shows that, for spatial integration of information by an ideal signal detector, the probability summation prediction formulated by Quick (1974) is consistent with that arrived at following a non-linear transduction followed by signal detection argument. The Quick function incorporates an accelerating non-linearity at low contrasts and a compressive non-linearity at high contrasts and has proved to be a good fit to our psychometric data in the circumstances in which we have employed it. Moreover, for certain experimental conditions of this study, the integration of shape information is approximately linear. That is, the index of the power function describing the reduction in threshold as number of cycles of modulation is increased approaches $-1$, demonstrating that the integration of information in these conditions is almost ideal and cannot be attributed to probability summation.

There are, however, a number of unanswered questions. As Marr and Hildreth (1980) noted, boundary contours are usually embedded in a complex array of background information and thus one task is to extract the relevant contour fragments in the analysis of shape. This step is minimized in most studies on global contour integration that have employed simple continuous, or Gabor (sinusoidal luminance gratings weighted by a Gaussian envelope) sampled, lines with little or no background information. While it has been recently shown that shape discrimination of RF patterns is not significantly affected by the presence of a background Glass texture (Badcock, Almeida, & Dickinson, 2013), discrimination is affected by surrounding the targets with other RF patterns (Habak, Wilkinson, Zakher, & Wilson, 2004). These findings support the argument that contours and coherent textures are detected by discrete processes, despite both processes using global integration of information presented at threshold levels for either shape discrimination in RF patterns (Bell & Badcock, 2008; Dick-
inson et al., 2012; Loffler et al., 2003) or detection of a texture defined by the orientation of the elements conforming to global rule in Glass patterns (Dickinson, Broderick, & Badcock, 2009). Glass patterns with orientations arranged perpendicular to the local radius of the pattern are described as having a concentric structure. Thresholds for detection of a structure in Glass patterns are often quoted as the proportion of coherently oriented elements within the pattern, with the remainder being randomly oriented. Dickinson et al. (2009) showed that the thresholds for the detection of concentric and radial structure decreased in proportion to the square root of the total number of oriented elements in the pattern. This relationship was interpreted as being due to the noise in the mechanism responsible for detection of the structure increasing with the square root of the total number of elements, requiring a similar proportional increase in the signal provided by the number of coherently oriented elements. The signal can, therefore, be regarded as linearly integrated.

The texture within Glass patterns has been described as a static flow (Kovács & Julesz, 1993) that implies a similarity with the movement of salient points across the retina known as optic flow. Optic flow can often be attributed to motion of the observer. Forward motion, for example, leads to radial optic flow and temporal integration of this optic flow yields a radial static flow. The flow, however, might also be attributed to the movement of objects in the visual field. An object rotated around an axis perpendicular to the fronto-parallel plane would produce a concentric flow in the part of the visual field occupied by that object. Dickinson et al. (2009) have shown that observers can selectively attend to the static flow in such circular areas and also within annular regions. Recent research (Schmidtmann, Gordon, Bennett, & Loffler, 2013) suggests that when a textured array is comprised of concentric elements the visual system preferentially processes such a texture by utilizing multiple individual annular detectors of varying diameter to process rings of contours rather than employing a single texture detector. Such a scheme would be useful in the analysis of concentric Glass patterns but it would be more limited when presented with a modulated path, or a modulated flow that might imply the existence of such a path. A requirement for the separation of detection of concentric and modulated flow is not surprising, then, given that a concentric flow can indicate a rotation of the visual field but a modulated flow cannot and, therefore, must describe shape (rotation of an object would result in the salient points of the object being displaced in a circular manner producing a concentric flow in the visual field but this would not give any indication as to the shape of the rotating object).

In Experiment 1, we examined shape integration strength when the contour and the background are comprised of identical elements (Gabor patches) and investigated the effect that the presence of background noise has on the global integration of shape. Integration was found to be robust to the presence of orientation noise. Dickinson et al. (2012) have recently suggested that perhaps as additional CoM are added to an RF pattern, a cue that might be pooled is the deviation in orientation from circular. This cue does not require the presence of a path and it was hypothesized that integration of orientation modulation information might occur in a texture of oriented elements. This was investigated in Experiment 1 by creating textures that conformed to RF pattern structure as stimuli. By “structure” we mean the appropriate orientation versus polar angle, equivalent to those of an RF pattern of the same amplitude (see Figure 1). These texture stimuli allowed for the investigation of whether integration would occur in the absence of explicit radial position information. In this experiment, pattern centers (centers of rotation) varied from trial to trial in order to minimize cues provided by the aperture edges. Integration was observed in RF textures.

In Experiment 2, we used dense texture patterns where the orientation of local elements was modulated in a manner consistent with an RF modulation to determine whether global integration requires the implied closure defined by a smoothly modulated closed flow (RF texture) of oriented elements around the pattern (see Figure 3), which we preclude in one set of stimuli by using elements oriented perpendicular to this flow. These patterns will be termed RF orthogonal (RFO) textures. Experiment 2 confirmed the RF texture results of Experiment 1 using a denser texture and then investigated whether global integration occurs in patterns with elements oriented perpendicular to the appropriate local RF orientation. This arrangement resulted in a flow that was predominantly radial, eliminating the closed nature of the RF texture flow. We found no consistent evidence for integration in patterns with local orientations perpendicular to those of an RF texture.

Since both RF contours and RF texture fields evoke global integration when judged against the conventional probability summation criterion for these patterns, we asked whether these results could arise from detecting the deviation of local elements from the concentric flow rather than the repetition of periodic features using a different measure of local processing. In Experiment 3 we used scrambled versions of the textures employed in Experiment 2 (patterns with permuted polar angles) to investigate whether the modulated flow was necessary for integration or whether local deviations from concentric orientation
were sufficient. Neither scrambled RF textures nor RFO textures (scrambled or otherwise) supported integration of information.

The series of experiments reported here show that contour and some texture processes (Badcock et al., 2013; Bell & Badcock, 2008) support global integration of shape information when shape discrimination is required. We observe that with textural variations, a continuous flow, and an implied closure of the textural elements (which we term “flowsure”) was necessary for global pooling to occur.

General methods

Participants

Each of the experiments had four experienced psychophysical observers. VB and ED were aware of experimental aims for Experiment 1, while in Experiments 2 and 3 KT and ED were aware, all other participants were naïve to these experimental aims. All observers have normal or corrected-to-normal visual acuity. Experiments were completed binocularly except for observer ED who has a divergent squint (normal acuity in both eyes) and completed testing monocularly by covering one eye with an opaque eye-patch. Participation was voluntary and informed consent was obtained prior to commencement. The treatment of participants in this study complied with the guidelines set by the Human Research Ethics Committee of UWA and in accordance with the tenets of the Declaration of Helsinki.

Apparatus

Custom stimuli were generated using MATLAB 7.0.4 (Mathworks, Natick, MA, USA) on an Intel® Pentium® 4 CPU 3.0 GHz (1024 MB RAM) and drawn on the frame buffer (256 MB) of a Cambridge Research Systems ViSaGe graphics system (Cambridge Research Systems, Kent UK). The stimuli were presented on a
Sony Trinitron Multiscan G520 Monitor (screen resolution: 1024 x 768 [34.13° x 25.6°], refresh rate: 100 Hz; Sony, Tokyo, Japan) at a viewing distance of 65.5 cm. Viewing distance was maintained with a chinrest and at this distance each square pixel subtended 2’ of visual angle. Testing occurred in a darkened room (ambient luminance < 1 cd/m²). Screen luminance was calibrated with an Optical OP 200-E photometer (Head model #265) and associated software (Cambridge Research Systems). The background luminance of the stimuli was set to 45 cd/m². A CRS CB6 button box was used to record observer responses.

**Experiment 1**

**Introduction**

The aim of Experiment 1 was to determine the integration strengths of a standalone RF contour, an equivalent contour in background noise, and also of a texture which conformed to an RF structure. RF patterns comprised of sampled contours have been shown to be globally integrated around their contours (Dickinson et al., 2010; Tan et al., 2013). Additionally, it has also been proposed that the ability to discern the shape of a Gabor sampled contour is poorer when the target contour is surrounded by a field of background noise (Casco, Robol, Barollo, & Cansino, 2011; McKendrick, Weymouth, & Battista, 2010). The argument is that the background noise introduces competing elements, which may interfere with contour formation. As mentioned previously, a coherent contained texture has been shown to enhance detectability of a contour (Machilsen & Wagemans, 2011) but the background elements might simultaneously compromise the shape information by providing inappropriate groupings of elements, effectively altering the shape. The implications for our patterns would be that noise patches that are inconsistent with the target RF modulation might be incorporated into the contour, compromising the integration process underlying shape analysis. The aim of this experiment was to assess whether presentation of a Gabor sampled RF contour in background noise hindered global integration of shape information.

A recent study by Dickinson et al. (2012) utilizing RF patterns observed that when the number of CoMs was equal, thresholds for discriminating modulated closed contours from circles were inversely proportional to the frequency of modulation. They proposed that one quantity that adheres to this relationship (for low amplitude RF patterns) is the maximum orientation difference from circularity. It is possible then that the local cue pooled across CoM is orientation difference from circularity. Closed contour shapes are generally defined by both orientation and precise position cues. We wanted to test this relationship and investigate whether positional modulation was necessary for the integration of shape. In this context “position” means the radial distance to the center of an element’s position, from the center of rotation required to make a contour with respect to the polar angle. To test this, a texture analogous to a Glass (1969) pattern was created; one in which elements conformed to an RF pattern’s orientation at a particular polar angle but where the element’s radial positions fell on an implicit grid but with some positional jitter so that the grid was not evident. The phase of the pattern was also randomized across trials to preclude the use of local position specific orientation cues in the detection of modulation. By using a texture we were able to create patterns with a form analogous to RF patterns but where precise radial position information was removed while orientation (with respect to polar angle) information was retained. This allowed us to investigate (1) whether integration of the pattern occurred in the absence of specific position information required to form a continuous contour and (2) how the discriminability for such patterns compared to that for a closed contour shape.

**Stimuli**

Stimuli were composed of Gabor patches with carrier gratings that had spatial frequencies of 3.75 cycles per degree (c/°) and all patches were in cosine phase (relative to the center of the envelope). The diameter of the envelope at half maximum contrast was 0.314°.

Stimuli were based upon a 15 x 15 implicit grid and the entire grid subtended 15° (each patch was located in a 1° square cell in the array). In the Contour-in-noise (CiN) and Texture conditions all square cells were utilized (225 patches in total), while in the Contour-only (CO) condition only the patches of the contour were drawn. The contour comprised 24 patches at equal intervals of polar angle. For the CiN condition, the 24 patches closest to the patches in the contour path were replaced by contour elements and all other patches were randomly oriented. To obtain the appearance of a random arrangement of patches, each noncontour patch was jittered by up to half the dimensions of the cell (vertically and horizontally) in which it was contained, so that there was no perceptible regular underlying positional structure and no overlap between adjacent Gabor elements in the field. This was also true for all patches in the Texture condition. All patches in the Texture condition had orientations that
were tangentially aligned to an underlying RF structure.

The contour and structure used in the three conditions conformed to that of an RF pattern. RF patterns can be defined by the equation:

\[ R(\theta) = R_0 \left(1 + A \sin(\omega \theta + \varphi)\right) \tag{1} \]

where \( R(\theta) \) is the radius of the pattern at an angle of \( \theta \) relative to the positive x-axis; \( R_0 \) is the base radius for the contour or the radial distance to a patch for the texture; \( A \) is the amplitude of modulation expressed as a proportion of \( R_0 \); \( \omega \) is the frequency of modulation (RF number); and \( \varphi \) the phase of the modulation. In this experiment, \( \varphi \) was randomized for all three conditions.

For the contour an angle of \( \alpha \) was formed between the perpendicular of the patches and the radius. This orientation, \( \alpha \), was specified by:

\[ \alpha(\theta) = \tan^{-1}\left(\frac{A \omega \cos(\omega \theta + \varphi)}{R(\theta)/R_0}\right) \tag{2} \]

The center of each RF pattern in the CO and CiN conditions was positioned at a random location within \( \pm 25\% \) of the base pattern radius from the center of the screen (equal to \( \pm 1.25^\circ \)). In the Texture condition there was no contiguous path. All of the patches were positioned relative to the implicit grid in the manner described above. None of the patches were modulated in position and therefore \( R(\theta) \) equated to \( R_0 \) in Equation 2 (above). Patches were modulated in orientation with polar angle according to the numerator in Equation 2, meaning that the patches were only tangent to the same path by chance but all were tangent...
to the same RF structure. Thus the Texture stimuli only incorporated the modulation of orientation and not the modulation of position. The lack of a contiguous path allowed the pattern center of rotation to be jittered up to 3.33° from the center of the screen. While there is a difference in the pattern center jitter, these conditions are still comparable because the RF cues in the Texture condition are scattered throughout the pattern.

**Procedure**

Three conditions were run in Experiment 1: Contour-only (CO), Contour-in-noise (CiN) and Texture (see Figure 1). In a two-interval forced choice task (2IFC), participants were asked to indicate which interval contained the pattern most deformed from circular (registering their response using the button box). The presentation order of test and reference stimuli was randomized. Patterns were presented sequentially and each pattern appeared on screen for 160 ms with an interstimulus interval (ISI) of 500 ms. The test stimuli in this experiment always had \( \omega = 3 \) (RF3), but could have one, two, or three cycles of modulation (CoM) of an RF3 (when less than three CoM occurred the unmodulated portions of the pattern were circular for the contours and concentric for the textures). A D1 (first derivative of a Gaussian) was fitted to the transitional part of the sinusoidal modulation to smooth the sections between the RF and circular or concentric sections as described elsewhere (Dickinson et al., 2012; Loffler et al., 2003; Tan et al., 2013). The patches of the reference stimuli were arranged tangentially to a circle (circular) for the conditions using RF patterns and perpendicular to the local radius (concentric) for conditions using RF textures.

The method of constant stimuli was employed to control stimulus presentation. There were nine amplitudes of test modulation (\( A \) in Equations 1 and 2) per CoM and 60 trials were completed for each of the nine amplitudes (540 trials per condition per CoM). The amplitudes were chosen to ensure adequate coverage of the psychometric function. Runs were self-paced with breaks as necessary. Experimental conditions and their differing numbers of CoMs were run in separate blocks, and these blocks were interleaved.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Texture Slope (( -\gamma ))</th>
<th>Texture PS prediction (( -1/Q ))</th>
<th>Contour-in-noise Slope (( -\gamma ))</th>
<th>Contour-in-noise PS prediction (( -1/Q ))</th>
<th>Contour-only Slope (( -\gamma ))</th>
<th>Contour-only PS prediction (( -1/Q ))</th>
</tr>
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<tbody>
<tr>
<td>VB</td>
<td>-0.917</td>
<td>-0.526</td>
<td>-0.886</td>
<td>-0.524</td>
<td>-1.003</td>
<td>-0.425</td>
</tr>
<tr>
<td>ED</td>
<td>-0.987</td>
<td>-0.71</td>
<td>-0.935</td>
<td>-0.471</td>
<td>-0.996</td>
<td>-0.524</td>
</tr>
<tr>
<td>KT</td>
<td>-0.92</td>
<td>-0.66</td>
<td>-0.942</td>
<td>-0.705</td>
<td>-0.815</td>
<td>-0.542</td>
</tr>
<tr>
<td>RO</td>
<td>-1.071</td>
<td>-0.723</td>
<td>-0.929</td>
<td>-0.481</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Observed index of the power function (Slope) and the corresponding index of the power function as predicted by PS for each participant in each condition. \( -1/Q \) predicts the index of the power function.

**Results**

The proportion of correct responses for each of the nine test amplitudes for each condition/CoM was calculated. Detection thresholds were obtained from the data by fitting a Quick (1974) function:

\[
p(A) = 1 - 2^{-(1+\gamma/Q)}
\]

(3)

to the psychometric data to ascertain amplitude thresholds.

In this function, \( p(A) \) is the probability of a correct response for an amplitude \( A \). The threshold in \( A \) for discrimination of the test-pattern from the reference-pattern at a 75% correct level and \( Q \) a measure of the steepness of the psychometric function (Quick, 1974; Wilson, 1980).

Thresholds were measured for 1, 2, and 3 CoM on the patterns with \( \omega = 3 \) and \( \Lambda \) decreased as a power function of the number of cycles:

\[
\Delta(n) = Kn^{-\gamma}
\]

(4)

where \( -\gamma \) is the index of the power function and \( K \) is a parameter that represents the fitted value of the threshold for a single CoM. The \( \gamma \) for a probability summation prediction is the reciprocal of \( Q \) in Equation 3 (Loffler et al., 2003; Quick, 1974; Wilson, 1980) and a rate of decrease significantly greater than that predicted by probability summation (PS) is an indication of global integration.

Slopes of all fits were significantly steeper than their respective PS predicted slopes, \( t(2) = 4.9, p = 0.039, r^2 = 0.92 \) (CO), \( t(3) = 7.24, p = 0.005, r^2 = 0.95 \) (CiN), \( t(3) = 10.42, p = 0.002, r^2 = 0.97 \) (Texture) as can be seen in Figure 2. Values for slopes and PS predictions are shown in Table 1. A one-way repeated-measures analysis of variance (ANOVA) found no significant effect of condition on fitted gradients (for participants that completed all three conditions), \( F(2,2) = 0.082, p = 0.922 \). An additional one-way ANOVA showed that there was a main effect of condition on discrimination sensitivity (\( K \) in Equation 4), \( F(2,2) = 87.19, p = 0.0005 \). A post hoc Tukey’s HSD showed that while CiN (\( M = 0.031, SD = 0.0012 \)) was not significantly different from CO (\( M = 0.027, SD = 0.0037 \)) both produced...
significantly higher sensitivity than Texture ($M = 0.065, SD = 0.0065$).

**Discussion**

The aim of this experiment was to address two questions: firstly, whether the presence of surrounding noise elements hindered global integration of a contour and secondly, whether global integration of shape was possible for a textured pattern that lacked precise contour-appropriate position information. Our findings indicate that the visual system is able to integrate shape information equally effectively (equal slope of threshold improvement) in both conditions. The fact that CiN has a steeper fit than PS, and also that sensitivity for CiN is not statistically different from CO, demonstrates that the introduction of potentially competing contour cues does not prevent global integration. It also seems to suggest that the visual system is able to discount the irrelevant background. A similar ability to detect RF contours in noise has been demonstrated by Schmidtmann et al. (2013), although we additionally show here that global integration is unaffected. The slopes for Texture were also steeper than PS, indicating that even in the absence of the radial position information required to form a contour the visual system is able to pool orientation information for processing globally. This suggests that orientation information alone is sufficient to induce global integration, consistent with the observation made by Dickinson et al. (2012) that orientation difference from circular is equated in RF patterns with the same number of cycles of modulation.

This result, however, does not imply that position information is completely irrelevant. In comparing observer thresholds for the different types of stimuli, our results show that observers are the least sensitive to textural changes. While position information might not be critical for global integration, decreased sensitivity for the Texture condition might be due to the absence of the precise position information and also, consequently, collinear facilitation of elements (Field et al., 1993). It is worth noting that while global integration occurs for shapes defined by contours and textures, they may very well be accomplished by distinct mechanisms (Badcock et al., 2013).

**Experiment 2**

**Introduction**

Experiment 2 extends on these findings to determine what it is about texture that is necessary for it to be globally integrated. The textures used in Experiment 1 had an RF structure, which adhered to a continuous, smoothly modulated, flow of orientation implying closure. The question remaining was whether global pooling of the shape implied by textures required a smoothly modulated flow of elements (going from $0^\circ$ to $360^\circ$) or whether it was sufficient to have just the presence of systematically modulated information. We assessed this by using two types of dense shape-texture structures: (a) RF textures (similar to the RF texture used in Experiment 1), (b) RF-orthogonal (RFO) textures (see Figure 3). RFO textures were analogous to an RF-texture but had element orientations that were orthogonal to those of the RF texture, preventing the appearance of closure to the modulated flow. This RFO-texture, therefore, required the extraction of modulated flow that could not be presumed to be parallel to a boundary of an object. Experiment 2 is divided into Experiments 2A and 2B which are essentially identical in methodology but employ different frequencies of modulation. Experiment 2B exploits the phenomenon reported in Loffler et al. (2003) that the efficiency of integration of modulation information in RF patterns improves with a decrease in modulation frequency. Experiment 2B is used to verify the conclusions drawn from the results of Experiment 2A.

**Experiment 2A**

**Introduction**

Experiment 2A used patterns with a modulation frequency of 5 cycles per $360^\circ$. The higher frequency of modulation in comparison with Experiment 1 was intended to allow for more samples of the power function describing the decrease of threshold for detection of modulation, with number of CoM. The density of the patterns was also increased with the intention of improving the resolution of sampling of the structure implied by the texture.

**Stimuli**

Stimuli were composed of Gabor patches with gratings that had a carrier spatial frequency $^2$ of 6 c/$^\circ$. A textured pattern was produced by placing the Gabor patches within a circular aperture with a radius of 8.5$^\circ$ of visual angle. As in Experiment 1, an angle of $\alpha$ was formed with the axis of the patch and the perpendicular
to the radius for the RF-structured texture, as described by Equation 2. In RFO patterns, 90° was added to the calculated $\alpha$ for the RF texture. Reference stimuli for the two types of textures were created using $d = 0$ (Equations 1 and 2). This resulted in stimuli that had concentric (for the RF) and radial (for the RFO) textures similar to their Glass pattern equivalents at 100% coherence (Badcock et al., 2013; Wilson & Wilkinson, 1998). It should be noted however that Glass patterns are typically comprised of dot pairs while the patterns we used are composed of Gabor patches (c.f. Achtman, Hess, & Wang, 2003).

The stimuli had a circular area at the center of each stimulus from which patches were excluded. Patches were excluded from this area because at the center, there were fewer elements making it impossible to represent enough different orientations to keep the orientation distribution uniform. Patches were only excluded if their centers were within 1° of visual angle of the center of the pattern and since the radial position of elements was independently jittered, excluding this region did not produce an informative modulated contour at the inner edge of the textures. The Gabor patches were systematically arranged in an implicit square grid. The distance between grid lines was $0.27^\circ$. To obtain the appearance of a random arrangement of patches, the patches were jittered at random within $\pm 0.10^\circ$ of their original position. There was an average of 3172.4 ($SD = 5.46$) patches per stimulus with the uncertainty due to random jittering of elements resulting in a variable number of patches falling within the specified annular stimulus region that was to be drawn. The density of patches within the stimulus was therefore 14.1 patches per square degree. The diameter of the envelope of each Gabor patch at half maximum contrast was $0.157^\circ$. The phase of the grating in each patch was randomly determined to be in either positive or negative sine phase (with the center of each patch therefore at background luminance). In instances where patches overlapped, gratings were added, although due to the patches being constrained to the cells of a Cartesian grid, the overlap was minimal and did not result in the creation of any additional shape cues informative to the task.

**Procedure**

The procedure was identical to Experiment 1 with the exception that for the RFO-structured texture, participants were instructed to select the interval within which they perceived the stimulus to be the most deformed from a radial structure. This set of instructions was different to that employed in Experiment 1 but was equivalent for the two stimulus types. For RF textures, the unmodulated patterns had a concentric structure while for the RFO patterns the unmodulated patterns had a radial structure. The two structure-types were run in separate blocks of trials and the task was completed for the RF- and RFO-structured textures with $\omega = 5$ in Equation 2, where number of CoM varied from 1–5 (separate blocks). The change to $\omega = 5$ was made to provide additional data points for fitting the power functions, while remaining in a range that has previously been shown to evoke global integration (Bell, Dickinson, & Badcock, 2008; Hess & Field, 1999; Loffler et al., 2003), although integration slopes are typically shallower with higher values of $\omega$.

**Results**

As in Experiment 1, a Quick (1974) function was fitted to the psychometric data and thresholds were observed to conform to a power function when plotted against CoM. Figure 4 shows the gradients of the fits (solid lines, means: RF: $-0.77 \pm 0.06$, RFO: $-0.62 \pm 0.03$), and, on average, they were steeper than their respective PS slopes (dashed lines, RF: $-0.41 \pm 0.05$, $t(3) = 22.72, p = 0.0002, r^2 = 0.99$, RFO: $-0.40 \pm 0.06$, $t(3) = 7.05, p = 0.0059, r^2 = 0.94$). Fits for RF-structured texture were also observed to be steeper than those for RFO, $t(3) = 5.86, p = 0.0099, r^2 = 0.92$.

**Discussion**

The aim of Experiment 2 was to understand whether it was necessary for a texture to have a smoothly modulated flow consistent with closure of the structure for global integration to occur. In this part of the experiment (Experiment 2A), we replicated the findings of Experiment 1 with a denser RF-structured texture, again demonstrating that a texture pattern with no contiguous contour could be globally processed. Although we observed that the slopes for the RFO textures were significantly steeper than $-1/Q$ (one criterion for probability summation), they were much shallower than for the RF textures ($-0.62$ instead of $-0.77$) and two observers (RG and ED in Figure 4) provided data quite similar to the probability summation predictions. For these reasons we were unconvinced that global integration was occurring with RFO patterns and decided to investigate further.

One possible explanation for this result is that the RFO patterns are processed by the detectors for radial Glass patterns. If this were indeed the case, the reference RFO texture (which was completely radial) would be perfectly detected by the radial Glass pattern detector and being able to select the test RFO texture would be the result of detecting the noise (i.e.;
deformation from radial) within the structure rather than the periodic modulation itself. Kurki and Saarinen (2004) have demonstrated good sensitivity for the detection of random orientations within an otherwise concentric Glass pattern (i.e., noise in structure), which also served to support the argument for the presence of detectors for concentric shapes. Given that research has also shown that detectors sensitive to radial Glass patterns exist (Badcock, Clifford, & Khuu, 2005; Dickinson & Badcock, 2007, 2009; Seu & Ferrera, 2001; Wilson & Wilkinson, 1998) it is likely that these radial Glass detectors operate in a similar manner to concentric Glass detectors. As such we would expect that a similar pattern of results described by Kurki and Saarinen (2004) for concentric patterns should apply to radial patterns. As the RFO textures are modulated, the orientations of some patches deviate from radial causing them to be perceived as noise. The number of patches that are not aligned radially increases in proportion to the number of cycles of modulation applied to the patterns. Such misalignments are small, due to the small amplitudes of modulation and, therefore, the radial signal might remain approximately constant. If the noise behaves statistically, increasing with the root of the number of misaligned patches, and the degree to which a single patch acts as noise depends linearly on the misalignment, then we might anticipate a slope of about $-0.5$ to arise due entirely to a statistical treatment of local deviations from the coherent structure. The results of Experiment 2A alone were, however, insufficient to support the conclusion. The average integration slope across the four observers for RFO textures was measured to be $-0.62$, somewhat steeper than the hypothesized $-0.5$. Experiment 2B examines integration in RFO4.

Experiment 2B

Introduction

Research into the integration of shape information in RF patterns (Loeffler et al., 2003) has typically demonstrated that when RF patterns of lower frequencies are used, they result in steeper integration slopes. We have shown that integration is also observed for RF textures, and integration slopes were seen to be steeper for RF3 textures than for RF5 textures. It might be expected then that, if integration were occurring in RFO textures, it would become stronger as frequency of modulation decreased. Conversely, should the RFO pattern be processed by the Glass pattern mechanism, as we hypothesize, then no difference would be expected across frequencies. As a test of this hypothesis we examined the degree to which integration was observed in RFO4 textures for comparison with the results of Experiment 2A for RFO5 textures.
Stimuli

RFO texture was created in the manner described for Experiment 2A above but with $\omega = 4$.

Procedure

Identical to Experiment 2A, with the exception that thresholds were measured for 1–4 CoM for the RFO4 texture.

Results

A Quick function (Equation 3) was fitted to the data and thresholds were again observed to conform to a power function. Figure 5 shows the slopes of the fits (solid lines, means: $-0.61 \pm 0.19$) and on average they were steeper than their respective $-1/Q$ PS slopes (dashed lines, means: $-0.44 \pm 0.06$); $t(3) = 3.31, p = 0.02, r^2 = 0.79$. The average of the slopes of the power functions are, however, equivalent for RFO4 patterns ($0.61 \pm 0.19$) and RFO5 patterns ($-0.62 \pm 0.03$), contrary to what might be expected from the change in radial frequency if the modulation information were being integrated. A subsequent two-tailed paired samples $t$-test showed that slopes for RFO4 were not significantly different from RFO5, $t(3) = 0.08, p = 0.94, r^2 = 0.002$, consistent with processing being due to a mechanism that, instead, integrates orientation difference from a radial structure but was indifferent to the modulation.

When compared against a slope of $-0.5$, the slopes of the RFO5 (from Experiment 2A) were shown to be different, $t(3) = 7.55, p = 0.005, r^2 = 0.95$, while slopes of RFO4 were not, $t(3) = 1.85, p = 0.16, r^2 = 0.53$.

Discussion

Replication of the experiment with an RFO4 texture again showed that slopes of the fits were steeper than a PS prediction of $-1/Q$; but again, resembled those potentially indicative of a statistical treatment of local deviations from the radial structure. When compared with paired samples $t$-tests, slopes for RFO5 and RFO4 were not different from each other. The lack of an increase in the slope going from an RFO5 to an RFO4 suggests that shape information within RFO textures is not globally integrated.

Theoretically, a slope of $-0.5$ would be suggested if the probability of detection of deviations from the base pattern (in this case radial) increased with the root of the number of elements that deviated in this manner. Unfortunately, we had varying results when comparing RFO4 and RFO5 to a slope of $-0.5$, which prevented us from suggesting that RFO patterns were processed by local processes. We address this in Experiment 3, by making a direct comparison between patterns that have an intact global structure and analogous patterns with the same set of local deviations but where the global structure has been removed. Experiment 3 further tests the hypothesis that detection of the RFO patterns is effected by a mechanism sensitive only to deviation of orientation from radial. Such a mechanism would be indifferent to the polar position of the elements that deviate in orientation from radial.

Experiment 3

Introduction

In Experiments 1 and 2 we demonstrated evidence for global processing for RF textures. The verdict on RFO textures, examined in Experiment 2, however, was less clear. The power functions were steeper than a probability summation prediction derived from the Quick function but shallower than for the RF
textures. In Experiment 2 we proposed that rather than being weaker integration of modulation information, this might be consistent with the detection of noise in an otherwise radial pattern. If this were the case, then the mechanism effecting this detection would be indifferent to modulated flow of the RFO texture. As the number of CoM increased in the textured stimuli used in Experiment 2, the number of local elements that differed in orientation from the base structure (concentric or radial) increased. In Experiment 3 we address whether increased discriminability of the texture (as CoM increased) could be sufficiently explained by an increase in the number of elements possessing orientations different from the base structure. To determine whether this was the case, we created a scrambled version of the textures used in Experiment 2. At a local level, when modulation is introduced, the number of elements with orientations that differ from concentric/radial (the base textures for RF/RFO textures, respectively) increases. If deviations from concentric/radial are detected using solely local, single element processes, then the probability of detecting deviations from concentric/radial, effectively the signal strength, might be expected to increase with the root of the number of elements that deviate in this way (Badcock & Wong, 1990). All of the patterns retain a strongly concentric/radial structure, however, as the amplitude of modulation is small. The noise due to the elements that deviate from the base structure, then, is seen in the context of a constant coherent signal. In Experiment 2B, we tested the expectation that threshold orientation modulation therefore might be expected to fall as the proportion of signal elements increases with a slope of −0.5 for RFO patterns and obtained varying results. The prediction of a slope of exactly −0.5 is, however, theoretically driven whereas comparison of the slopes for the modulated textures and the scrambled versions of the stimuli provides a conclusive empirical test of whether the modulation information is integrated in RFO patterns.

(i.e., systematic orientation modulation with respect to polar angle).

**Procedure**

The procedure for this experiment was the same as Experiment 2, where participants had to indicate which pattern was most deformed from circular/radial. Thresholds were measured for 1–5 CoM for scrambled RF5 and scrambled RFO5 texture and 1–4 CoM for scrambled RFO4 structured texture.

**Results**

Thresholds are derived from the Quick function (Equation 3). The power function (Equation 4) describes the threshold versus the number of CoM. Thresholds for participants in the scrambled conditions were observed to fall as CoM increased (see Figure 7). The slope of the fits for each participant is shown in Table 2.

The critical test was whether scrambling the position of the elements of the pattern made any difference to the slope since this would indicate that global structure was important. In the following, significance levels were Bonferroni corrected for multiple comparisons (critical level = 0.05/3 = 0.0167). A comparison of the two RF5 stimulus types (structured vs. scrambled) showed that the scrambled had significantly shallower slopes, $t(3) = 13.23, p = 0.0009, r^2 = 0.98$.

If the orthogonally structured patterns were using only local orientation differences, scrambling should have minimal impact. Consistent with this prediction, scrambling the patterns did not significantly alter the slopes for the RFO5 patterns, $t(3) = 2.15, p = 0.12, r^2 = 0.61$, or the RFO4 patterns, $t(3) = 0.36, p = 0.74, r^2 = 0.04$. These results supported the prediction that the detection of RFO patterns relied only on local orientation information.

**Discussion**

In this experiment we observed that for the RF5 patterns, scrambling the local elements produced lower integration slopes suggesting a critical process has been disrupted. This demonstrates that for structured RF texture, coherent shape information yields a performance enhancement that exceeds that predicted by analyzing local elements. This suggests that scrambling a smoothly modulated RF texture, such that the local element orientation information with respect to circular is unchanged, but the percept of structure arising from the relationship between local elements is removed,
produces thresholds that are consistent with detecting local differences rather than global structure thus indicating that observers are utilizing the coherent structure information and not depending solely on the detection of local differences from circularity when discriminating structured RF textures.

In contrast to the RF textures, the data for the RFO texture did not seem to consistently indicate any global processing. Scrambling the RFO5 textures did not produce a significant difference in slopes (between the structured and scrambled), suggesting that the visual system may not be using any available structure for global processing in either case. We again observed a similar pattern of results with RFO4 texture, where scrambled and structured were not different from each other. Doing a direct comparison of the slopes for the modulated textures versus their scrambled analogues provided a conclusive empirical test of whether the modulation information was integrated. The most parsimonious conclusion is that global processes integrating modulation of orientation information are unlikely to be involved with the RFO textures used in our tasks.

Figure 6. (A) Example of a pattern with a structured RF5 texture. (B) Example of a corresponding scrambled RF texture. (C) Example of a pattern with a structured RFO5 texture. (D) Example of a corresponding scrambled RFO texture. In all four examples the CoM = 5. The patterns in (B) and (D) contain patches that have populations of orientations deviations with respect to the local radius that are identical to the patches in (A) and (C) respectively. However, these patches are permuted at random such that their positions are inappropriate for the perception of an RF/RFO texture.
This study set out to examine global integration of information in the visual system. In Experiment 1 we showed that when an RF contour is embedded in noise integration of shape information in the pattern is not compromised. While Schmidtmann and colleagues (2013) have previously conducted work examining the detection of contours in noise, their study did not determine integration strengths for contours in noise. Since the integration of a contour occurs despite the presence of potentially competing background cues, it seems that the visual system is able to discount the irrelevant background information when processing shape contours. Experiment 1 also demonstrated that shape information in a texture containing an RF-structure that lacks the precise position information required to form smooth continuous contours can be globally pooled based solely on the orientation information present. Research by Dickinson and colleagues (2012) suggests that orientation deviations might be the local features that determine thresholds for contours in noise. The manner in which we investigate integration in Experiment 1, is one which has been widely used in previous research involving RF patterns (Bell & Badcock, 2008; Dickinson et al., 2010; Loffler et al., 2003; Tan et al., 2013) but which has been criticized for being based on a High Threshold assumption in the method for the calculation of PS. There are varying methods in which PS can be calculated, which, in turn, would serve as a base for comparison against any summation slope (i.e., whether integration was occurring). However, Wilson (1980) has explicitly examined whether the High Threshold assumption is critical and given the nonlinear nature of the transducer for RF modulation (Bell, Wilkinson, Wilson, Loffler, & Badcock, 2009; Figure 4), the method was shown to be valid. In addition the summation slopes we observe in Experiment 1 are extremely steep and approximate a slope of \(-1\) (perfect information related to the formation of a path does affect an observer’s sensitivity to the discrimination of a shape. Evidence for this comes from the fact that despite Texture and CO producing similar integration slopes, indicating comparable efficiencies of integration of shape information; observers do, however, show lower discrimination thresholds for complete contiguous paths over textures. Potential explanations for these lower thresholds for the continuous path include collinear facilitation and also the possibility that the pattern centers are better defined resulting in more precise judgments of local angle with respect to the center.

General discussion

Table 2. Observed index of the power function (Slope) for the scrambled textures with 95% confidence intervals for four participants.

<table>
<thead>
<tr>
<th>Participant</th>
<th>RF5 scrambled</th>
<th>RFOS scrambled</th>
<th>RFO4 scrambled</th>
</tr>
</thead>
<tbody>
<tr>
<td>KT</td>
<td>(-0.51[-0.62, -0.41])</td>
<td>(-0.51[-0.76, -0.28])</td>
<td>(-0.54[-1.02, -0.06])</td>
</tr>
<tr>
<td>ED</td>
<td>(-0.61[-0.80, -0.42])</td>
<td>(-0.48[-0.76, -0.21])</td>
<td>(-0.62[-0.99, -0.25])</td>
</tr>
<tr>
<td>TM</td>
<td>(-0.48[-0.55, -0.41])</td>
<td>(-0.59[-0.71, -0.46])</td>
<td>(-0.57[-0.72, -0.42])</td>
</tr>
<tr>
<td>RG</td>
<td>(-0.57[-0.66, -0.49])</td>
<td>(-0.56[-0.79, -0.33])</td>
<td>(-0.60[-0.76, -0.44])</td>
</tr>
</tbody>
</table>
integration), which allows us to safely reject any notion that the stimuli used in Experiment 1 are not globally processed, given that multiplicative noise is not seen with these stimuli (Tyler & Chen, 2000).

In Experiment 2 we moved on to investigate whether implied closure of a smoothly modulating flow of elements was necessary for global integration of shape structure to occur in textures. Two textures that contained systematic modulation of orientation were employed. Both types of texture had smoothly modulating orientations, but only the RF-texture stimuli had orientations that defined a texture flow around the pattern implying closure. It was observed that both RF- and RFO- textures had slopes for the power functions, describing the decrease in threshold as cycles of modulation were added, that were steeper than probability summation predictions derived from the fits to the psychometric functions. This might be interpreted as evidence for global integration for both stimulus types. However, slopes for the RF textures were much steeper than for the RFO textures and the values of the slopes for the RFO textures resembled those expected if only local processes were involved. Typically, for RF patterns, integration efficiency is seen to improve as the frequency of modulation is reduced and so, in an attempt to enhance the detectability of potential global integration, the integration of shape information in RFO4 textures was measured for comparison with that for RFO5 textures. No improvement in efficiency of integration was observed, suggesting that the discrimination of RFO patterns from radial patterns is performed using local information. As mentioned, a common property of both the RF- and RFO- textures was the systematic addition of orientation modulation information with respect to the polar angle at regular intervals. This property alone, however, appears to be insufficient to evoke integration in textures with an underlying shape-structure. In addition to this periodic modulation, a smooth flow of orientated elements around the texture pattern that implies closure is observed to be necessary for local information to be integrated. It would seem that this must be provided by a process that tolerates radial positional noise when forming potential contours, although Hayes (2000) shows that when forming extended linear contours such tolerance is weak.

Schmidtmann et al. (2013) have recently proposed that textured Gabor arrays might be processed by multiple annular detectors of differing diameters that sum information globally, but only within each detector’s specific annulus. This could imply that a ring of elements within the textured array would have to be nearly contiguous for such an annulus detector to be activated. However, data obtained using our RF texture stimuli showing that integration occurred despite the lack of any contiguous ring of elements suggesting this contiguity might not be crucial for global processing. Schmidtmann et al. (2013) did introduce positional jitter to their stimuli and found that the visual system could tolerate up to 5% positional jitter with no loss in sensitivity, but as more jitter was introduced an increase in coherence threshold was observed. They argued that this increase in threshold could be explained by elements falling into the receptive fields of adjacent annular detectors and this could be described probabilistically. This again would seem to suggest that the texture detector we described above could potentially be explained by the probability of elements falling into adjacent annular detectors. However, Tan et al. (2013) have demonstrated that shapes defined by explicit paths, and shapes defined by differences in textures, are processed independently. When a shape is defined by both a path and texture, the two cues do not sum linearly, instead the visual system uses either one or the other in a probabilistic manner. If indeed the texture detector operated by way of activating multiple annular detectors then it would be expected that the path and texture cues would sum when used in tandem, however the results from the previous paper (Tan et al., 2013) did not support this.

Because the RFO5 and RFO4 patterns showed similar efficiencies of integration we concluded in Experiment 2 that the mechanism that allowed such patterns to be discriminated from purely radial patterns relied upon local information. Unfortunately, comparisons to a theoretical prediction of local processing showed varying results for RFO4 and RFO5 slopes. In Experiment 3 we tested this conclusion by measuring the efficiency of integration in RF and RFO patterns that had been scrambled, in the sense that the positions of the elements had been permuted while retaining their orientations with respect to the local radius. Comparison of the structured textures versus their scrambled counterparts would also serve as a conclusive empirical test for whether modulation information inherent in the texture was integrated. The RF textures that contained a coherent underlying structure showed steeper integration slopes than their scrambled counterparts. The RFO patterns, however, had the same slopes whether scrambled or not, suggesting the inherent global structure was not being utilized. Thus, we propose that global integration of a modulated texture requires the presence of a coherent flow that implies closure. Discrimination of the RFO patterns and the scrambled patterns from coherent concentric or radial patterns might rely on the mechanism responsible for the detection of coherent organization in Glass patterns (Dickinson et al., 2009; Wilson & Wilkinson, 1998).

The RF textures used in our experiments were created by modulation of orientations from familiar
concentric or radial Glass pattern structures. In experiments using conventional Glass patterns, textures comprised of randomly oriented local elements are doped with coherent orientations and thresholds for discrimination of such patterns from wholly random patterns are measured. Dickinson et al. (2009) showed that threshold as a proportion of the total number of oriented elements decreased in proportion to the root of the total number of oriented elements. The noise was assumed to increase with the root of the total number of elements leading to the assumption that the signal due to the coherent elements summed linearly. Conversely, Kurki and Saarinen (2004) have also shown that not only is it possible to detect noise amongst signal, when trying to do so, the detection of orientation noise benefits from the presence of coherent global structure. If the discrimination of scrambled and RFO textures from purely radial patterns relies upon the mechanism responsible for the processing of Glass pattern structure, then evidence of integration in RF textures reveals an additional mechanism that is responsible for the analysis of modulated textures.

In summary, this study has demonstrated four main points. Firstly that integration of a contour is not hindered in random orientation noise. Secondly global integration of a texture pattern can occur in the absence of specific radial position information and that this integration strength is no different to that of a closed contour shape. Thirdly, we find that a smoothly modulated flow that implies closure (flowsure) is necessary for global integration of texture. Lastly in processing modulated textures, analysis of the local orientation differences in the absence of modulation of flow is inadequate to account for integration of information in RF textures and the presence of a coherent underlying structure is necessary for such modulated textures to be globally processed. The lack of any flowsure of elements in the RFO texture might be a reason why such textures are only processed locally.

Keywords: radial frequency patterns, RF patterns, texture perception, integration

Acknowledgments

This research was supported by an Australian Research Council Grant DP1097003, DP0666206 & DP110104533 to DRB and a SIRF scholarship funded by the University of Western Australia to KWST.

Commercial relationships: none.

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Footnotes

1 The experiments were conducted as part of the separate PhD Theses of Bowden and Tan.
2 These patterns extend previous work examining sensitivity to shape changes with texture segmentation borders (Tan et al., 2013); smaller Gabors than used in Experiment 1 were chosen to allow a finer grain texture.

References


