Critical Factors of Global Shape Processing in Human Vision

Robert J. Green
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School of Psychological Science
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Thesis Abstract

The detection and identification of objects is a primary function of the visual system and the bounding contours which make up these objects are frequently shapes which can be described by deformed circles. Within the literature there is on-going debate about whether information on these contours is being integrated together to create a global percept or whether discrimination relies purely on local features, with an increased likelihood of discrimination with more local elements (probability summation). The recent objection is concerned with the previous use of high threshold theory (HTT) for generating probability summation estimates, as Baldwin, Schmidtmann, Kingdom, and Hess (2016) found evidence to suggest this method was inappropriate. Within their study, they found observer thresholds were not significantly different to probability summation when estimated using signal detection theory (SDT). They suggested this called into question a significant amount of research which had used the HTT method. Within this thesis first we demonstrate strong experimental evidence for the global processing of low frequency radial frequency (RF) patterns (circular patterns which have their radius modulated as a function of their polar angle; Chapter 2). We then compare our results against HTT and SDT probability summation estimates. We found that the HTT method used by Loffler, Wilson, and Wilkinson (2003), and followed in subsequent studies, likely produced the correct conclusions about global shape processing occurring around low frequency RF patterns. These results were contrary to Baldwin et al. (2016) who suggested RF patterns were not globally processed and Schmidtmann, Kennedy, Orbach, and Loffler (2012) who suggested global shape processing did not occur around RF patterns with partial modulation (i.e. containing unmodulated sectors of the contour). In Chapter 3 we investigated the difference between fixed and random phase presentations of RF patterns as a potential explanation of the difference between Baldwin et al. (2016) and our findings in Chapter 2. We also compared observer
thresholds for open contour modulated lines to closed contour RF patterns to determine whether closed contours are required for global integration. There was a significant effect of fixed phase presentation on observer thresholds for RF patterns, reducing observer thresholds at 1 cycle of modulation and also reducing their strength of integration around the contour. There was no such effect on modulated lines, which also displayed a different pattern of results to the RF patterns, with thresholds decreasing from 1 to 2 cycles of modulation, but not from 2 to 3 cycles of modulation. These results collectively suggest the fixed phase presentation used by Baldwin et al. (2016) caused an interaction between local and global cues which reduced observer integration strength, resulting in their inability to reject probability summation estimates. The modulated lines displayed a different pattern of results to the RF patterns and were unaffected by fixed phase presentation, indicating these two stimuli are processed differently by the human visual system contrary to previous suggestions (Mullen, Beaudot, & Ivanov, 2011; Schmidtmann & Kingdom, 2017). Because of our concern with the methodology of Baldwin et al. (2016) we revisited their experiment which examined whether it was more efficient to combine information within a single contour than when it was spread across multiple contours (Chapter 4). Local processing of features and probability summation would not be affected by such a change but if the critical mechanism is contour processing it would. By removing the spatial certainty in the location of deformation, we found strong evidence for integration of information within a single contour, but not across multiple contours. This was further evidence that the results of Baldwin et al. (2016) were influenced by the interaction between local and global cues due to their use of spatial certainty. Work conducted as part of my honours thesis in 2012 suggested that the temporal displacement of an RF pattern created by viewing the stimulus through an implicit vertical slit, did not reduce integration strength for an RF3. Given that research by Or, Thabet, Wilkinson, and Wilson (2011) used a dot’s motion to trace out the path of an RF3 and found a significantly reduced strength of integration, we extended my
previous work and investigated whether there was again an interaction between local and
global cue which was causing this reduction (Chapter 5). We found that, similar to Chapter 4,
when we removed the salient local cue (this time the dot’s change in speed at locations of
deformation), observer thresholds returned to those found for RF patterns viewed through a
slit. Furthermore, we found no significant difference in the observer thresholds for an RF3
viewed through a moving slit or revealed by a dot tracing out the contour. This provides
convergent evidence for the suggestion that motion trajectories are being processed in the
ventral visual stream (Tanaka & Yotsumoto, 2016). Therefore, this thesis demonstrated
strong evidence for the integration of information around closed continuous contours. These
stimuli were found to be processed differently to open contour modulated lines and that
measures of integration are obscured by salient local cues. The information is able to be
presented over time but can only be integrated when the information falls on the same
contour as we would expect in the natural scene. This is obviously important in the tracking
of objects in motion as well as tracking stationary objects with apparent motion as we move
around within the visual scene so that appropriate actions can be taken.
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Statement of Candidate’s Contribution

The research in this thesis was designed, implemented and written up for publication by the author (Robert J. Green). All work involved collaboration with my two supervisors (David R. Badcock and J. Edwin Dickinson). All work reported herein was conducted by the author. It must be noted that Experiments 1 and 2 of Chapter 5 were conducted as part of my honours thesis and is not examinable. It was included to create a coherent journal submission. Experiment 3 of Chapter 5 is work conducted during my candidature and is examinable for the purposes of this thesis. My co-authors have individually provided approval for the pieces of work to be included in this thesis.

Robert J. Green

David R. Badcock

J. Edwin Dickinson
Publications Arising from this Thesis


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Manuscripts submitted for publication

Chapter 1:
General Introduction
1.1. Grouping in the visual system

The visual system aids in the navigation of our environment as well as our interactions with other objects, animals and people. One of the critical functions performed by the visual system is the detection and discrimination of objects, so that appropriate actions may be taken. There are many mechanisms which the visual system uses in object detection and arguably the most important among these is the combination of local orientation information (lines, corners etc.) into whole shapes.

In order to effectively combine information, elements with common parameters are grouped together by the visual system. This process is referred to as perceptual grouping and was first described systematically by Gestalt psychology, where Wertheimer (1923) examined various arrangements of pattern elements (dots, lines, and simple shapes) and noted a number of critical factors which affected the grouping of these elements. Wertheimer (1923) showed that identical dots were grouped together based on their proximity (Figure 1.1B), close dots tend to be grouped together in favour of those further away. Dots that were similar in colour (Figure 1.1C) and size (Figure 1.1D) also tended to group together, along with those with the same motion (common fate; Figure 1.1F).

Considering lines and simple shapes, he also demonstrated that lines tend to be grouped using good continuation or continuity (e.g. Figure 1.1I is seen as two lines crossing over one another, rather than two arcs back to back) and closure (taking Figure 1.1I and closing the contours results in Figure 1.1J and now the perception of two shapes back to back). Other factors affecting perceptual grouping are similar orientation, symmetry, parallelism and common region (Figure 1.1E, G, H and K respectively).
The change in the perception of two overlaying lines (Figure 1.1I) to two discrete shapes back to back (Figure 1.1J) by closing the contour demonstrates the power of closure in the visual system. As can be seen in Figure 1.1 the closure cue is easily able to override the continuity cue. However, closure does not require a continuous contour, it can consist of discrete elements arranged to form a closed contour path (note: I will refer to stimuli made up of discrete local elements which form a closed contour, such as the one depicted in Figure 1.2B, as closed contour paths; stimuli consisting of one continuous contour which similarly forms a closed contour, such as the RF patterns discussed below, as closed continuous contours). Kovacs and Julesz (1993) used Gabor patches to create both open contour (Figure 1.2A) and closed contour paths (Figure 1.2B). As can be seen from Figure 1.2 below and demonstrated by the results of Kovacs and Julesz (1993), the closed contour path had a lower path detection threshold (measured percentage correct as a function of element spacing) amongst noise than the open contour path, again demonstrating the power of closure in the visual system.
Closure is also important in the discrimination of two-dimensional shapes. Elder and Zucker (1993) used open outline shapes (distorted squares with portions of the contour missing) and closed outline shapes (distorted squares with complete contours) to show discrimination is rapid for closed contours and slow for open contours. By increasing the amount of closure for the open outline shapes they were able to show improvement in discrimination and they suggested this was evidence of a perceptual closure continuum.

Although, not all studies suggest closure is the feature responsible for improved performance. Pettet, McKee, and Grzywacz (1998), similar to Kovacs and Julesz (1993), used Gabor patches to create open and closed contour paths, embedding these patterns in a field of randomly oriented Gabor patches (similar to Figure 1.2). They suggested it was the addition of orientation changes to create the open contour path which was reducing observer performance. By adding similar orientation changes within closed contour paths,
they were able to reduce observer performance of the closed contour paths to that found for open contour paths. Additionally, Tversky, Geisler, and Perry (2004), using the same stimulus paradigm but using lines in place of Gabor patches, controlled for the effects of density, eccentricity, and uncertainty and found no advantage of closed contour paths compared to open contour paths. Both of these studies suggest that closure alone is not sufficient to cause improvement in performance and it is instead, the combination of cues such as continuity and proximity.

However, in reply to these studies, Mathes and Fahle (2007) again used Gabor patches to investigate the effect of closure on the perception of open and closed contour paths. Controlling the smoothness of curvature change between the open and closed contour paths, they found that closure did account for improvement in performance, however, noted that this effect was relatively small and other factors such as inclusion of a turning point along the contour results in larger changes in performance than closure. They suggested the way turning points were including in previous studies (Pettet et al., 1998; Tversky et al., 2004) had been a confounding factor and after controlling for this, the effect of closure was restored.

Recently Persike and Meinhardt (2017) have also suggested the importance of corners in path detection. They used discrete line elements and Gabor patches to create both straight line and corner stimuli. These were used to investigate the effect of corners on paths with varying degrees of inflection. They found that highly bent contours composed of straight line elements, which are usually difficult to detect (Field, Hayes, & Hess, 1993), were rendered highly salient with the simple addition of single element corners (i.e. not produced by the combination of two elements side-by-side) to the path. These results were found for both discrete line elements and Gabor patches and led Persike and Meinhardt (2017) to suggest that corners are extremely effective in facilitating perception of jagged contours.
when they clearly indicate the direction required for path continuation. Therefore, past research does suggest that path detection is aided by non-low-level cues such as closure and corners and we will now discuss the combination of local elements into global percepts.

1.2. Global Processing

In order to see a pattern as a closed perceptual unit it seems necessary to have a global descriptor for it. To generate that percept some global accumulation of the elementary evidence is required. Global processing is the integration (or pooling) of local orientation information resulting in sensitivity greater than would be expected if detection was based purely on local features. This process has been shown to occur for a variety of different stimuli (Glass & Pérez, 1973; Loffler, Wilson, & Wilkinson, 2003; Saarinen, Levi, & Shen, 1997; Smith, Snowden, & Milne, 1994; Tan, Bowden, Dickinson, & Badcock, 2015).

Glass patterns were first introduced in 1969 when Leon Glass used the perceptual grouping effects of proximity, and size to demonstrate global structure from a large field of random dots (Glass, 1969). He achieved this by spraying black paint onto a sheet of white paper, and then superimposed the image on itself, rotating it 6.5°. The resultant effect was similar to the circular pattern in Figure 1.3, concentric circles about the point of rotation. Following this, more global patterns (radial, hyperbolic, spiral and oval) were created by Glass and Pérez (1973) using computer generated dot pairs. They concluded that the dot pairs are being grouped together to create a local orientation cue and this information is integrated together around the stimulus to reveal the global shape (Glass & Pérez, 1973).
Figure 1.3. Glass patterns used by Wilson and Wilkinson (1998): circular; hyperbolic; radial; and parallel. Note that all four patterns are at 100% coherence (all dot pairs contain signal i.e. conform to the global pattern), however, the circular pattern appears to produce the strongest percept while the parallel pattern appears to produce the weakest percept.

This idea was extended by Wilson and Wilkinson (1998) who again used computer generated dot pairs to generate Glass patterns (Figure 1.3), but used them to determine the salience of these patterns. They did this by measuring observers’ coherence thresholds, the proportion of dot pairs conforming to the global shape which were required for detection of the stimulus (note: detection in this thesis will be used to mean selection of the stimulus containing signal out of two intervals, one containing signal and noise, the other containing only noise [in the current example noise is randomly oriented dot pairs]). Observers were able to detect the presence of coherent structure in all 4 patterns, but similar to Kovacs and Julesz (1993), they found that observers were most sensitive to the circular (closed contour) pattern. Thresholds for the circular pattern were 1.5 to 2 times (depending on density of dots) lower than the radial or hyperbolic patterns, and 2 to 4 times lower than the parallel
pattern (although there are slight individual differences in these values, the pattern of results is consistent across observers).

There are objections to a global processing explanation for these Glass pattern results including the aperture used (Dakin & Bex, 2002) and whether there is global processing occurring at all (Schmidtmann, Jennings, Bell, & Kingdom, 2015; this is addressed below). However, there is evidence for the cortical specialisation for concentric shapes in V4 (Dumoulin & Hess, 2007; Pei, Pettet, Vildavski, & Norcia, 2005) and the increased sensitivity to circular patterns can be seen to suggest the importance of closure to the visual system (Tan, Dickinson, & Badcock, 2013) and its ability to detect global shape with minimal information.

Objects may have organised texture within them, but they also typically have bounding contours which are closed when they are not occluded. Given the strong effect of closure for stimuli composed of discrete local orientation cues, the obvious next step is to examine the factors involved in the perception of these bounding continuous closed contour shapes. As objects and closed shapes are often coarsely circular in shape Wilkinson, Wilson, and Habak (1998) created patterns which were deformed from circular and measured the amount of deformation required for an observer to detect a difference between the test pattern and a circle. The test patterns were deformed by sinusoidally modulating a circle’s radius as a function of polar angle. They called these stimuli radial frequency (RF) patterns (which will be discussed in further detail below) and by changing the number of complete sine waves used to modulate the pattern’s radius they were able to approximate simple shapes (Figure 1.4).
Figure 1.4. An RF3, RF4 and RF5 from left to right respectively. Amplitude of the sine waves used to modulate these patterns is $1/(1 + \omega)$ where $\omega$ is the number of sine waves to complete $2\pi$ radians. This is far above threshold for these patterns, but used for illustrative purpose.

In their first experiment Wilkinson et al. (1998) found detection thresholds (measured as amplitude of the modulating sine wave) as low as 2-4” of visual angle for some of the patterns, which is less than the approximately 36” centre-to-centre separation between photoreceptors in the fovea centralis (Westheimer, 1972) indicating a hyperacuity. Analysing the thresholds of a variety of RF patterns with different frequencies, they attempted to explain detection as a function of either local curvature or local orientation. Neither of these could adequately explain their results and therefore they concluded that global processing of these stimuli using cells sensitive to concentric information in V4 provided a better explanation (Wilkinson et al., 1998).

For their second experiment Wilkinson et al. (1998) further examined the possibility of local contour changes (curvature and orientation) being able to account for detection of their stimuli by comparing their results for RF patterns to those for modulated line stimuli which had also been modulated using sine waves but along a constant direction in Cartesian space rather than around a circle. The line stimuli consisted of line pairs half the circumference of the equivalent unmodulated RF pattern in length and separated by the diameter of the RF patterns. This resulted in stimuli with the same path length and the same (nearest) eccentricity as the RF patterns. Observers were required to indicate the presence of modulation on the target at 2 different luminance contrast levels (100 and 12.5%) for both modulated line and RF patterns at 6 different frequencies (2, 3, 4, 5, 6, and 12). Their results suggested change in luminance contrast had significantly less effect on detection.
thresholds for the RF patterns (particularly low frequency patterns) than for the modulated lines and concluded the detection processes underlying the two stimuli were not the same (a conclusion later questioned by Mullen, Beaudot, & Ivanov, 2011; and Schmidtmann & Kingdom, 2017 which is discussed in Chapter 3)

Earlier research by Tyler (1973) measured threshold detection for sinusoidally modulated lines. He concluded that for lines with a low number of cycles of modulation per degree of visual angle, sensitivity was a result of detecting the maximum orientation difference in the stimulus (i.e. the difference between the vertical line component and the oblique line component created by the sine wave; a local orientation cue which provides no additional benefit when there are multiple cues). This local processing result was noted by Wilkinson et al. (1998) and again rejected as a possible explanation for the modulation detection thresholds for RF patterns (although the maximum deviation from circular was investigated by Dickinson, McGinty, Webster, & Badcock, 2012 up to RF6 and found to co-vary across RF patterns at 1 cycle of modulation, a result which is discussed in Chapter 4). Wilkinson et al. (1998) tested up to RF24 with performance plateauing around RF4-RF6, although this was for fully modulated patterns and allowed global integration to make an additional contribution to their results. They suggested that maximum deviation from circular could not be a local processing explanation for RF patterns. This is because the jittering of the pattern between intervals meant observers were unable to make a local comparison as the information was being presented in spatially separate locations. To use deviation from circular as a cue would require the observer to relate the information to other features of the pattern (e.g. object centre), a necessarily global process, again suggesting the difference in processing of modulated lines and RF patterns.

Tyler (1973) did, however, show a departure from the use of local orientation cues for modulated lines with spatial modulation frequencies above 0.3 cycles per degree of
visual angle. The line stimuli generated by Wilkinson et al. (1998) had a minimum of approximately 0.9 cycles per degree (for the RF3 equivalent) and a maximum of approximately 3.1 cycles per degree (for the RF10 equivalent). This puts these lines in the “high frequency” area according to Tyler (1973) and he suggested that these lines were not processed by an orientation cue, but rather information was integrated over a distance of approximately 2.5° of visual angle. Given the lines presented in Wilkinson et al. (1998) were approximately 1.5° of visual angle, it is possible that detection thresholds for the lines may have been a result of integration of information along the length of the stimuli. However, Wilkinson et al. (1998) did not directly test integration along modulated lines, but the fact that detection thresholds for RF patterns remain unaffected by the change in contrast suggests, at the very least, that integration around the RF patterns is significantly stronger than along a line. This again, is showing the power of closure in the visual system and the likely global processing of RF patterns but will be revisited experimentally in a subsequent chapter, comparing perception of lines and RF patterns within observers (see Chapter 3).

1.3. Visual area V4

For glass patterns and RF patterns the evidence presented so far has indicated that simple orientation (V1) or curvature (V1/V2) cues cannot account for the contrast or modulation detection thresholds of these stimuli. Instead, it seems to indicate that the critical aspect of processing occurs in mid-level vision, visual area V4. We will now discuss briefly the ventral visual (form) pathway and some of the models used to explain the combination of information in V4, with a particular emphasis on RF patterns, as they are the focus of this thesis.

The ventral visual pathway contains both ascending (feedforward) and descending (feedback) connections (Shipp, 2007) and in the past has been thought of as a hierarchy of visual processing stages (Felleman & Van Essen, 1991; Van Essen, Anderson, & Felleman,
In this hierarchical model, information from the retina is transmitted to the primary visual cortex (V1). Here simple line orientation is detected (Hubel & Wiesel, 1968) which is followed by curvature detection in V1 (Dobbins, Zucker, & Cynader, 1987) or V2 (Wilson, 1985). This contour information is combined into part or whole simple shapes (Merigan, 1996; Pasupathy & Connor, 2002; Yau, Pasupathy, Brincat, & Connor, 2013) in V4, which is followed by more complex object processing in LOC (lateral occipital cortex; Cichy, Chen, & Haynes, 2011; Lerner, Hendler, Ben-Bashat, Harel, & Malach, 2001) and IT (inferotemporal cortex; Desimone, 1991; Konkle & Oliva, 2012).

Given this hierarchical processing of information as it travels through the ventral visual pathway there have been a number of explanations as to how local line orientation and curvature information may be combined in V4 (Carlson, Rasquinha, Zhang, & Connor, 2011; Habak, Wilkinson, Zakher, & Wilson, 2004; Pasupathy & Connor, 1999; Pasupathy & Connor, 2001; Poirier & Wilson, 2006; Roe et al., 2012). First we will discuss feature extraction as a possible description of the integration of local information in area V4.

As its name suggests, feature extraction involves the identification of local feature elements by position and curvature sensitive cells. The evidence for this comes from studies of monkey area V4. Pasupathy and Connor (1999) used single-cell recording in area V4 (in a macaque monkey) to measure responses to stimuli. They used a variety of convex and concave shape fragments, along with two equal length lines used to create simple angles and found systematic tuning for angles and curves (i.e. contour features; see Figure 1.5). The response variation was greatest for convexity and orientation, meaning neurons changed their response depending on whether the shape fragment was concave or convex and on which direction the shape fragment was oriented. They also showed a strong bias towards convex and outline features compared to concave features (Pasupathy & Connor, 1999).
They concluded that lower-level factors (e.g. spatial frequency and orientation) could not explain their results and therefore, there was strong evidence for feature extraction in V4.

*Figure 1.5. Adapted figure from Pasupathy and Connor (1999). Stimuli used in their investigation of macaque area V4. The white dot is the fixation point and the dashed circle is the estimated receptive field tested.*

Following this Pasupathy and Connor (2001), again using single-cell recording in area V4, but this time in two rhesus monkeys, examined simple 2D shapes which were combinations of convex and concave boundary elements. They used sharp, medium and broad convex curves, along with medium and broad concave curves, but not sharp concave curves (to limit stimulus set size and due to the preference for convexity noted above). They found evidence to suggest neurons did not appear to respond to single global shapes, but rather were responsive to curvature information at a specific location in relation to the object’s centre (e.g. a cell may be responsive to convex curvature for the upper right portion of a shape and not respond to changes in curvature at other locations on the shape). Similar to their previous work (Pasupathy & Connor, 1999) they also found a bias towards sharp convex curvature, although they note it may be a result of not testing the sharp concave curvature and they also found evidence for cells with tuning for multiple adjacent curvature features on approximately circular contours (Pasupathy & Connor, 2001).

These findings (Pasupathy & Connor, 1999; 2001, 2002) are also supported by Carlson et al. (2011). They used single cell recording and computer simulation of V4 neurons to investigate the effect of low and high degrees of curvature of macaque area V4. Consistent with the findings of Pasupathy and Connor (1999; 2001, 2002), their single cell
recording suggested a strong preference for high degrees of convex and concave curvature in area V4. The training objective for the model neurons was to minimise discrimination error by optimising tuning parameters such as curvature and polar angle preference. By varying the sparseness of the model neurons in their simulation they found non-sparse tuning distributions demonstrated a weighting towards low curvature, whereas the sparse tuning distributions indicated a weighting towards a high degree of curvature. Taken together, their results suggest that V4 contains sparsely tuned neurons with a preference for high degrees of curvature, further supporting the role of V4 in object extraction.

There was, however, a dispute about whether macaque area V4 was equivalent to human area V4. To answer this question Hansen, Kay, and Gallant (2007) used fMRI to map the topographic organisation of human V4 and its surrounding area. They found a high degree of similarity between the human and macaque V4 areas in topography and organisation, suggesting the evidence from single cell recordings of macaque neurons in V4 are generalizable to humans. Furthermore, Gallant, Shoup, and Mazer (2000) tested a human observer with a ventral V4 lesion on a variety of tasks designed to target low and mid-level perception. In order to test mid-level visual processing they used both Glass patterns and RF patterns. They found the observer did not have any perceptual deficits for low-level tasks such as luminance, orientation, and motion detection, however, there were significant deficits for intermediate form, attention, and colour tasks. These deficits to intermediate form are strong evidence for the use of area V4 in the processing of not only Glass patterns, but RF patterns, the focus of this thesis (additional evidence of V4 activation in shape perception is described in the section on RF patterns below).

Given these findings it has been suggested that visual area V4 is combining the local retinotopic orientation and curvature information from V1 and V2 into size invariant (El-Shamayleh & Pasupathy, 2016) object-centred features (Brincat & Connor, 2004; Roe et al.,
There is evidence to suggest the integration of this object-centred information begins in area V4 (Pasupathy & Connor, 2001; Pasupathy & Connor, 2002; Yau et al., 2013), with corners or points of convexity playing an important role and, therefore, it would suggest that object integration begins at area V4, integrating over larger receptive fields (Wilson & Wilkinson, 2015) as information moves up the visual pathway to LOC and IT.

In an attempt to explain how local orientation information from simple closed contour shapes, particularly RF patterns, could be integrated in area V4 by the visual system, Poirier and Wilson (2006) created a five stage model accounting for the perception of RF patterns. At stage 1, the contour information is recovered by orientation selective filters (V1). Stage 2 recovers the object’s centre using large systematically placed paired filters orthogonal to the object contour filters in stage 1. The output of these large filters is combined for a range of orientations, producing an energy response corresponding to the object’s centre. Stage 3 determines the number of objects and their average radii by counting responses from oriented receptive fields in a direction from the object’s centre. Stage 4 uses curvature detectors deriving input from specific combinations of orientation filters. The responses of these filter combinations (for spatially contiguous elements) are multiplicatively combined with a maximal response given if all filters are responding to the contour (as shown in Figure 1.6B) and no response if one or more of the filters is unresponsive. This results in a contour fragment coded for position in relation to the object’s centre as would be preferred by the V4 neurons reported by Pasupathy and Connor (1999). In the final stage, periodicity in the curvature response (shown in Figure 1.6F) is collected from populations with specific preferences for angle and location (stage 4) and neurons selective for specific equally spaced corners respond indicating object shape (RF pattern frequency).
Figure 1.6. Proposed filters in the Poirier and Wilson (2006) model. (A) Filters for the detection of object centre: small orientation filters (shown parallel to the contour) encode the object’s contour, whilst large orthogonal filters on either side of the centre encode concentric line elements. (B) Curvature detectors: response is maximal when the contour matches the specific combination of filter orientations as depicted and no response if one or more sampled filters are unresponsive. An example stimulus (C) with some of the proposed stages of the model moving left to right (D to G). (D) Filters at right angles to contour orientation determining the shape’s position (E). Curvature information is recovered in relation to object centre and polar angle (F), which can be represented as a function of Fourier energy (G).

This precise model is stimulated by both Glass and RF patterns (which of course was intended by Poirier & Wilson, 2006) and Badcock, Almeida, and Dickinson (2013) investigated the masking and position coding effects that the model predicts using these two pattern types. As mentioned, these two patterns require the integration of information in order to create a global percept and despite their obvious difference in appearance, both produce strong responses from the model. This similarity in model response suggests an interaction between the two stimuli when combined, however, the results did not support the model prediction, instead indicating these two patterns are processed by separate mechanisms in the visual system and suggesting alteration of this present model is required.

Notwithstanding the results of Badcock et al. (2013), the model provided by Poirier and Wilson (2006) does give good insight into some of the mechanisms required in the
ventral visual stream for the perception of RF patterns. As mentioned previously, feedforward connections are also accompanied by a number of feedback connections (Shipp, 2007), so a simple unidirectional hierarchical processing of information, such as the one presented in the model, is unlikely. It has more recently been suggested that these feedback connections, along with other evidence including neurons that bypass “steps” in the hierarchy (Sincich & Horton, 2003; Ungerleider, Galkin, Desimone, & Gattass, 2008), indicate that the traditionally held hierarchical view of the ventral stream is incomplete and that adjustments to this theory need to be made (Kravitz, Saleem, Baker, Ungerleider, & Mishkin, 2013). They propose that instead, the visual system can be thought of as a parallel processor of information, with feedforward and feedback connections that project to multiple layers of the visual cortex (Kravitz et al., 2013).

A relevant example of the effect of feedback connections is the investigation of monkey neuronal responses in ventrolateral prefrontal cortex (vPFC) and V4 to occluded and unoccluded stimuli (Fyall, El-Shamayleh, Choi, Shea-Brown, & Pasupathy, 2017). Timings of the response peaks in the two areas for the different stimuli suggested vPFC responds to occluded stimuli, sending feedback signals which facilitate V4 responses when the stimulus is occluded. One other possibility is that a shape extracted in V4 may facilitate signal to noise discrimination earlier in the ventral visual stream, which is a subject for further investigation.

Therefore, V4 appears to be highly relevant in the perception of shape. Object centre and convex curvature appear to play important roles in the extraction of shape fragments. These features are described well in the model by Poirier and Wilson (2006) and this gives us a good idea about the stages involved in simple shape perception.
1.4. Radial Frequency (RF) patterns

RF patterns have been briefly discussed, but now we will look at them in detail and discuss some of the research findings made using RF patterns. As previously mentioned, RF patterns were created by Wilkinson et al. (1998) by sinusoidally modulating the radius of a circle as a function of its polar angle using the equation:

\[ R(\theta) = R_0 \times (1 + A \sin(\omega \theta + \phi)) \]  

(1)

where \( \theta \) is the angle created with the x axis, \( R_0 \) is the mean radius, \( A \) is the amplitude of modulation (proportion of mean radius), \( \omega \) is the frequency of modulation (number of cycles per \( 2\pi \) radians i.e. the RF number) and \( \phi \) is the phase of the sinusoidal modulation. Increasing the amplitude increases the deformation and, therefore, the salience of the pattern and changing the phase changes the location of the deformation on the pattern.

Loffler et al. (2003) wanted to look at the change in detection thresholds within an RF pattern by changing the number of cycles of modulation present in the pattern, but keeping their wavelength constant. In other words, they wanted to selectively remove cycles of the sine wave for a given RF pattern (e.g. an RF3 shown in Figure 1.7) and replace them with path conforming to a circle. An RF3 with one, two and three cycles of modulation is called an RF3(1), RF3(2) and RF3 respectively. This would enable them to examine the effect of increasing signal around the contour, whilst holding the length of path deformation for each “signal” constant (i.e. maintaining the relative width of the “bumps”).
In order to ensure a smooth transition between the modulated path (sine wave) and the unmodulated path (circle) for patterns with less than all cycles of modulation present, Loffler et al. (2003) used the first derivative of a Gaussian function (D1). This was applied by replacing the first half and last half of the train of modulation with the first half and last half of the D1 respectively. Thus, for one cycle of modulation, the pattern of deformation conforms solely to a D1. This smoothing function is critical to removing a potential local cue from the stimulus (see Figure 1.8), and therefore, a potential experimental confound, but it does require the D1 to closely match the properties of a single cycle when used in its stead.

**Figure 1.7.** An RF3(1), RF3(2) and RF3. Phase is the same for all three patterns to illustrate the addition of each cycle to the pattern, but also the effect of fixed phase presentation discussed below.

**Figure 1.8.** An RF3(1) without the D1 smoothing function used by Loffler et al. (2003). The red circles show the local cues created by joining the sine wave to the circle.

Loffler et al. (2003) used the method of constant stimuli (MOCS) in a two-interval forced choice task, with one interval containing an RF pattern and the other a circle. Data was collected for patterns with a specific number of cycles of modulation for each of the RF numbers tested (RF3, RF5, RF10 and RF24). The 75% correct detection thresholds were
calculated by fitting a Quick function to the data for each of the cycles of modulation for a given RF e.g. an RF3(1). The Quick function is defined as:

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

(2)

where \(p\) is the probability of correct response, \(A\) is the amplitude of modulation as a proportion of the radius on an unmodulated circle (\(A\) in Equation 1), \(\Delta\) is the threshold at the 75% correct response level and \(\beta\) controls the slope of the psychometric function. These detection thresholds were then fitted using a power function, with the slope of the line plotting threshold amplitude against the number of modulation cycles on the contour indicating the strength of integration of signal within the pattern (Figure 1.9). Perfect integration of signal would result in linear summation and a slope of -1.

Figure 1.9. Results reproduced from Loffler et al. (2003). For low frequency patterns (RF3 and RF5), observer thresholds are significantly steeper than probability summation estimates. For the RF10 Loffler et al. (2003) suggest above 5 cycles of modulation observer thresholds conform to probability summation, while all observer thresholds conform to probability summation estimates for the RF24. It can be seen that the slope decreases with increasing RF number, possibly indicating the increase in saliency of the individual cycles with decreased polar angle.
Loffler et al. (2003) suggested their results for the RF3 and RF5 patterns were indicative of global pooling of signal around the pattern due to their relatively steep slopes. They argue that if detection was from local features we would expect either a flat line (slope = 0), or a slope predicted by probability summation. Probability summation is the statistical improvement of threshold as more cycles are added, due to the increased likelihood of detecting local deformation simply because there are more local positions that are deformed. Loffler et al. (2003) do not report the values they used to calculate their probability summation estimates, however, they likely used the same method as Loffler and Wilson (2001) which was \( \frac{1}{\bar{\beta}} \) where \( \bar{\beta} \) is the average psychometric slope from Equation 2, calculated across all conditions contributing to the estimated integration function. There are two theories under which probability summation has been modelled for RF patterns: high threshold theory (HTT; Quick, 1974; discussed further in the section on high threshold theory) and signal detection theory (SDT; discussed further in the section on signal detection theory). More recent studies typically calculate probability summation estimates for each pattern (i.e. separately for an RF3, RF5 etc.), however, it appears that Loffler et al. (2003) has calculated one value (-0.33) which they use as a comparison for all patterns. Given this calculated value, they conclude that thresholds for both the RF3 and RF5 must be a result of global shape processing, while the thresholds for the RF24 and RF10 (when it has more than 5 cycles) are a result of probability summation. However, given Loffler et al. (2003) show that the strength of integration changes for different patterns and subsequent research has found variation in probability summation estimates between observers (Dickinson, Han, Bell, & Badcock, 2010; Tan et al., 2013), we cannot be certain their probability summation estimates, and therefore their conclusions, are warranted for all of the patterns.

To investigate the effect of spatial certainty, Loffler et al. (2003) used fixed phase and random phase RF patterns. They note that one of the potential problems with spatial certainty (i.e. knowing where the deformation is going to occur [fixed phase]) is that it may
restrict the observer’s attention to just a limited portion of the pattern’s contour rather than the entire stimulus. If the observer’s attention was focused in this way it may result in detection thresholds being a function of the local deformation being attended. For example, consider the 3 patterns in Figure 1.10. There is deformation on the right side of all 3 stimuli regardless of the number of cycles. If the observer’s attention was focused only in the area depicted by the grey ellipse, detection thresholds could be a result of that single cycle for all 3 patterns, and therefore, we would expect the same observer thresholds for 1, 2 and 3 cycles of an RF3 (assuming selective attention is possible in this context, something which is likely influenced by the mean radius of the RF pattern which controls the distance between points of deformation).

![Figure 1.10](image)

*Figure 1.10.* A reproduction of the patterns from Figure 1.7, however, a theoretical attentional spotlight (high contrast) has been used to illustrate an area an observer would be able to solely attend to detect deformation for all 3 patterns.

Loffler et al. (2003) did not obtain the same threshold for all 3 cycles of modulation for their fixed phase RF patterns. Instead, when comparing to the same frequency RF pattern in random phase, they found an increase in sensitivity (decrease in thresholds for detection) for all patterns (RF3, RF5 and RF24) and a decrease in the strength of integration around the contour (decreased slope) for the RF5 and RF24. Their results suggest that while spatial uncertainty increased thresholds it could not solely account for the decreases in observer thresholds with increasing number of cycles. They also suggest that fixed phase presentations, have a decreased strength of integration when compared to random phase presentations, possibly a result of the increased salience of local cues, however, this was only found for 2 of the 3 patterns tested and, therefore, requires further investigation.
In their final experiment Loffler et al. (2003) examined the effect of breaking an RF5 up into its component cycles and changing the relative location, and orientation of those pieces (Figure 1.11: Exploded; Jittered; Spiral), as well as placing occluders at either the points of zero crossing, convex or concave maximum curvature (Figure 1.11: Gap). To create the relocated components they separated the 5 cycles of the RF5 at the zero-crossing (of the modulating sine wave) after the convex curvature and: moved the components further away from the object centre (exploded); jittered their location either further or closer to the object centre, such that it created a discontinuous contour (jitter); or rotated them orthogonal to their starting position (spiral).

Figure 1.11. Adaptation of the examples of the stimuli used in the final experiment of Loffler et al. (2003). Note, the gap condition involved the occlusion of parts of the path, while the
exploded, jittered, and spiral conditions all involved the moving of the component cycles of the RF5.

They found threshold levels for the exploded and spiral patterns were not significantly different from those obtained with only 1 cycle of modulation, indicating that disrupting the pattern in those ways resulted not only in disruption of global processing, but also disruption of probability summation (even though observers were attempting to monitor the whole stimulus). Interestingly, they found that the jitter pattern resulted in thresholds poorer than for 1 cycle of modulation, they argued that the discontinuity of the contour was disrupting both the observer’s global processing of the stimulus and detection of the local information as well. For the “exploded” and “spiral” conditions, thresholds were similar to those for 1 cycle of modulation. For the “gap” condition, thresholds were elevated compared to a complete RF5, but less elevated than the exploded, spiral, and jitter conditions. There was a significant difference between all three of the occluder locations in the gap condition, with the concave curvature occluders providing the lowest thresholds, followed by the zero-crossing occluders, and the convex occluders resulted in the highest thresholds. As all these thresholds were below those for the other conditions it suggests that occluding sections of the path does disrupt global processing, but not completely as in the other conditions. It also supports the findings of (Pasupathy & Connor, 1999; Pasupathy & Connor, 2001) previously mentioned, that convex curvature appears to be more important than concave curvature in the global processing of simple shapes, as the thresholds for the convex occluders resulted in the greatest increase in thresholds.

However, more recently the zero-crossing (also previously discussed as maximum deviation from circularity) was hypothesised by Dickinson et al. (2012) to be a critical feature in RF pattern detection. They re-plotted observer data using the maximum deviation from circularity (the difference between the RF tangent and a circle’s tangent) as a function of cycles of modulation, finding them to co-vary across different frequency RF patterns. In
other words, at their threshold for detection the maximum deviation from circular was the same for a given number of cycles of modulation (e.g. 1 cycle of modulation) for different RF patterns (they tested RF2, RF3, RF4, and RF6). Although this feature co-varied across different frequencies Dickinson et al. (2012) suggested it was not a local feature which was solely being detected (also originally rejected by Wilkinson et al., 1998), but rather that this was the salient feature which was being integrated within the contour.

A potential explanation for why results from Loffler et al. (2003) found that removal of information on the points of convex curvature resulted in a larger change in threshold than for the zero-crossing, is because the occluders used by Loffler et al. (2003) only covered half the zero-crossings. A sine wave produces two zero-crossings per cycle of modulation, so in order to block out all of them on an RF5, 10 “gaps” would have been needed. This may have resulted in a greater increase in observer thresholds than occluding the points of convex curvature, however, this would also have removed twice as much of the path, potentially confounding the results. This was not tested in the current thesis but would be useful for future research to confirm the critical features involved.

After Loffler et al. (2003) and Wilkinson et al. (1998) demonstrated low frequency RF patterns were globally integrated shapes, there were a number of subsequent experiments using RF patterns to examine properties of mid-level vision including: the integration of luminance and contrast defined shapes (Bell & Badcock, 2008); shape after-effects (Anderson, Habak, Wilkinson, & Wilson, 2007; Dickinson, Almeida, Bell, & Badcock, 2010); importance of polar angle between points of maximum curvature (Bell, Dickinson, & Badcock, 2008; Dickinson, Bell, & Badcock, 2013); local orientation contributions to global shape perception (Bell, Badcock, Wilson, & Wilkinson, 2007; Day & Loffler, 2009; Wang & Hess, 2005); effect of curvature on pattern perception (Dickinson, Cribb, Riddell, & Badcock, 2015; Habak et al., 2004); investigating shape channels involved in different frequency RF
patterns (Bell & Badcock, 2009); visual perception of enucleated observers in their unaffected eye (Steeves, Wilkinson, González, Wilson, & Steinbach, 2004); effects of lesions on mid-level perception (Gallant et al., 2000); and developmental differences in global integration of shape (Almeida, Dickinson, Maybery, Badcock, & Badcock, 2010a, 2010b, 2013; Cribb, Badcock, Maybery, & Badcock, 2016). These studies used either the same method as Loffler et al. (2003) to examine global shape processing (comparing thresholds for patterns with different numbers of cycles of modulation to those predicted by probability summation for a given RF number), or used the full patterns (an RF pattern with all cycles of modulation) under the assumption that this pattern was globally processed.

Convergent evidence from physiological studies seemed to indicate that the assumption of global processing of RF patterns was well founded. Wilkinson et al. (2000) used fMRI to measure activity in V1, V4 and the fusiform face area (FFA) while presenting either concentric, radial or parallel sinusoidal gratings to the observers. To maintain the attention of the visual system, the concentric patterns were changed from circles to RF patterns, while spokes of contrast modulation were rotated through the radial patterns, and the orientation of parallel patterns was changed every 2-3 seconds. Wilkinson et al. (2000) found no significant difference in the activation in V1 between the 3 conditions, however, in area V4, there was significantly more activation for the concentric and radial patterns compared to the parallel patterns. In addition to this, they also found that concentric patterns produced significantly more activation in FFA than both radial and parallel patterns. They argued that these results, along with a previous fMRI study looking at the areas of activation in the visual pathway for scrambled and unscrambled natural scenes (Grill-Spector et al., 1998) are consistent with global pooling in V4. The increased activation for these concentric/RF patterns in area V4, and FFA compared to parallel (line) gratings, can be taken as evidence for the processing of RF patterns within these areas.
Bowden, Dickinson, Fox, and Badcock (2015) used Gabor patches to create contours with closure, similar to those used by Kovacs and Julesz (1993; see Figure 2B) and measured cortical action potentials using electroencephalogram (EEG). The patterns were embedded amongst randomly oriented Gabor patches functioning as noise. Their first experiment investigated closed contour paths using a circle, RF4, RF4(3), and RF3(2), however, instead of comparing them to open contour paths, as done by Kovacs and Julesz (1993), they were compared to an RF3. By doing this they were able to examine the effect of the number of corners presented, and the polar angle separating those corners from each other. They found that similar to the behavioural results of Loffler et al. (2003) and the biological data of Pasupathy and Connor (2001), points of maximum (convex) curvature are critical for shape construction, both at threshold, and suprathreshold levels. They also found that the polar angle between corners, not number of corners was another critical feature for shape construction. Their behavioural results, combined with that from their EEG data, suggested global pooling of orientation information in V4.

Research using fMRI has also suggested the importance of area LOC in perception of RF patterns. Rainville, Yourganov, and Wilson (2005) found unmodulated RF patterns (circles) exhibited the least amount of activation in LOC compared to modulated patterns. Increasing the amplitude of the RF pattern increased activity in LOC and they suggested this was evidence of active shape integration in this area. This result was replicated by Betts, Rainville, and Wilson (2008), as they again found the lowest activation in LOC when the pattern was unmodulated, suggesting a population coding for deviations from circularity. With additional research supporting the involvement of LOC in the identification of RF patterns (Gorbet, Wilkinson, & Wilson, 2014; Salmela, Henriksson, & Vanni, 2016; Vernon, Gouws, Lawrence, Wade, & Morland, 2016), it would suggest feature extraction is occurring in human V4 and the global integration of this information occurs in LOC.
Despite the convergent evidence presented so far, there has been recent research which has questioned whether the comparisons of integration slopes to those predicted by probability summation has allowed that demonstration of global shape processing with either Glass or RF patterns (Baldwin, Schmidtmann, Kingdom, & Hess, 2016; Kingdom, Baldwin, & Schmidtmann, 2015; Schmidtmann, Jennings, Bell, & Kingdom, 2014). The main argument concerns the use of procedures derived from HTT in the generation of probability summation estimates, while others methods for showing global influences were not discussed. It has been argued, that the HTT derived method of analysis has been resulting in incorrect data analysis and, potentially, incorrect conclusions for RF patterns (Baldwin et al., 2016), and Glass patterns (Schmidtmann et al., 2014) alike and that analysis of these patterns based on SDT procedures results in observer improvements appearing to be a function of probability summation, rather than global processing. Therefore, the underlying assumptions of both HTT, and SDT will be discussed, along with the potential problems when examining RF patterns of fixed phase.

1.5. High threshold theory

Quick (1974) developed the Vector-Magnitude model to account for contrast detection by building on a probability summation model proposed by Sachs, Nachmias, and Robson (1971). The model proposed by Sachs et al. (1971) contained signal and noise from each channel, which was then combined with an inclusive-OR function to indicate detection. The major difference between HTT and SDT models was the addition of noise after the combination of signals from the independent channels (populations of neurons selective for a particular stimulus range). Quick (1974) proposed that the excitations from these independent channels are combined by a magnitude function which is then followed by the addition of the noise prior to detection. One of the main assumptions underlying Quick’s model is the high threshold assumption: the detection threshold is high in relation to the
noise, resulting in either a fixed amount or zero noise above threshold and that no signal

The simple application of HTT to produce a probability summation power function to
describe observer thresholds with increasing cycles of modulation for an RF pattern has

\[ Th = ax^{-B} \] (3)

where \( B \) is equal to \( 1/\bar{\beta} \), where \( \bar{\beta} \) is the average of the slopes of the psychometric functions (\( \beta \) in Equation 2 above) for all stimuli used to calculated the power function, \( \alpha \) is the 75% threshold at 1 cycle of modulation or when the number of stimulus elements is 1, and \( x \) is the number of cycles of modulation. This has been the analysis method for a
number of papers investigating global processing of RF patterns (Bell & Badcock, 2008;
Dickinson, Almeida, et al., 2010; Dickinson et al., 2012; Hess, Wang, & Dakin, 1999; Loffler et al., 2003; Schmidtmann, Kennedy, Orbach, & Loffler, 2012; Tan et al., 2013).

Tyler and Chen (2000) noted that one of the main issues for HTT probability
summation estimates was additive noise. Given the HTT model adds noise after the
combination of the independent channels, noise which sums together within detectors of
the stimuli would be inappropriate for analysis using HTT. They also note, for Pelli (1985) to
adapt HTT to the two alternative forced choice (2AFC) paradigm he assumed the observer
was monitoring a larger number of channels than those being stimulated, therefore, use of
HTT for stimuli which stimulate as many channels as the observer is monitoring, would be
invalid. Therefore, it would not be valid for fixed phase RF patterns, where the observer
knows which channels to monitor for signal, this however, is not an issue for the majority of
previous research which has used random phase RF patterns, in which the observer needs to
monitor all channels thought to be detecting the different sections of the contour as they do not know where the signal will be presented.

1.6. Signal Detection Theory

Signal detection theory (SDT) assumes the noise is a larger proportion of the activity at threshold than HTT. It is assumed for a given stimulus, e.g. an RF3(1), the noise distribution ($N$ in Figure 1.12) will remain constant, and that increasing the stimulus intensity will result in the signal distribution ($S$ in Figure 1.12) moving (unchanged) away from the noise distribution. If the criterion ($k$) is unmoved, this change will result in an increase in the proportion of hits (responding signal when signal is present – red shaded area), but no change in the proportion of false alarms (responding signal when only noise is present – blue shaded area). Note, we have only described increasing the stimulus intensity (i.e. signal) in a single interval.

![Figure 1.12. Depiction of an increase in stimulus intensity for a single interval. Signal (red line) and noise (blue line) distributions under SDT. For a given criterion $k$, the probability of a false alarm is $\int_{-\infty}^{0} N$ (light blue shaded area), and the probability of a hit is $\int_{k}^{\infty} S$ (light red shaded area). Increasing the stimulus intensity results in the signal distribution moving away from the noise distribution (bottom), and a greater proportion of hits.](image)
The 2AFC paradigm is unable to test the relationship between the signal and noise as there is no response criterion, it is simply the selection of the interval with the largest response. Therefore, in order to examine the relationship between signal and noise it requires using a single interval task and moving the criterion for a set stimulus intensity. This is what Baldwin et al. (2016) did in their examination of a single RF4, and a diamond arrangement of four RF4 patterns (quad condition). They used a 4-point scale for observers to respond how confident they were that the interval presented (containing either signal or noise) contained signal (i.e. the method forces the observers to indicate different confidence or criterion levels). Binning these responses cumulatively they were able to create receiver operating characteristic (ROC) curves, which plots proportion of hits to proportion of false alarms for the different criterion levels.

Green and Swets (1966) showed that observer responses modelled within the HTT framework and plotted as ROC curves produce straight line fits. This is based on the assumption that noise alone is rarely or never above threshold and thus the number of hits will be equal to the true value of hits plus a guessing factor, resulting in a proportional relationship and a straight line fit. Therefore, if observer responses do not produce a straight line fit, but rather a curved fit, then there is evidence the noise alone can result in responses above threshold and that SDT is the preferred framework to model probability summation estimates.

Baldwin et al. (2016) used ROC curves to investigate performance using RF4s and found that for both the single RF patterns, and the quad RF patterns, non-linear curves provided a significantly better fit than straight lines. They suggested this was strong evidence against the use of HTT analysis for RF patterns and that previous studies using HTT analysis methods may have come to the wrong conclusions about their results (this assumes they were using a similar strategy to those employed by observers in typical RF detection
tasks, a point which we will discuss in Chapter 3). Therefore, we need to re-examine the evidence for global processing of RF patterns in light of this information and find out whether previous conclusions were wrong.

In order to use SDT in the analysis of RF patterns we must review the formula used to calculate probability summation. It is defined in Kingdom et al. (2015) as:

$$P_c = n \int_{-\infty}^{\infty} \phi(t - d') \Phi(t)^{QM-n} \Phi(t - d')^{n-1} dt ...$$

$$+ (Q - n) \int_{-\infty}^{\infty} \phi(t) \Phi(t)^{QM-n-1} \Phi(t - d')^n dt$$

(4)

where $P_c$ is the percentage correct and set at 75%, $t$ is sample stimulus strength, the heights of the noise and signal distributions at $t$ are given by $\phi(t)$ and $\phi(t - d')$ respectively, $\Phi(t)$ and $\Phi(t - d')$ are the areas under the noise and signal distributions to the left of $t$ (see Figure 1.13 below), $Q$ is the number of monitored channels, $M$ is the number of alternatives in the forced choice task, and $n$ is the number of stimulus components.

*Figure 1.13. Signal and noise distributions under SDT with relevant notation for determining probability summation (reproduced from Kingdom et al., 2015).*

Within the current literature (Baldwin et al., 2016; Kingdom et al., 2015; Kingdom & Prins, 2010; Schmidtmann et al., 2014) the variables $Q$ and $n$ are not clearly defined for their use with RF patterns. Figure 1.14 from Kingdom et al. (2015) shows the difference between fixed attention windows, and matched attention windows. There they describe matched
attention windows as referring to situations where the number of stimuli and the number of channels monitored are the same, whereas, a fixed attention window has fewer stimuli than the number of channels being monitored.

Figure 1.14. A reproduction of Figure 2 from Kingdom et al. (2015). The matched attention window describes a scenario where the number of stimuli ($n$) is equal to the number of channels ($Q$), analogous to an RF3. The fixed attention window describes a scenario where the number of stimuli are less than the number of channels, analogous to an RF3(2).

Assuming that a channel refers to a restricted area on the contour, you would need to know the number of locations stimuli could fall within to accurately apply SDT. In order to easily quantify the number of channels monitored, Baldwin et al. (2016) used fixed phase presentations of their RF patterns. However, this was an idea originally rejected by Wilkinson et al. (1998) when creating the patterns, as they believed this may result in an attentional spotlight being used, rather than the observers attending to the whole stimulus. In their investigation of fixed phase RF patterns, they found that fixed phase stimuli usually resulted in poorer global integration and therefore, the use of fixed phase stimuli in Baldwin et al. (2016) may have introduced a potential confound to their experiment.

Using random phase RF patterns means the pattern can appear in any orientation, provided the included cycles of modulation maintain their wavelength. This means signal can appear at any location on the contour and the observer is required to monitor a large
number of channels (assuming probability summation). Given random phase patterns are employed to stop observers using an attentional spotlight, this provides a problem in the analysis of RF patterns using SDT. As the number of channels monitored is a critical value in the calculation of the probability summation estimates, and therefore, in determining whether a pattern is being globally integrated or not, it is important to find out how to correctly estimate or measure this parameter.

There are challenges in applying both HTT and SDT to the analysis of RF patterns, therefore, it is important that we establish whether RF patterns are being globally processed using experimental methods first. Once we have established how these patterns are processed we will examine HTT and SDT probability summation estimates to determine how to correctly apply SDT to RF patterns, and whether the conclusions reached in previous studies using HTT were correct (Chapter 2) in spite of concerns regarding the methods.

1.7. Integration across contours

If detection of RF patterns is due to local processing, then it should not matter whether local features are presented on a common contour or instead distributed across multiple contours, they should both result in the same improvement in performance. However, given the importance of the object centre in the coding of curvature information (Pasupathy & Connor, 1999; Pasupathy & Connor, 2001; Pasupathy & Connor, 2002) noted previously, we might expect that object centre is an important factor in integration of signal across contours. Habak et al. (2004) examined the masking effects of nested RFs patterns, modulated circles with the same centre but differing radii. Masking effects on detection of contour modulation were greatest when both patterns were in phase (i.e. convexities aligned with convexities and concavities aligned with concavities) and this effect increased with the number of in phase cycles of modulation. These effects declined steeply with increased distance between mask and target and were found to be largely phase dependent.
Habak et al. (2004) suggested an interaction between local orientation receptors is unable to account for their results. This is because at threshold the target is more closely related to a circle than the mask pattern, however, the RF pattern resulted in increased detection thresholds for the target whereas there was no masking effect of the circle. Increasing the mask amplitude results in a decrease in orientation similarity (i.e. the local orientations of the target and mask become less parallel) which should result in a decrease in masking if effects were due to similarity of local orientation cues. But again, the results were contrary to this, with the increased amplitude of the mask resulting in greater masking effects. They suggested this indicated mid-level visual processing involvement for the effects found for their stimuli.

Additionally, Schmidtmann, Gordon, Bennett, and Loffler (2013) tested the influence of the position of orientation information on integration around closed contour paths. They did this by embedding the paths, defined by Gabor patches and conforming to an RF pattern, within fields of randomly oriented Gabor patches (see Figure 1.15). They placed elements conforming to the contour on either a single annulus or across multiple annuli. Their results suggested that the combination of information exceeded that predicted by probability summation for both conditions, however, observers performed significantly poorer when detecting information spread over multiple annuli (note, Schmidtmann later questions this outcome for both Glass and RF patterns ). Taken together with Habak et al. (2004) it would suggest that it is possible for information to be integrated together across annuli but begs the question about whether information can be integrated across contours which do not share a common centre.
Therefore, Baldwin et al. (2016) tested the strength of integration across 4 RF4(1) patterns (quad RF condition) evenly distributed around a central fixation with the cycle of modulation directed to the fixation point (see Figure 1.16) and within a single RF4 with fixed phase (single RF condition). There were two presentations: blocked, where there was only a single condition presented within a block of trials (e.g. single RF4 with 2 cycles of modulation); and interleaved, where all variations of the stimulus were presented within a block of trials (e.g. quad RF with 1, 2, 3, or 4 cycles of modulation). The distance between the fixation and the closest portion of contour in the quad RF condition was 1.3° of visual angle, a distance which Habak et al. (2004) may suggest would result in integration of information across contours, however, it would be quite diminished.
Baldwin et al. (2016) were unable to find evidence in their data to reject either probability summation or additive summation (the addition of signal and its uncorrelated noise). They suggested their results indicated there was no difference in the integration of information within RF patterns compared to integrating across RF patterns. However, there was actually evidence in the difference in processing of these two stimuli within their pattern of results for the interleaved and blocked conditions. For the quad RF condition, there was a difference in observer thresholds when the patterns only had 1 cycle of modulation, with the blocked presentation being significantly lower than the interleaved presentation. This difference in thresholds decreased as the number of cycles of modulation increased until these two thresholds converged at 4 cycles of modulation. This suggests that for both presentation types the observer was monitoring 1 location which allowed the cue to be seen on every trial when 4 cycles were present, but on increasingly fewer trials with lower numbers of modulation cycles. For the single RF condition, there was a different pattern of results. The thresholds for the blocked and interleaved presentations were the

Figure 1.16. Stimuli use by Baldwin et al. (2016) to investigate integration: within a single RF pattern (a); and across RF patterns (b).
same at 1 cycle of modulation and diverged (the interleaved presentation thresholds becoming lower than the blocked presentation thresholds) with increasing numbers of cycles of modulation. Similar to the quad RF condition, the blocked presentation of the single RF condition showed no improvement in performance with increasing cycles of modulation. This pattern of results would require the observer to be not only monitoring 1 location, but disregarding the rest of the contour, a finding contrary to Loffler et al. (2003).

The decrease in observer thresholds for the interleaved presentation relative to the blocked presentation with increasing cycles of modulation suggest that the observer changed strategies for the interleaved presentation, monitoring the entire contour. This change in strategy resulted in integration occurring around the contour and the lower thresholds. Therefore, we would suggest there is evidence within the results of Baldwin et al. (2016) for the integration of information within RF patterns but not across RF patterns.

1.8. Interactions between local and global cues

Human vision is a highly efficient system, using the most salient features available to enable detection. The interaction between local and global cues can help to further explain the results found by Baldwin et al. (2016). Dickinson et al. (2012) showed that a salient local cue can result in the flattening of integration slopes for RF patterns. This is because the magnitude of the global cue increases with the increasing number of cycles of modulation. At 1 cycle of modulation the global signal is therefore, weak and the visual system detects the salient local cue. As the cycles of modulation increase, the global signal increases until it is more salient than the local cue (Figure 1.17). This means that as the number of cycles of modulation increases the observer thresholds are driven first by local cues and then by global cues, obscuring the true slope which describes the global integration of the stimulus. Therefore, in Chapter 3 we investigate the effects of fixed phase presentations (as a potential source of salient local cues) on RF patterns to determine whether this can explain
the pattern of results found by Baldwin et al. (2016). Furthermore, we revisit their paradigm in Chapter 4, but this time increasing the spatial uncertainty of the location of deformation. This will discourage the observer from using a local processing strategy, removing the potential confound of Baldwin et al. (2016).

Figure 1.17. Adaptation of Figure 6 from Dickinson et al. (2012) displaying the results from 1 of 2 observers. The data points show the observer thresholds for a negative cosine condition which contains a salient local cue. When the local cue is removed (sine phase condition) the results conform to the red line. This shows how the salient local cue is used preferentially when the global cue is comparatively weak.

The interaction between local and global cues may also explain results found by (Or, Thabet, Wilkinson, & Wilson, 2011). Work conducted during 2012 as part of my honours thesis suggested that integration of RF patterns remained unchanged when viewed using an implicit slit. The vertical slit either: drifted over a stationary RF pattern; remained stationary whilst an RF pattern moved behind it; or appeared at random horizontal locations revealing the RF pattern in a piecemeal fashion. Integration slopes obtained using an RF3 for all 5 observers were approaching -1 (liner summation) for a conventional (freely visible RF pattern) and all 3 slit viewing conditions. Duration of the presentation of each interval was extended for the moving slit condition up to 4000 ms. There was no effect on observer
thresholds or strength of integration. Therefore, when we considered the results of Or et al. (2011), who used a difference of Gaussian dot (DoG) to trace out the path of an RF3 pattern and found an integration slope of -0.64 (a value significantly less than for our slit viewing conditions), we hypothesised that a salient local cue may be interacting with the global cue reducing the integration slope.

The stimulus used by Or et al. (2011) traced out the RF pattern at a constant angular velocity. This angular velocity results in a change in speed around the areas of deformation. Or et al. (2011) realised this could result in a potential speed cue which the observer may use to determine the presence of deformation. Therefore, they measured observer thresholds for a number of different RF patterns comparing the results for presentations having constant angular velocity (dot moves at a constant rate of polar angle around the path) and constant Cartesian speed (dot moves at a constant rate of the path length; we will refer to as constant retinal speed). They found no significant differences between these presentations and suggested the potential speed cue was not affecting observer performance.

As mentioned, they investigated whether there was evidence for integration of information with increasing cycles of modulation for an RF3 (Figure 1.18). Observer thresholds decreased significantly faster than those estimated by probability summation modelled under HTT, suggesting there was integration of information for these patterns. Or et al. (2011) suggested that as these patterns were defined by motion, their results were evidence of integration of motion information to produce a global motion percept. As the integration slope of these patterns was -0.64, significantly shallower than the slopes found for a low frequency pattern such as the RF3 (-0.75 Dickinson, Han, et al., 2010; -0.79 Dickinson et al., 2012; -0.86 Loffler et al., 2003; -0.92 Tan et al., 2013) they suggested that the presentation of information over time (temporal displacement) resulted in degradation
of signal. However, the work from our lab (presented as Experiments 1 and 2 of Chapter 5) and from Bell, Sacks, and Burr (2015) suggested that contour-defined RF patterns viewed over time did not display reduced integration slopes. Therefore, Chapter 5 investigates the effect of constant angular velocity on motion RF patterns and whether a speed cue created by the deformation is sufficient to cause a local cue which results in reduced integration slopes for this stimulus.

![Diagram of RF patterns with N values of 0.5, 0.5, 1, and 3, showing concave and convex bumps.](image)

*Figure 1.18. Reproduction of Figure 5 from Or et al. (2011). The dashed line depicts the path the dot will take for the reference interval (red) and target interval (white).*

The purpose of this thesis is to examine critical features involved in global shape processing. Firstly, as there was a dispute about whether integration was occurring around the continuous contour path of an RF pattern, we investigated whether observers were able to make global shape judgements at their threshold for detection (Chapter 2). This necessarily involves the integration of information around the contour, and would provide experimental, rather than theoretical-prediction based evidence for the existence of global shape processing in RF patterns. We also investigated whether an RF3 is processed in the same manner as other low frequency RF patterns and compared HTT estimates to those modelled under SDT (Chapter 2). Thus enabling us to determine if incorrect conclusions were drawn by previous research which used the HTT method to assess global integration in RF patterns.
Secondly, we tested the hypothesis that the inability of Baldwin et al. (2016) to reject probability summation was a result of their use of fixed phase stimuli (Chapter 3). We compared fixed phase and random phase presentations of RF3s to determine whether there was an interaction between local and global cues as described by Dickinson et al. (2012). Furthermore, we examined the suggestion that modulated lines and RF patterns are processed by a common mechanism (Mullen et al., 2011; Schmidtmann & Kingdom, 2017). We achieved this by comparing the pattern of results for modulated lines to those found for RF patterns and the effect of fixed and random phase presentation on modulated lines (Chapter 3). If they are indeed processed by a common mechanism, then we would expect a similar pattern of results between the modulated lines and RF patterns and also a similar effect of the fixed and random phase presentations.

Our results from Chapter 3 led us to reinvestigate integration within RF patterns and across RF patterns using a similar paradigm to Baldwin et al. (2016), but with increased spatial uncertainty for deformation (Chapter 4). This increased uncertainty would require the observer to monitor the entire stimulus, giving the greatest chance for global processing around the stimulus and allowing us to determine whether there is evidence for integration both within and across RF patterns. Integration may be expected to be restricted to within a contour if it is a mechanism contributing to the processing of global shape. However, if processing of these patterns is intrinsically local, then we would expect probability summation to perform as well across contours as within contours.

Finally, we also tested the local and global cue hypothesis on the relatively shallow integration slope found by Or et al. (2011) for their motion RF3. We removed the potential speed cue by using a dot which traced out the path at a constant retinal speed and compared the results to those found for a constant angular velocity condition. If there was an effect of this cue and integration in motion RFs is possible, we should find increased
integration slopes for the constant retinal speed condition compared to the constant angular velocity condition and the difference should be the most pronounced at 1 cycle of modulation.
References


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Chapter 2:
Convergent evidence for global processing of shape

Robert J. Green, J. Edwin Dickinson, & David R. Badcock


Keywords: Shape perception; global processing; signal detection theory; RF patterns; probability summation; discrimination at threshold
Abstract

There is an ongoing debate over whether there is convincing evidence in support of global contour integration in shape discrimination tasks, particularly when using radial frequency (RF) patterns as stimuli (Baldwin, Schmidtman, Kingdom, & Hess, 2016). The objection lies in the previous use of high-threshold-theory (HTT), rather than signal detection theory (SDT) to model the probability summation estimates of observer thresholds to determine whether integration of information is occurring around the contour. Here we used a discrimination at threshold method to establish evidence of global processing of two frequently used RF patterns (RF3 and RF5) which does not require mathematical modelling. To provide a bridge between current and past research we examined the two proposed methods, finding that HTT produced probability summation estimates which were more conservative than SDT (when an appropriate number of channels was used to generate estimates). We found no difference in observer thresholds when an RF pattern was presented as the only test stimulus in a block of trials or when two RF patterns were interleaved and no evidence for a decrease in psychometric slopes with increasing numbers of stimulus elements. These findings are contrary to what is predicted by SDT for a stimulus whose detection conforms to probability summation. Therefore, our results find no evidence which support probability summation, further demonstrating the importance of using random phase RF patterns while measuring integration around a contour and providing strong evidence for global shape processing around low frequency RF patterns.

Keywords: Shape perception; global processing; signal detection theory; RF patterns; probability summation; discrimination at threshold.
2.1. Introduction

One important function of the visual system is the identification of shapes within the visual field so that appropriate actions can be taken. Construction of a global representation of simple shapes is thought to be first achieved in lateral occipital areas (Vernon, Gouws, Lawrence, Wade, & Morland, 2016) by the combination of information from local responses to the image earlier in the visual stream (Van Essen, Anderson, & Felleman, 1992; Vernon et al., 2016). Global shape processing, in our case based on the integration of local information around the shape’s contour, can aid in the detection and discrimination of different shapes. This has been examined by numerous previous studies using radial frequency (RF) patterns (Almeida, Dickinson, Maybery, Badcock, & Badcock, 2013; Almeida, Dickinson, Maybery, Badcock, & Badcock, 2014; Baldwin et al., 2016; Bell, Badcock, Wilson, & Wilkinson, 2007; Bell, Dickinson, & Badcock, 2008; Dickinson, Han, Bell, & Badcock, 2010; Green, Dickinson, & Badcock, in press-a; Loffler, Wilson, & Wilkinson, 2003; Schmidtmann, Kennedy, Orbach, & Loffler, 2012; Wilkinson, Wilson, & Habak, 1998; Wilson & Propp, 2015). RF patterns are derived from circles by sinusoidally modulating their radius as a function of the polar angle. They are defined by their RF number (the number of wavelengths (\(\omega\)) it takes to complete 360 degrees) and the number of cycles (the number of wavelengths actually incorporated into the otherwise circular pattern; see Figure 2.1 below). Adjusting the amplitude of the sine wave used to modulate the circle adjusts the salience of deformation, resulting in an object stimulus parameter which is suitable for deformation-threshold estimation. In the initial paper describing RF patterns, Wilkinson et al. (1998) found subjects had sensitivity to radial deformations as small as 2-4” of visual angle. This distance is smaller than the centre-to-centre separation between photoreceptors in the human fovea (approximately 36”; Westheimer, 2010) which suggests a hyper-acuity and therefore a high degree of sensitivity to these patterns.
Figure 2.1. Anticlockwise from bottom left: RF3(1), RF3(2), RF3, RF5, RF8, and RF12. All patterns have their amplitude defined by the same equation $1/(1+\omega^2)$, where $\omega$ is the RF number and results in a pattern well above threshold levels, but shown for illustrative purposes. Changing the RF number changes the polar angle separating lobes on successive cycles at amplitude maxima (angle subtended at the centre of the pattern by adjacent points of maximum curvature), while changing the number of cycles (and changing the amplitude) changes the amount of signal present.

In the past, researchers have examined global processing of shapes by comparing observed thresholds to those predicted by an estimation of probability summation assuming local processing (Almeida et al., 2014; Dickinson et al., 2010; Loffler et al., 2003; Schmidtmann et al., 2012; Tan, Dickinson, & Badcock, 2013). Probability summation is the increased likelihood of detecting a single local deformation as the number of elements (cycles, or repetitions of the local information) increase. If thresholds decrease significantly faster, when more cycles are added, than predicted by probability summation, there is evidence for global processing occurring. Prior researchers have presented evidence for global processing of patterns up to RF10 but suggest local processing (probability summation) occurs for higher numbered RF patterns (Loffler et al., 2003).

The technique of probability summation estimation used in the majority of these studies of RF patterns was introduced by Loffler et al. (2003) and modelled under the framework of high threshold theory (HTT; Quick, 1974; Wilson, 1980). Recent work has noted previous rejection of HTT as a general theory of threshold detection (Baldwin et al., 2016; Kingdom, Baldwin, & Schmidtmann, 2015; Schmidtmann, Jennings, Bell, & Kingdom, 2015; Schmidtmann et al., 2012) and suggested that signal detection theory (SDT) is a better
framework to use for generating probability summation estimates. Baldwin et al. (2016) collected data for the detection of single modulation cycles and created receiver operating characteristic (ROC) curves which provided compelling evidence against the use of HTT and modelled a number of different SDT probability summation estimates, however, their observer thresholds were not significantly different to either their probability summation estimates or their additive summation estimates (summing of individual component estimates by a mechanism sensitive to the compound stimulus). They were also unable to discriminate between probability summation and additive summation predictions using their methods. Although this raises the question of whether incorrect conclusions have been reached by using either method, other techniques have provided evidence for global processing of low frequency RF patterns (e.g. parallel processing in visual search, Almeida, Dickinson, Maybery, Badcock, & Badcock, 2010a; Almeida, Dickinson, Maybery, Badcock, & Badcock, 2010b; Dickinson, Haley, Bowden, & Badcock, 2018; independent processing of low and high RFs at deformation threshold, Bell et al., 2007; and pattern indentification at deformation-detection threshold, Dickinson, Bell, & Badcock, 2013; Dickinson, Cribb, Riddell, & Badcock, 2015) and there is also evidence that the methodology employed by Baldwin et al. (2016) may have led to their inability to reject probability summation (see Green, Dickinson, & Badcock, 2017; Green, Dickinson, & Badcock, in press-b).

However, there is still currently some confusion about whether global processing occurs for radial frequency patterns above RF3. This has prompted the authors of the current paper to re-investigate whether there is evidence for global processing of an RF3 (a pattern which Baldwin et al., 2016 agrees demonstrates evidence of global processing) and an RF5 (a pattern with a higher frequency than the RF4 used by Baldwin et al., 2016, and therefore, should result in integration which is poorer than an RF4 in typically developing individuals; Wilkinson et al., 1998). By comparing the pattern of results we can determine
whether there is a difference in the way an RF3 is processed compared to other low frequency RF patterns.

Using a discrimination at threshold task, we will first determine whether there is evidence that RF3 and RF5 patterns are detected in discrete information channels (Watson & Robson, 1981). We will use the RF patterns to compare their detection thresholds to the thresholds required to discriminate between them in the same observers. If, following Watson and Robson (1981), as past researchers have suggested (Dickinson et al., 2013; Dickinson et al., 2015; Graham, 1989; Watson & Robson, 1981), we are able to discriminate between RF patterns at the same threshold required for their detection, then this will be evidence of independent processing based on global shape information. This is because to discriminate between patterns requires a global judgment of shape.

This global shape judgment requires, at minimum, the combining of information at two separate corners on the shape’s contour and is, therefore, evidence of integration of information around the contour. If there is integration of information around the shape’s contour at threshold for detection, then there is global processing occurring at detection threshold. Dickinson et al. (2013) found that the local difference in presentations of an RF3 and RF6 each containing only a single cycle, was not sufficient to discriminate between these patterns at their threshold for detection and that two cycles or more of modulation were required on each pattern for discrimination to be achieved.

Schmidtmann et al. (2012) suggested that incomplete RF patterns (i.e. an RF pattern which has a portion of the contour conforming to a circle) demonstrate improvements in threshold which can be explained by probability summation. Only when the complete RF pattern is viewed (i.e. all cycles of modulation are present) does integration of information occur around the contour. Therefore, by using a discrimination at threshold task for each possible number of cycles of modulation of an RF3 and RF5, we will be able to directly test
this assertion. If observers are able to discriminate between incomplete RF patterns at their threshold for detection, it will provide strong evidence against integration only occurring for complete RF patterns as Schmidtmann et al. (2012) have suggested.

This paper will investigate whether there is evidence of global processing for RF3 and RF5 patterns; two patterns with previously strong evidence for global integration but which may differ in their ability to reject probability summation using SDT due to their different strengths of integration around the contour. We will then use the data collected to analyse whether SDT estimates of probability summation can indicate the presence of global processing and how these differ from HTT estimates. Given the majority of previous research has used HTT and either an RF3 or RF5 to examine global processing around the contour of RF patterns (see Appendix A of Baldwin et al., 2016), the inclusion of HTT and SDT estimates allow the evaluation of the suggestion by Baldwin et al. (2016) that incorrect conclusions may have been reached by previous researchers.

While some of these issues have been investigated by Dickinson et al. (2013) and Green et al. (2017) the purpose of this manuscript is to: (1) test whether there is a difference in the processing of RF3 and RF5 patterns; (2) directly test the assertion that integration only occurs around complete RF patterns as suggested by Schmidtmann et al. (2012); and (3) examine additive summation estimates from SDT, along with probability summation estimates generated when modelled using SDT and HTT for two different RF patterns and determine whether these agree with the evidence for integration provided by the discrimination at threshold task.
2.2. Methods

2.2.1. Observers

Two of the authors and two naïve observers participated in the current study after giving informed consent. All subjects had normal or corrected-to-normal visual acuity which was assessed using a LogMAR chart and no observers reported significant astigmatisms. ED has a divergent squint and used a black opaque occluder (eye patch) to cover his left eye during testing. The research protocol was approved by the University of Western Australia human ethics committee and conforms to the declaration of Helsinki.

2.2.2. Stimuli

The stimuli used were radial frequency (RF) patterns following Wilkinson et al. (1998). An RF pattern is a deformed circular contour with the radius modulated by:

\[ R(\theta) = R_0 \times (1 + A\sin(\omega\theta + \varphi)) \]  \hspace{1cm} (1)

where \( \theta \) is the angle created with the x axis, \( R_0 \) is the mean radius (1° of visual angle in all conditions), \( A \) is the amplitude of modulation (proportion of mean radius), \( \omega \) is the frequency of modulation (number of cycles per 2\pi radians) and \( \varphi \) is the phase of the sinusoidal modulation. A first derivative of a Gaussian (D1) was used to ensure a smooth transition between modulated sectors and unmodulated sectors, replacing the first half and last half cycles of the train of modulation, as also employed by Loffler et al. (2003). Therefore, at 1 cycle, the modulated sector conforms solely to a D1, with a maximum gradient identical to that of a sine wave with the same amplitude (Loffler et al., 2003). Additional cycles were always added adjacent to other cycles of modulation to maintain the polar angle between adjacent points of maximum curvature (corners) of the RF pattern, a feature shown to be important in the perception of RF patterns (Dickinson et al., 2013; Dickinson et al., 2015). The cross section of the luminance profile of the path conformed to a
fourth derivative of a Gaussian (D4) with a frequency spectrum peaking at 8 c/deg

\( f_{\text{peak}} = \sqrt{2}/\pi \sigma \); Equation 2 from Wilkinson et al., 1998) resulting from sigma (\( \sigma \)) of 3.376′ of visual angle.

### 2.2.3. Apparatus

Stimuli were generated using a PC (Pentium 4, 3GHz) and custom software written in MatLab 7.0.4 (Mathworks, Nantucket, 2002). The observers viewed a Sony Trinitron G520 monitor (100Hz refresh rate) which presented the stimuli from the frame buffer of a Cambridge Research Systems (CRS) ViSaGe (Rochester UK, 2002) visual stimulus generator. Screen resolution was 1024 x 768 pixels and viewing distance was stabilized at a distance of 65.5cm using a chinrest which resulted in each pixel subtending a visual angle of 2′. An Optical OP 200-E photometer (head model number 265) was used to linearise the luminance response and to calibrate background luminance to 45 cd/m\(^2\) and maximum luminance to 90 cd/m\(^2\), resulting in a Weber contrast of 1. Responses were signalled using the left and right buttons of a CRS, CB6 button box. A square fixation point (6′ side length) was used to indicate the centre of the screen, where stimuli were presented, with the centre of each pattern able to vary ± 6′ of visual angle in the horizontal and vertical directions, randomly selected on a trial by trial basis.

### 2.2.4. Procedure

Participants were shown both RF3 and RF5 patterns (modulated and unmodulated) at the start of the experiment on the test screen to familiarise themselves with the stimuli. A two-interval-forced-choice (2IFC) paradigm was used for all three conditions, with a reference stimulus in one interval which consisted of a circle (\( A = 0 \) in Eq. 1), and a test stimulus, either an RF3 with 1, 2 or 3 cycles of modulation or an RF5 with 1, 2, 3, 4 or 5 cycles of modulation, in the other interval. The order of presentation was randomised.
between trials. Each stimulus was presented for 160 ms, with a 300 ms inter-stimulus interval, as used in previous similar studies employing RF patterns (Bell et al., 2007; Bell et al., 2008; Dickinson et al., 2013). In the first condition (1RF detection), observers reported which interval (first or second) contained the pattern that appeared most deformed from circular. Within a block of trials only one RF pattern, with a fixed number of cycles, was presented (e.g. only an RF3 with 2 cycles of modulation). In the second condition (2RF detection), observers again reported which interval contained the pattern most deformed from circular, however, a block of trials contained both RF patterns on different trials (one interval containing a circle, the other containing either an RF3 or RF5) but with the same number of cycles where possible, resulting in the following pairings: RF3(1 [cycle]) and RF5(1); RF3(2) and RF5(2); RF3(3) and RF5(3); RF3(3) and RF5(4); and RF3(3) and RF5(5). The third condition (2RF discrimination) was presented in the same way as 2RF detection, however, observers reported which pattern was displayed in either interval (i.e. the response was RF3 or RF5). Trials were presented using the method of constant stimuli (MOCS), sampling 9 amplitudes of modulation, with 60 trials per amplitude spread over 3 separate blocks each containing 180 trials.

Observers randomly interleaved the different blocks of 1RF detection (to help determine the appropriate MOCS step size to use) then randomly interleaved the blocks from 2RF detection and 2RF discrimination. To generate the HTT probability summation prediction for the conditions, a Quick function (Quick, 1974) was fit to the data as follows:

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

(2)

where \( p \) is the probability of correct response, \( A \) is the amplitude of modulation as a proportion of the radius on an unmodulated circle, \( \alpha \) is the threshold at the 75% correct response level and \( \beta \) controls the slope of the psychometric function. As all participants were experienced psychophysical observers, no lapse rate was applied to the Quick function.
Probability summation slope (threshold as a function of number of cycles of modulation) under HTT is estimated by $1/\bar{\beta}$, where $\bar{\beta}$ is the average of the slopes of the psychometric functions for all cycles of the RF pattern (Wilson, 1980). To determine the SDT estimate of probability summation, $d$ prime ($d'$) was estimated using:

$$d' = (gA)^\tau$$

(3)

where $d'$ is the internal strength of a signal, $g$ is a scaling factor incorporating the reciprocal of the internal noise standard deviation, $A$ is the stimulus intensity, and $\tau$ is the exponent of the internal transducer (relationship between stimulus intensity and perceptual salience). Figure 2.2 below illustrates the signal and noise distributions under SDT.

![Signal and noise distributions](image)

*Figure 2.2. Parameters for calculating probability summation under SDT, from Kingdom et al. (2015).*

The estimated proportion correct for probability summation under SDT was given by Kingdom et al. (2015):

$$P_c = n \int_{-\infty}^{\infty} \phi(t - d') \Phi(t)^{Q_{M-n}} \Phi(t - d')^{n-1} dt ...$$

$$+(Q - n) \int_{-\infty}^{\infty} \phi(t) \Phi(t)^{Q_{M-n-1}} \Phi(t - d')^n dt$$

(4)

where $P_c$ is the percentage correct and set at 0.75, $t$ is sample stimulus strength, the heights of the noise and signal distributions at $t$ are given by $\phi(t)$ and $\phi(t - d')$, the areas under the noise and signal distributions to the left of $t$ are $\Phi(t)$ and $\Phi(t - d')$ respectively,
$Q$ is the number of monitored channels within the perceptual system, $M$ is the number of alternatives in the forced choice task, and $n$ is the number of stimulus components or local cues. This equation is implemented in the Palamedes toolbox, version 1.8.1 (Prins & Kingdom, 2009, downloaded in 2016 from http://www.palamedestoolbox.org).

2.3. Results

Using the Quick function (Eq. 2), estimates of 75% correct detection and discrimination thresholds were calculated for all conditions. Figure 2.3 below shows the discrimination (grey open circles) and detection (black filled circles) thresholds for each of the four observers individually and also the averaged results, when the target was an RF3 that varied in the number of cycles presented on the otherwise circular contour. Note, the conditions were: 1RF detection, discrimination of a single RF pattern (e.g. RF3(2)) and a circle; 2RF detection, again discrimination of an RF pattern and a circle, however, RF3 and RF5 stimuli were interleaved; and 2RF discrimination, discrimination of RF3 and RF5 stimuli.
Figure 2.3. RF3 detection (black solid circles) and discrimination (grey open circles) thresholds for all 4 observers (top and middle) and average of those observers (bottom left), error bars represent 95% confidence intervals. Detection thresholds are fitted using a power function (black solid line). Note for 1 cycle, discrimination thresholds appear to be greater than detection thresholds, this does not appear to be the case for 2 or 3 cycles.

2.3.1. RF3 data analysis

A repeated measures 2 (detection, discrimination) x 3 (1 cycle, 2 cycles, 3 cycles) factorial ANOVA examined the effect of both number of cycles and condition (2RF detection or 2RF discrimination) on thresholds. There was a significant main effect of both condition,
F(1,3) = 24.31, p = .02, η²_p = .89, and cycles, F(2,6) = 284.21, p < .001, η²_p = .99. There was also a significant interaction, F(2,6) = 34.12, p = .001, η²_p = .92. Visual inspection of the data and the significant interaction prompted the investigation of differences between discrimination and detection thresholds. Bonferroni-adjusted, paired-samples, t-tests revealed discrimination thresholds were significantly greater than detection thresholds at 1 cycle (p < .05), but there were no significant differences between discrimination and detection thresholds at 2 or 3 cycles (p’s > .05). Bonferroni-adjusted, paired-samples, t-tests also showed a significant difference between all numbers of cycles (all p’s < .05).

Within SDT the number of channels being monitored (Q in Equation 4) is important in both probability summation and additive summation calculations. As shown in Kingdom et al. (2015), increasing the number of channels increases the predicted threshold using a SDT probability summation model. The effect of increasing the number of channels (Q) is greatest at low numbers and if we assume the number of channels monitored is equal to either the number of lobes on the RF pattern (although this is unlikely to be correct for random phase patterns where many locations need to be monitored) or a common local feature (e.g. point of maximum convexity), we would expect to see a systematic increase in detection thresholds of the 2RF detection condition compared to the 1RF detection condition due to the monitoring of either 8 (3 channels from the RF3 plus 5 channels from the RF5) or 5 channels (only the larger number of 5 channels is required) instead of 3.

To examine the effect of number of stimuli presented within a block on thresholds a repeated measures 2 (1 RF pattern, 2 RF patterns) x 3 (1 cycle, 2 cycles, 3 cycles) factorial ANOVA was used. Figure 2.4 shows the thresholds averaged across the four observers. There was a significant main effect of number of cycles, F(2,6) = 66.78, p < .001, η²_p = .96, but not for number of stimuli, F(1,3) = .01, p = .93, η²_p = .003. There was also no interaction effect, F(2,6) = .02, p = .99, η²_p = .01. It is clear there is no difference between the two tasks in our
data and this provides evidence against the number of channels being a low value (e.g. the RF number). It suggests that for random phase patterns either the number of channels is the same for both RF patterns (e.g. the number of simple oriented V1 receptive fields falling on the contour, as random phase can result in deformation occurring at any location), or that the number of channels being monitored is so large for a single RF pattern that increasing the number of potentially–relevant channels by adding another pattern has a negligible effect.
Further investigation of the effect of the partner stimulus was also conducted. As described above for the 2RF detection task, the RF5(3), RF5(4), and RF5(5) were all partnered with an RF3(3). As can be seen from the 95% CIs in Figure 2.5 there was no effect of the partner stimulus on detection thresholds for an RF3(3). Statistical analysis using a one-way repeated measures ANOVA also returned no significant difference in the RF3(3)
thresholds, $F(2,6) = .16, p = .86, \eta^2_p = .05$. This provides further evidence for the number of channels being equal or sufficiently large that it does not substantially affect observer thresholds.

Figure 2.5. Detection thresholds for an RF3 at 3 cycles of modulation for all observers with 95% confidence intervals, and the averaged thresholds (bottom right). The x-axis shows the other test stimulus that was presented within the same block of trials, an RF5 at 3 cycles RF5(3), 4 cycles RF5(4), and 5 cycles RF5(5) of modulation.

2.3.2. RF5 data analysis

The same statistical analyses used for the RF3 were used to examine the data collected for the RF5. Figure 2.6 shows the detection (2RF detection) and discrimination (2RF discrimination) thresholds for all observers for an RF5 and their averaged results. As with the RF3, there was a significant main effect of both condition $F(1,3) = 14.46, p = .03, \eta^2_p = .83,$ and cycles, $F(4,12) = 204.36, p < .001, \eta^2_p = .99$. There was also a significant interaction effect, $F(4,12) = 26.10, p < .001, \eta^2_p = .90$. Bonferroni-adjusted, paired-samples, t-tests were again
used to examine the difference in thresholds between discrimination and detection
conditions. Discrimination thresholds were significantly greater than detection thresholds at
1 cycle (p < .05), but there were no significant differences between discrimination and
detection thresholds at 2, 3, 4 or 5 cycles (p’s > .05). Bonferroni-adjusted, paired-samples, t-
tests showed a significant difference between all numbers of cycles (all p’s < .05).
Figure 2.6. Detection (black solid circles) and discrimination (grey open circles) thresholds with 95% confidence intervals for an RF5 at 1, 2, 3, 4 and 5 cycles of modulation. Detection thresholds are fitted with a power function (black solid line; -0.67 for the group data). Note, discrimination thresholds appear to be higher than detection thresholds at 1 cycle of modulation.

The effect of number of stimuli presented within a block was examined (i.e. 1RF detection compared to 2RF detection). Figure 2.7 shows the thresholds averaged across the four observers for an RF5 presented as the only test stimulus in a block of trials (1RF detection) and thresholds when it was presented with an RF3 interleaved (2RF detection).
Again, similar to the RF3 data, there was a significant main effect of number of cycles, 

$$F(4, 12) = 133.94, p < .001, \eta^2_p = .98,$$

but no significant main effect of number of stimuli, 

$$F(1, 3) = 1.27, p = .34, \eta^2_p = .30,$$

and no interaction effect, 

$$F(4, 12) = .71, p = .60, \eta^2_p = .19.$$

The data demonstrates equivalent thresholds for these two conditions at every number of cycles and, therefore, having an RF3 within the same block of trials as an RF5 has no measurable effect on its thresholds for detection.
Figure 2.7. Detection thresholds for all 4 observers along with their averaged results for an RF5 when it is the only test stimulus within a block of trials (1RF detection; grey open circles) and when it is paired with an RF3 (2RF detection; black solid circle). A power function (solid black line) with a slope of -0.67 fits both data sets for the grouped results ($R^2 = .99$ for both data sets).
2.3.3. Psychometric Slopes

SDT predicts that for thresholds conforming to probability summation in a fixed attention window scenario, the slope of the psychometric functions should become shallower with increasing number of stimulus components (Kingdom et al., 2015; Pelli, 1985). We tested the psychometric slopes of the RF3 using a 3 (1RF detection, 2RF detection, 2RF discrimination) x 3 (1 cycle, 2 cycles, 3 cycles) repeated measures ANOVA. There was no significant main effect of either condition, $F(2,6) = 5.00, p = .053, \eta^2_p = .63$, or number of cycles $F(2,6) = 0.72, p = .53, \eta^2_p = .19$. There was also no significant interaction effect, $F(4,12) = 2.42, p = .11, \eta^2_p = .45$. Linear trend analysis of the effect of number of cycles on the psychometric slope was also not significant $F(1,3) = 0.66, p = .48, \eta^2_p = .18$. Visual inspection of the data (see Figure 2.8 below) would indicate there is no consistent pattern of change in the psychometric slopes.

![Figure 2.8](image)

*Figure 2.8. Average psychometric slopes of all 4 observers with 95% confidence intervals across the 3 conditions. There appears to be no consistent pattern across the data, contrary to SDT probability summation predictions.*

The same method was used to examine the RF5 data. A 3 (1RF detection, 2RF detection, 2RF discrimination) x 5 (1 cycle, 2 cycles, 3 cycles, 4 cycles, 5 cycles) repeated measures ANOVA was used. There was a significant main effect of cycles, $F(4,12) = 4.61, p = .02, \eta^2_p = .61$, but no significant main effect of condition, $F(2,6) = .63, p = .57, \eta^2_p = .17$, and no significant interaction effect, $F(8,24) = 1.03, p = .45, \eta^2_p = .23$. Pairwise comparisons indicated
psychometric slopes at 1 cycle of modulation were significantly less than at 4 and 5 cycles of modulation, and that the slope at 2 cycles of modulation was significantly higher than 3 cycles of modulation. No other differences were found. Linear trend analysis of the effect of number of cycles on psychometric slopes was also not significant, $F(1,3) = 8.70, p = .06, \eta^2_p = .74$. If the linear trend was significant it would suggest psychometric slopes are trending upwards (steeper), the opposite of that predicted by SDT probability summation. However, it is clear from visual inspection of the data (Figure 9) that there again appears to be no real pattern. Much more extensive data collection may have reduced the variability in the data allowing greater sensitivity to changes in the slope of the psychometric function but the current data do not suggest the extra time would be usefully spent.

![Figure 2.9. Average psychometric slopes of all 4 observers with 95% confidence intervals across the 3 conditions. Again, as with the RF3 data, there appears to be no consistent pattern across the data.](image)

#### 2.3.4. High Threshold Theory

Both HTT and SDT provide probability summation slope estimates, a prediction for the index of threshold as a function of the number of cycles of modulation when fitted by a power function. Modelled under HTT, the slope of this line is predicted by $1/\bar{\beta}$, where $\bar{\beta}$ is the average slope of all the psychometric functions measured for the RF pattern (Equation 2). This was done for each observer and compared to the slope estimate from the power function fitted to their detection thresholds using a paired samples t-test. For the RF3, the detection slope ($M = -0.81, 95\% CI [-0.59, -1.03]$) was significantly steeper than the
probability summation slope ($M = -0.47, 95\% CI [-0.34, -0.60])$, $t(3) = 3.31$, $p = .045$, $d = 1.66$.

For the RF5, the detection slope ($M = -0.68, 95\% CI [-0.53, -0.82]$) was also significantly steeper than the probability summation slope ($M = -0.44, 95\% CI [-0.39, -0.49]$), $t(3) = 4.36$, $p = .022$, $d = 2.18$. Figure 2.10 shows the group detection thresholds and probability summation estimate averaged across four observers for both the RF3 (left) and RF5 (right).

Figure 2.10. Average detection thresholds (black solid circles) with fitted power functions (solid line; -0.81 for RF3; and -0.68 for RF5) for the 4 observers with 95\% confidence intervals and probability summation estimates for HTT (red dashed line; -0.45 RF3 and -0.35 RF5), SDT with a low number of channels (black dashed line; -0.51 RF3 and -0.49 RF5), SDT with a high number of channels (grey dashed line; -0.26 RF3 and -0.29 RF5), and SDT additive summation (fixed attention window; green dashed line; -0.81 RF3 and -0.97 RF5).

2.3.5. Signal Detection Theory

The calculations used to estimate percentage correct for probability summation (Equation 4) within SDT rely on a number of parameters as previously outlined. $d'$ was calculated using PAL\_SDT\_2AFC\_PCtoDP from the Palamedes toolbox (Kingdom & Prins, 2010), estimates of $g$ and $\tau$ were derived from the best least squares fit of Equation 3 to each observer’s data. This single pair of parameters was then used in the SDT summation calculations for that observer. $M$ was set to 2 (number of intervals presented), however, the two parameters $Q$ (number of channels being monitored) and $n$ (number of local elements) are less easily specified. For the probability summation formula $n \leq Q$, therefore, for an RF3, the minimum number of channels would need to be 3 with number of local elements being equal to number of cycles. It is also possible that each cycle of an RF pattern provides two
cues, as Dickinson, McGinty, Webster, and Badcock (2012) found evidence for maximum orientation deviation from circular to be a critical feature and this occurs twice a cycle. Therefore, an RF3 would need a minimum of 6 channels, with the number of local elements equal to twice the number of cycles. The phase of the RF pattern is also likely to have an effect on the number of channels being monitored. If phases are fixed then it is reasonable to match the number of monitored local channels to the number of cycles, or to just use one cycle, since observers could know where the critical local information will occur on each trial, but random phases were employed in this study meaning that observers could not reliably predict the location of any contour feature from trial to trial. Since the cue proposed as critical by Dickinson et al. (2012) is very restricted in area, a conservative estimate is one channel per degree of phase (which results in a separation of 1° of visual angle, the limit of two-point acuity; Westheimer, 1976), thus an RF3(3) would have 120 channels (as an RF3(3) would be identical to the same pattern rotated 120°) and an RF5(5) would have 72 channels. Thus, we had 4 probability summation estimates: \( \pi = \text{cycles} \quad Q = \text{RF number}; \ \pi = 2x \ \text{cycles} \quad Q = 2 \times \text{RF number}; \ \pi = \text{cycles} \quad Q = 360/\text{RF number}; \) and \( \pi = 2x \ \text{cycles} \quad Q = 360/\text{RF number}. \)

A paired samples t-test was used to compare the detection threshold slope with each of the four SDT estimates of probability summation. Table 1 shows the results for both RF3 and RF5 data. Note that for the RF5, p-values are non-significant for the lower numbers of channels, meaning SDT is indicating there is no evidence for global processing of these stimuli unless there are a large number of channels contributing to performance.
In addition to the probability summation estimates, additive summation predictions were also calculated using SDT (although the authors have reservations about the validity of these predictions which we explain in the discussion section). As can be seen in Figure 10, additive summation estimates closely fit the observed data for an RF3. A four-fold observer level cross-validation (i.e. using each observer as a fold) confirmed that additive summation had a lower average RMSE (0.0014) and, therefore, provided a better explanation of the data than probability summation with a low number of channels (0.0030). For the RF5, additive summation estimates were significantly steeper than observer thresholds (assessed using visual inspection; Cumming, 2014) and cross-validation suggested probability summation estimates with a low number of channels provided the best fit for the data (0.00077), followed by additive summation (0.0013), then probability summation with a high number of channels (0.0020).
2.3.6. Summary

We have found evidence suggesting RF patterns with different wavelengths can be discriminated from each other at their detection thresholds when the number of cycles of modulation is greater than one. That is, we are able to make global shape judgements of RF patterns at their threshold for detection when there is more than one cycle of modulation. This is strong evidence for global processing of these patterns which is not dependent on HTT or SDT probability summation predictions and shows that local differences are poorly discriminated (i.e. at 1 cycle of modulation, see also Dickinson et al., 2013). We’ve also found no difference in detection data for an RF5 when presented with different RF3 partners in the same block of trials. This suggests these two stimuli are independently processed, further evidence against the assumption that probability summation is supporting the measured thresholds.

The HTT method produced probability summation estimates that were typical of previous research (Loffler et al., 2003; Wilkinson et al., 1998). Observer slopes for both patterns were steeper than those found by Baldwin et al. (2016) and the thresholds decreased significantly faster than their respective estimates of probability summation which has typically been taken as evidence of global processing. This evidence is consistent with the conclusions arising from our data comparing detection and discrimination thresholds for these patterns, which is generated independently of HTT. SDT estimates of probability summation varied, with all probability summation slope estimates being significantly shallower than the detection slope for an RF3 but only significantly shallower for an RF5 when estimated on the assumption that the higher number of channels was relevant; numbers that seem to be warranted with random phase stimuli. Additive summation estimates approximated observer thresholds for an RF3, but were significantly steeper than observer thresholds for an RF5. Taken together, SDT estimates were able to
identify integration in the strongly integrating RF3 pattern, but were less conclusive for the weaker integration of the RF5 (the implications of which are discussed below).

2.4. Discussion

The results provide strong evidence that observers were able to discriminate between RF patterns at their threshold for detection when the number of cycles of modulation was greater than one. Discrimination of the patterns would, at minimum, require the use of two points on the object’s contour to make a global judgement about the pattern’s shape. The authors of the current paper believe these points to be corners (Dickinson et al., 2012), and the critical feature the polar angle subtended by separation of the corners at the centre of the pattern (Dickinson et al., 2013), which is discussed below. This discrimination at threshold is evidence that the observers are integrating information along the contour of the pattern and, therefore, demonstrating global processing of radial frequency (RF) patterns at threshold, a result supported by parallel visual search performance (Almeida et al., 2013).

Signal Detection Theory (SDT) only rejected probability summation for RF5 patterns when the number of channels being monitored was appropriate for random phase stimuli but could also do so for RF3 with a much smaller channel estimation. Additionally, additive summation predictions seemed appropriate for RF3 patterns, but were significantly steeper than observer thresholds for an RF5. If we were purely using SDT to examine whether there was integration around the contour of an RF5, we likely would have drawn incorrect conclusions. Even though the additive summation estimates provided a better fit than the probability summation with a high number of channels, it would easily have been argued that observer data was significantly different to both predictions (assessed using visual inspection; Cumming, 2014) and that the data was inconclusive. Therefore, more investigation is required to determine the appropriate number of channels required in the accurate generation of probability summation predictions using SDT and whether the
current models are able to generate appropriate additive summation estimates for RF patterns. We know for the probability summation predictions to be shallow enough to correctly reject probability summation of an RF5, the number of channels needs to be relatively high. But the exact value and whether it changes for each individual pattern is still unclear.

Although we have suggested a large number of channels is required to correctly reject probability summation for low frequency RF patterns, we do not believe there are a large number of channels which are monitored by the visual system when detecting deformation in low frequency RF patterns. Our results have already demonstrated strong evidence against probability summation, as observers were able to discriminate between the patterns at threshold. This suggests integration of information around the contour and furthermore, it suggests, as outlined by Watson and Robson (1981), there are independent labelled detectors for the RF3 and RF5 (i.e. in their terms there is an RF3 channel and an RF5 channel). This would suggest one channel, rather than a large number, is responsible for the processing of each RF pattern, although it does not prove it is specifically an RF channel (Dickinson et al., 2013).

Interestingly, there was no change in observer thresholds when the RF patterns were presented as blocked or interleaved (i.e. when only a single possible RF was presented within a block of trials or when both the RF3 and RF5 were presented within the same block of trials). This would suggest there is no penalty for monitoring for the presence of different RF patterns at the same time. Kingdom et al. (2015, p. 3) note that changing from blocked to interleaved presentation should also result in changes in threshold for stimuli conforming to probability summation under SDT. Therefore, as there is no difference in thresholds between blocked and interleaved conditions, we conclude this is evidence against probability summation driving the processing of low frequency RF patterns. Furthermore,
there was no evidence of psychometric slopes becoming more shallow with increasing numbers of cycles of modulation (see Figure 2.8 and 9), a key feature of the SDT probability summation model (Baldwin et al., 2016; Pelli, 1985). In fact, previous research examining the effect of increasing numbers of cycles of modulation on psychometric functions have also found no evidence for a decrease in the slope of the psychometric functions (Baldwin et al., 2016; Cribb, Badcock, Maybery, & Badcock, 2016), further evidence against SDT probability summation for low frequency RF patterns which again, does not rely on summation estimates.

Analysis of the data using High Threshold Theory (HTT) is consistent with our evidence for global shape processing, with detection thresholds decreasing faster than those predicted by probability summation. HTT, therefore, seems not to have falsely identified that global shape processing was occurring in both the RF3 and RF5 stimuli. With the current evidence from the ROC curves presented in Baldwin et al. (2016) we agree HTT analysis is not the most appropriate for RF patterns, however, we wished to include HTT to use as a comparison to SDT. We can see from the data that when an appropriate number of channels is used in the SDT calculation, estimates are shallower than when HTT based estimates are employed. This suggests the HTT estimates of probability summation can be more conservative than SDT and that previous researchers who used this method (along with random phase RF patterns, as most did) and found evidence of global processing, likely would have done so using SDT analysis.

Schmidtmann et al. (2012) investigated the integration of information around complete RF patterns (a pattern with a fully modulated contour e.g. RF3) and incomplete RF patterns (where there is a portion of the contour which is an unmodulated circle e.g. RF3(2)). They suggested that integration of information only occurs around low frequency complete RF patterns, not for incomplete RF patterns. However, the current results provide
strong evidence against this suggestion, as we have demonstrated that discrimination at threshold is possible for incomplete RF patterns. Therefore, integration of information is occurring around patterns with incomplete modulation of their radius.

The difference in interpretation between the current results and those found by Schmidtmann et al. (2012) may arise from their use of a theoretical value for probability summation, rather than a value calculated from the pertinent data in their study. They chose to use a value of -0.33 for probability summation, following Loffler et al. (2003), however, research calculating probability summation typically show estimates greater than -0.33 (Bell & Badcock, 2008; Dickinson et al., 2010; Dickinson et al., 2012; Green et al., 2017; Tan et al., 2013), although the slopes of probability summation estimates do tend to reduce with increasing RF number. Perhaps these patterns, similar to those used in other studies (Baldwin et al., 2016; Mullen, Beaudot, & Ivanov, 2011), contained a salient local cue which caused a flattening of integration slopes (see Dickinson et al., 2012; and Green et al., 2017). This cue may have been created by not employing the D1 smoothing function to join the sine wave to the circular contour.

Results of the current paper revisit those of Baldwin et al. (2016) who were unable to reject either probability summation or additive summation estimates using SDT (also see Green, Dickinson, & Badcock, in press). Their results are most likely due to their use of fixed phase stimuli. Indeed, they acknowledge the use of fixed phase stimuli was likely the cause of their lack of improvement in detection when adding cycles of modulation to their blocked condition (with a slope of -0.18 for single RF and 0.06 for quad RF; Baldwin et al., 2016). This lack of change in detection thresholds for their blocked conditions demonstrates how locally observers can focus their attention, as it reflects a complete disregard of the increase in number of local elements. Baldwin et al. (2016) did use an interleaved condition to increase spatial uncertainty (finding a slope of -0.53 for the single RF and -0.60 for the quad RF
conditions), however, we do not believe this is analogous to a random phase pattern (we found -0.81 for an RF3 and -0.68 for an RF5), as the deformation in their study could only occur in 1 of 4 known locations and thus still only requires a small number of channels to be monitored. This highlights the problem with using fixed phase stimuli when attempting to measure global processing – if the observers know where to look to detect deformation, they are not required to monitor the whole pattern. This would make it possible to use a local attentional strategy (see Chapter 3) and reduce the likelihood of monitoring global processing occurring around a shape.

Similar to Baldwin et al. (2016), past research has also claimed to have found evidence against global processing of RF patterns (Mullen et al., 2011), however, like the methodology of Baldwin et al. (2016), they also created a salient local cue which observers could use for detection. Dickinson et al. (2012) showed that by removing the certainty by which this local cue location could be determined, thresholds changed and global processing of the pattern was observed. Their results were originally compared to HTT probability summation estimates, however given this is likely a more conservative analysis and the steepness of the slopes (average of -0.81 across 4 observers) it is likely their RF4 thresholds would have been significantly steeper than probability summation under either method of estimation. Thus, we expect that if Baldwin et al. (2016) had used random phase RF patterns (i.e. removing the spatial certainty of the deformation), they too would have obtained thresholds reflecting global shape processing for RF patterns.

As noted, discrimination at threshold required two or more cycles of modulation and suggests a critical feature appears, which is not present with only one cycle of modulation. In line with previous research (Bell et al., 2008; Bowden, Dickinson, Fox, & Badcock, 2015; Dickinson et al., 2013; Dickinson et al., 2015), we believe this critical feature to be polar angle subtended at the centre of the RF between the estimated corner locations. The results
of the current study support that of Dickinson et al. (2013) who also found observers were able to discriminate RF patterns with more than two cycles of modulation at their threshold for detection. Again, similar to Dickinson et al. (2013), we found that at one cycle of modulation, observers were unable to discriminate between RF patterns at the threshold for detection (see Figure 2.3 and Figure 2.6).

To test if polar angle is the critical feature, Dickinson et al. (2013) examined detection and discrimination thresholds for differing numbers of cycles of an RF3 and an RF6. Results showed observers were able to discriminate between an RF3 with 3 cycles of modulation and an RF6 with 6 cycles of modulation at their thresholds for detection. They then tested an RF6 with 3 adjacent cycles of modulation and an RF6 with 6 cycles of modulation. As both patterns have the same polar angle between nearest corners, but differing number of cycles, it would be expected that observers would be unable to discriminate between the patterns at detection threshold if polar angle was the cue (this assumes the outer polar angle does not affect discrimination). This is exactly what they found. Furthermore, when they tested discrimination and detection thresholds for an RF3 with 3 cycles of modulation and an RF6 with only every second cycle of modulation present (i.e. it approximated the polar separation of an RF3, but the cycles of modulation were half the wavelength), they found observers were unable to discriminate between these patterns at threshold. Therefore, there is strong evidence that the critical feature in discriminating between RF patterns at threshold is polar angle.

Although detection at threshold for discrimination requires two or more cycles of modulation, it is not evidence that global shape processing only occurs when two or more cycles are present. The discrimination task is a task that requires a global judgement to be made. This judgement appears to be greatly affected by the presence of an internal polar angle (as demonstrated by Dickinson et al., 2013). Once this cue is available, the judgement
can be made at the threshold for detection, providing evidence that observers are able to see the global shape and, therefore, global shape processing is occurring. The inability to discriminate between RF patterns with one cycle of modulation is not evidence of a lack of global processing. The authors of the current study still maintain that integration of information around the pattern’s contour occurs regardless of the number of cycles of modulation, and therefore, an observer’s threshold at 1 cycle of modulation is a valid data point when estimating that observer’s strength of integration but it is insufficient to identify the particular RF pattern.

Results of the current study support previous research suggesting low frequency RF patterns are globally processed. Analysis of data using high threshold theory (HTT) was consistent with these results, suggesting use of this method may not have distorted the conclusions obtained with previous RF pattern data. Signal detection theory (SDT) is a more appropriate method, however, it appears that further work is required to determine the appropriate number of channels required for both probability and additive summation calculations to produce accurate estimates for RF patterns. The evidence for global integration of contour information is therefore still compelling.

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The purpose of Chapter 2 was to investigate the suggestion that low frequency RF patterns conform to probability summation estimates and therefore, do not display evidence of global integration of orientation information around the contour (Baldwin et al., 2016). We used experimental method, rather than theory, to establish evidence for the integration of two commonly used low frequency RF patterns (RF3 and RF5). Our results demonstrate that for probability summation to generate appropriate estimates for random phase low frequency RF patterns it would require the monitoring of a large number of channels, however, discrimination at threshold provides strong evidence against probability summation. Instead, it suggests independent labelled channels (i.e. single independent channels) are responsible for the detection of low frequency RF patterns. Given this strong evidence for global integration of information around low frequency RF patterns, we hypothesised that the fixed phase presentation used by Baldwin et al. (2016) caused a salient local cue which obscured the measure of observer global integration. It has also been previously suggested that RF patterns and modulated lines (stimuli whose deformation is thought to be detected by local features) are processed by a common mechanism within the visual system (Mullen et al., 2011; Schmidtmann & Kingdom, 2017). Therefore, in Chapter 3 we investigated the effect of fixed and random phase presentation on both RF patterns and modulated lines. The purpose of Chapter 3 was to firstly determine if the use of fixed phase presentation of RF patterns was a plausible explanation for the differences between the results found in Chapter 2 and those found by Baldwin et al. (2016). Secondly, to compare the integration of information around RF patterns and along modulated lines, to determine whether there is evidence for the processing of these two stimuli by a common mechanism within the visual system.
Chapter 3:
Global processing of random-phase radial frequency patterns but not modulated lines

Robert J. Green, J. Edwin Dickinson, & David R. Badcock


*Keywords: Shape perception; global processing; signal detection theory; RF patterns; line modulation; probability summation; phase*
Abstract

Previously, researchers have used circular contours with sinusoidal deformations of the radius (radial frequency (RF) patterns) to investigate the underlying processing involved in simple shape perception. On finding that the rapid improvement in sensitivity to deformation, as more cycles of modulation were added, was greater than expected from probability summation across sets of local independent detectors, they concluded that global integration of contour information was occurring. More recently this conclusion has been questioned by researchers using a method of calculating probability summation derived from signal detection theory (Baldwin, Schmidtmann, Kingdom, & Hess, 2016). They could not distinguish between global integration and probability summation. Furthermore, it has been argued that RF patterns and lines are processed in a similar manner (Mullen, Beaudot, & Ivanov, 2011; Schmidtmann & Kingdom, 2017). The current study investigates these claims using fixed phase (where the local elements have spatial certainty), and random phase (where the local elements have spatial uncertainty) for both RF patterns, and modulated lines. Thresholds were collected from eight naïve observers and compared to probability summation estimates calculated using both methods derived from high threshold theory and signal detection theory. The results indicate global processing of random phase RF patterns and evidence for an interaction between local and global cues for fixed phase RF patterns. They also show no evidence of global integration with modulated line stimuli. The results provide further evidence for the global processing of random phase RF patterns and indicate that RF patterns and modulated lines are processed differently.

Keywords: Shape perception; global processing; signal detection theory; RF patterns; line modulation; probability summation; phase.
3.1. Introduction

The perception of shapes is a critical task for the human visual system as it helps us navigate and interact with the world around us. However, the processes underlying the recognition of simple shapes are still not fully understood. A stimulus which has been extensively used in the study of simple shape perception is the radial frequency (RF) pattern. These patterns are made by sinusoidally modulating a circle’s radius such that it approximates simple shapes (e.g. triangle, square etc.). Adjusting the amplitude of the sine wave adjusts the size of the deformation which adjusts the salience of the stimulus, while changing the wavelength, and therefore the number of complete sine waves that can fit around the circle’s circumference (the RF number) changes the shape it deforms into.

Previous studies interested in the visual system’s ability to globally integrate shape information, using RF patterns have examined the effect of varying the number of complete cycles of modulation on the RF pattern whilst the wavelength remains the same (see Figure 1; Dickinson, Bell, & Badcock, 2013; Dickinson, Cribb, Riddell, & Badcock, 2015; Dickinson, McGinty, Webster, & Badcock, 2012; Loffler, Wilson, & Wilkinson, 2003; Schmidtmann, Kennedy, Orbach, & Loffler, 2012; Tan, Dickinson, & Badcock, 2013). They found that observer thresholds for detecting the presence of modulation decreased faster than was predicted by probability summation (the increased chance of detection of local features due to an increase in the number of local elements available to detect) when modelled under High Threshold Theory (HTT; Loffler et al., 2003) and concluded there was evidence of integration around the contour (global processing) of these shapes when there are less than 10 cycles of modulation (Loffler et al., 2003).
A recent study by Baldwin et al. (2016) has suggested the method used in the generation of probability summation estimates based on HTT is inappropriate and may have resulted in incorrect conclusions being drawn in these earlier papers. They collected observer responses when modulation was applied to either a single RF or instead was distributed across four RFs (quad RF) having observers rate detectability on a four level scale (confident present, probably present, probably absent, confident absent) and then subsequently plotted receiver operating characteristic (ROC) curves. Analysis of their data demonstrated the curved prediction of signal detection theory (SDT) was significantly better at describing their data than the straight line prediction of HTT, indicating that the HTT model typically used in RF pattern analysis is not appropriate for this task. They suggest that the use of SDT based methods is preferable and that this might yield different results with the changes in thresholds not being significantly different to those predicted by probability summation. Indeed, in their paper, the predicted improvement due to probability summation matched that obtained from their observers (when the stimuli with different numbers of modulation cycles were shown in interleaved presentations) and thus they were unable to reject probability summation and concluded their data describing detection thresholds as a function of number of cycles of modulation provided no compelling evidence of global processing for an RF4.
One potential problem, which is noted by the authors of Baldwin et al. (2016), is the use of fixed phase RF patterns which meant the patterns were always shown in the same orientation. This was likely used because one of the parameters in SDT is “the number of channels monitored”. This parameter depends on the number of possible locations the local feature can appear. By having fixed phase stimuli the authors were able to more easily specify this parameter, by assuming a feature per cycle, however, they departed from the typical methodology employed in RF pattern research (random phase with many more than four possible locations for deformation). The use of a fixed phase and the resulting certainty in location of deformation created a salient local cue which may have been preferentially used (in both their blocked and interleaved conditions), reducing the detection thresholds at low numbers of cycles and thus flattening the integration slopes. It is for this reason that previous researchers have used random phase stimuli to ensure global monitoring of the pattern.

The current study agrees with Baldwin et al. (2016) that the results of their blocked conditions, where they find almost no change in thresholds as a function of the number of cycles, are a result of the observer attending to a salient local cue. For there to be apparently no increase in sensitivity the observer would be required to be only detecting one feature. Therefore, we would describe their results in both blocked conditions as local processing of a single feature. Their findings are contrary to those of Loffler et al. (2003) who used a blocked design and measured both fixed phase and random phase RF patterns. Thresholds decreased with increasing number of cycles for both fixed phase and random phase conditions, with fixed phase being shallower than random phase for the RF5 and RF24 patterns. There was no difference between the slopes of the fixed and random phase conditions of the RF3, potentially suggesting a strong global cue for this stimulus which is used preferentially or the use of only two points on the curve (one of which was a half cycle,
not frequently used in RF detection tasks) may not have yielded equivalent estimates to those for the RF5 and RF24 patterns. The current study will revisit this particular result.

Furthermore, we suggest the interleaved conditions used by Baldwin et al. (2016) were also affected by the use of fixed phase stimuli. Interleaving the patterns did introduce spatial uncertainty and we agree that this was the cause of the steepening of their integration slopes, however, there were still only 1 of 4 possible locations where information could arise. This may have resulted in the interaction of a salient local cue produced by the fixed phase with the global cue of the whole pattern, producing a shallower function which was unable to support the rejection of probability summation. Further discussion of this is provided in the discussion section.

Another paper challenging the evidence of global processing in RF patterns is Mullen et al. (2011). In one of their experiments they compare the detection thresholds for RF patterns to those of modulated lines (sinusoidally modulated lines analogous to uncoiled RF patterns). They conclude that detection of RF patterns may not be different to that of modulated lines, a point which is cited by Baldwin et al. (2016). This finding was contrary to Wilkinson, Wilson, and Habak (1998) who, when originally creating RF patterns, compared detection thresholds of fully modulated RF patterns and modulated lines at varying contrasts. They found a different pattern of results for the two types of stimuli as pattern contrast was varied and concluded there were different processes underlying the detection of these two stimuli, although a recent report by Schmidtmann and Kingdom (2017) provides a common method for describing curvature in RF and line patterns which predicts a similar outcome across the two pattern types.

Dickinson et al. (2012) noted that the use of local cues with a predictable location by Mullen et al. (2011) may have altered the outcomes (see also Schmidtmann et al., 2012, for additional critique of Mullen et al.’s (2011) methods) and, therefore, the current study aims
to examine the effect of fixed phase and random phase presentations on contour integration with both RF patterns and modulated lines. By comparing the observer thresholds to those predicted by probability summation modelled within the framework of SDT we can determine whether there is evidence of global processing of these patterns and compare these results to predictions based on HTT to determine if incorrect conclusions are likely to have been drawn by previous research using this theory. The comparison of RF patterns and line stimuli will allow assessment of the suggestion of Wilkinson et al. (1998) that closed contours (RF patterns) are processed differently to lines, although in this case we will explicitly measure integration of the distributed information.

3.2. Methods

3.2.1. Observers

Eight observers participated in the current study as part of their course requirement. All participants at the time of testing were naïve to the main aim of the study. All observers gave informed written consent and had normal or corrected-to-normal visual acuity which was assessed using a logMAR chart. Research was approved by UWA human ethics committee and conforms to the declaration of Helsinki.

3.2.2. Stimuli

Two stimulus types were used. The first were radial frequency (RF) patterns following Wilkinson et al. (1998). An RF pattern is a circular contour with the radius \( R \) modulated as a function of polar angle \( \theta \):

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

(1)

where \( \theta \) is the angle created with the x axis, \( R_0 \) is the mean radius (1° of visual angle), \( A \) is the amplitude of modulation (proportion of mean radius), \( \omega \) is the frequency of
modulation (number of cycles per $2\pi$ radians) and $\varphi$ is the phase of the sinusoidal modulation. When partially modulating the patterns, a first derivative of a Gaussian (D1) was used to ensure a smooth transition between modulated sectors and unmodulated sectors, replacing the first half and last half cycles of the train of modulation, as also employed by Loffler et al. (2003). Therefore as in previous studies, at 1 cycle, the modulated sector conforms solely to a D1, with a slope and amplitude identical to the sine waves used when there is more than 1 cycle of modulation (Loffler et al., 2003). The cross section of the luminance profile of the path conformed to a fourth derivative of a Gaussian (D4; Wilkinson et al., 1998). Using $f_{\text{peak}} = \sqrt{2}/\pi \sigma$ (equation 2 from Wilkinson et al., 1998) the peak spatial frequency of 8 c/deg results from the sigma ($\sigma$) of 3.376’ of visual angle.

The other stimuli used were modulated lines, equivalent to an RF pattern which had been unwound to form a single straightened line. These are defined by:

$$L_x(L_y) = A \sin(\omega L_y + \varphi)$$

where $L_x$ is the horizontal location of the line, $L_y$ is the vertical location of the line, $A$ is the amplitude of modulation (as a proportion of 1° visual angle, analogous to RF patterns). The wavelength ($\omega$) is the number of cycles per length of modulated sector (i.e. per 6.28°, which is analogous to the circumference of an unmodulated 1° radius RF pattern) and was set to 3, resulting in a length of 2.09° per cycle of modulation. A random starting location ($\varphi$) between 0 and 6.28°, 4.19°, or 2.09°, for 1, 2, and 3 cycles respectively, was used and corresponded to a length of 3, 2, and 1 cycles of modulation. An additional 1° of unmodulated line was added to the top and bottom of the stimulus, so the top and bottom would always have an unmodulated portion (see Figure 3.2). Because the modulated sector joins an unmodulated sector for all cycles of modulation a D1 was used to ensure a smooth transition between modulated sectors and unmodulated sectors, replacing the first half and last half cycles of the train of modulation as employed for the RF patterns described above.
Also similar to the RF patterns described above, the cross section of the luminance profile of the path conformed to a fourth derivative of a Gaussian (D4) with a frequency spectrum peaking at 8 c/deg.

Figure 3.2. Modulated line stimuli used: 1 cycle (left); 2 cycles (middle); and 3 cycles (right) of modulation.

3.2.3. Apparatus

Stimuli were generated using a PC (Pentium 4, 2.4GHz) and custom software written in MatLab 7.2.0 (Mathworks, Natick, 2002). The observers viewed a Sony Trinitron CPD-G420 CRT monitor (100Hz refresh rate) which presented the stimuli from the frame buffer of a Cambridge Research Systems (CRS) VSG2/5 visual stimulus generator. Screen resolution was 1024 x 768 pixels (34.15° x 25.6°) and viewing distance was stabilized at a distance of 58.75cm using a chinrest which resulted in each pixel subtending a visual angle of 2'. An Optical OP 200-E photometer (head model number 265) was used to linearise the luminance response and to calibrate background luminance to 45 cd/m² and maximum luminance to 90 cd/m², resulting in a Weber contrast of 1 for all stimuli. Responses were signalled using the left and right buttons of a mouse. The stimuli were randomly jittered a maximum of ±6' of
visual angle horizontally, and vertically and observers were able to freely view the stimuli, as a fixation may have provided a point of comparison, and therefore, a confound.

3.2.4. Procedure

A two-interval-forced-choice (2IFC) paradigm was used for all four conditions, with a reference stimulus in one interval, which consisted of a circle ($A = 0$ in Equation 1) for the RF conditions or a line ($A = 0$ in Equation 2) for the line conditions, and a test stimulus, either an RF3 or a modulated line (with 1, 2 or 3 cycles of modulation) in the other interval (for the RF and line conditions respectively). Order of presentation was randomised between trials. Each stimulus was presented for 160 ms, with a 300 ms inter-stimulus interval, as used in previous similar studies employing RF patterns (Bell & Badcock, 2008; Bell, Badcock, Wilson, & Wilkinson, 2007; Dickinson et al., 2013). In both conditions the observer reported which interval (first or second) contained the pattern which appeared most deformed from circular or linear (again, for the RF and line conditions respectively). There were four conditions in total, a fixed phase RF, random phase RF, fixed phase line, and random phase line. For the fixed phase conditions $\varphi = 0$, resulting in the line deformation starting 1° from the bottom of the stimulus as depicted in Figure 3.2 and the RF patterns having the orientations depicted in Figure 3.3 below. Observers were informed where the deformation was going to occur for these fixed phase conditions and shown example stimuli. For the random phase conditions $\varphi$ was varied randomly between trials resulting in uncertainty in the location of deformation.

Figure 3.3. Orientations for 1 (left), 2 (middle), and 3 (right) cycles of modulation for the fixed phase RF condition. Amplitudes are well above threshold, but shown for clarity.
Data was collected using the PSI method (Kontsevich & Tyler, 1999), implemented using the Palamedes toolbox (Prins & Kingdom, 2009, available at http://www.palamedestoolbox.org), and analysed using a weighted Quick function (Quick, 1974; see equation 3). Observers completed 150 trial blocks at 1, 2, and 3 cycles (blocked design) of modulation for each condition. To generate the HTT probability summation prediction for the conditions, we used the formula $-\frac{1}{\bar{\beta}}$ where $\bar{\beta}$ is the average of the parameter $\beta$ in the Quick function (Quick, 1974), across all numbers of cycles of modulation. The Quick function is defined as:

$$p(A) = 1 - 2^{-(1+(A/\alpha)\beta)}$$

(3)

where $p$ is the probability of correct response, $A$ as defined in equations 1, and 2, $\alpha$ is the threshold at the 75% correct response level and $\beta$ controls the slope of the psychometric function. To determine the SDT estimate of probability summation, $d$ prime ($d'$) was estimated using:

$$d' = (gA)^\tau$$

(4)

where $d'$ is internal strength of a signal expressed in standard deviations of the internal noise distribution, $g$ is a scaling factor incorporating the reciprocal of the internal noise standard deviation, $A$ is the amplitude (stimulus intensity), and $\tau$ is the exponent of the internal transducer (determines the steepness of the function converting increased stimulus intensity to increased perceptual response). The values for $g$ and $\tau$ were obtained by inputting observer scores as $d'$ (converted from percentage correct using the function PAL_SDT_2AFC_PCToDP from the Palamedes toolbox, version 1.8.1; Prins & Kingdom, 2009) at the given amplitude ($A$). According to Kingdom, Baldwin, and Schmidtmann (2015) the estimated percentage correct given by probability summation modelled within the framework of SDT was given by:
\[ P_c = n \int_{-\infty}^{\infty} \phi(t - d') \Phi(t)^{QM-n} \Phi(t - d')^{n-1} dt \ldots \]

\[ + (Q - n) \int_{-\infty}^{\infty} \phi(t) \Phi(t)^{QM-n-1} \Phi(t - d')^n dt \]  

where \( P_c \) is the percentage correct and set at 75%, \( t \) is sample stimulus strength, the heights of the noise and signal distributions at \( t \) are given by \( \phi(t) \) and \( \phi(t - d') \) respectively, \( \Phi(t) \) and \( \Phi(t - d') \) are the areas under the noise and signal distributions below the criterion \( t \), \( Q \) is the number of monitored channels, \( M \) is the number of alternatives in the forced choice task, and \( n \) is the number of stimulus components. This equation is also implemented in the Palamedes toolbox using the function \text{PAL\_SDT\_PS\_PCtoSL} \ (Prins & Kingdom, 2009).

Probability summation estimates modelled within the framework of SDT were calculated for a high and a low number of channels \( (Q) \). Following Cribb, Badcock, Maybery, and Badcock (2016) we used 3 channels, with \( n \) increasing by 1 with each cycle of modulation added for the “low” calculation and 120 channels, again with \( n \) increasing by 1 for the “high” calculation. As outlined in Cribb et al. (2016) the number 120 is the number of 1 degree rotations (out of 360°) a RF3 with 3 cycles of modulation could make before the pattern was repeated (see Chapter 6 for further discussion of rationale for number of channels). This was chosen as: the maximum difference in orientation (the zero-crossing of the sine wave) is a very local feature which is detected first (Dickinson et al., 2012) in modulation detection tasks; random phase results in spatial uncertainty with regard to this feature.

### 3.3. Results

Figure 3.4 shows the geometric means and 95% confidence intervals for the 8 observers for all conditions and presentations. There is a clear difference in the steepness of
the slopes when comparing the fixed phase presentation (which appears to have a dog-leg) of the RF pattern (light red circles) to the random phase presentation (dark red circles) of the RF pattern, which appears to be primarily a result of the difference between conditions at 1 cycle of modulation. To investigate the effect of fixed phase and random phase presentation of RF patterns on observer thresholds a repeated measures 2 (fixed phase, random phase) x 3 (1 cycle, 2 cycles, 3 cycles) factorial ANOVA was performed. There was a significant main effect of phase $F(1,7) = 7.68, p = .03, \eta_p^2 = .52$, and there was a significant main effect of cycles, $F(2,14) = 22.26, p < .001, \eta_p^2 = .76$, and a significant interaction effect, $F(2,14) = 9.61, p = .002, \eta_p^2 = .58$. Bonferroni-adjusted pairwise comparisons revealed a significant difference between 1 cycle ($M = .028, SE = .003$) and 2 cycles ($M = .015, SE = .001; p = .01$), 2 cycles and 3 cycles ($M = .010, SE = .001; p = .03$), and 1 cycle and 3 cycles ($p = .001$). Given the interaction effect, simple main effects of phase were examined at each level of cycles using paired samples t-tests. There was a significant difference between fixed phase and random phase thresholds for an RF3 with 1 cycle of modulation, $t(7) = 3.70, p = .008, d = 1.30$, but not at 2 cycles, $t(7) = 0.42, p = .69, d = 0.14$, or 3 cycles, $t(7) = 0.47, p = .65, d = 0.17$. 
Figure 3.4. Geometric means and 95% confidence intervals for thresholds of 8 observers for fixed phase RF patterns (light red circles), random phase RF patterns (dark red circles), fixed phase modulated lines (grey boxes), and random phase modulated lines (black boxes). Thresholds are fitted by a power function with slopes of -0.54 (fixed phase RF; light red line), -1.09 (random phase RF; dark red line), -0.44 (fixed phase line; grey line), and -0.61 (random phase line; black line).

Figure 3.5 shows a clear difference between the random phase RF pattern observer slope (averaged across the 8 observers) and all three of its probability summation estimates. Statistical analysis of the data was performed using a repeated measures one-way (observer slope, HTT PS, SDT (low) PS, SDT (high) PS) ANOVA. There was a significant main effect of slope, $F(3,21) = 20.45$, $p < .001$, $\eta^2_p = .75$. Planned comparisons revealed observer slopes ($M = -1.06, SE = .12$) were significantly steeper than all probability summation estimates (HTT ($M = -.37, SE = .04$), $p = .001$; SDT low ($M = -.59, SE = .07$), $p = .01$; SDT high ($M = -.30, SE = .03$), $p = .001$).
Figure 3.5. Thresholds averaged across 8 observers with 95% confidence intervals for the random phase RF condition. Solid black line is the fitted power function; dashed lines are for probability summation estimates HTT (red; -0.37), SDT low (black; -0.59), SDT high (grey; -0.30).

At the request of a reviewer we used a 8-fold observer level cross validation (i.e. using each observer as a fold) to determine which model, linear summation or probability summation (modelled using SDT with a low number of channels, the most conservative estimate), provided a better explanation of the current data. We performed the cross validation in 3 different ways, with all results supporting our previous statistical test and indicating that probability summation cannot account for our data.

In our first method the training data provided estimated thresholds for both models and these were directly compared to the thresholds of our test data by calculating the average root-mean-squared-error (RMSE). Linear summation had a lower average RMSE (.077) than probability summation (.096). In the other two methods the training data provided an estimate of the slope ($B$) used in the power function $Th = Cx^B$, where $Th$ is threshold, $C$ is threshold at 1 cycle of modulation, and $x$ is the number of cycles of modulation. The parameter $C$ was either free to vary such that it provided the best fit of the test data with the estimated parameter $B$ (method 2) or it was defined by the test data’s measured threshold at 1 cycle of modulation (method 3). Similar to method 1, linear
summation (.030, .033 respectively) had a lower average RMSE than probability summation (.048, .060 respectively). The results of all 3 methods suggest that linear summation provides a more accurate account of our data.

In contrast to the random phase RF data, Figure 3.6 shows that observer slopes for the fixed phase RF patterns (averaged across the 8 observers) are not significantly steeper than any of the probability summation estimates. The same method was used to examine global processing in the fixed phase RF condition and indicated a significant main effect of slope, $F(3,21) = 3.55, p = .03, \eta_p^2 = .33$. However, planned comparisons revealed no significant difference between observer slopes ($M = -.55, SE = .07$) and the probability summation estimates (HTT ($M = -.52, SE = .07$), $p = .82$; SDT low ($M = -.81, SE = .16$), $p = .18$; SDT high ($M = -.42, SE = .08$), $p = .29$) with these fixed phase RF patterns and unadjusted post-hoc pairwise comparisons indicated the main effect was due to a significant difference between the high SDT probability summation estimate and the low SDT probability summation estimate ($p = .001$).
Figure 3.6. Thresholds averaged across 8 observers with 95% confidence intervals for the fixed phase RF condition. Solid red line is the fitted power function; dashed lines are for probability summation estimates HTT (red; -0.51), SDT low (black; -0.81), SDT high (grey; -0.42).

It is readily apparent from the data (Figure 3.4) that there is a similar pattern of results for the fixed phase and random phase presentations of the modulated line stimulus. Analysis of the observer thresholds for these presentations was performed using a repeated measures 2 (fixed phase, random phase) x 3 (1 cycle, 2 cycles, 3 cycles) factorial ANOVA. There was a significant main effect of phase $F(1,7) = 9.15, p = .02, \eta_p^2 = .57$, and significant main effect of cycles, $F(2,14) = 23.87, p < .001, \eta_p^2 = .77$. There was no significant interaction, $F(2,14) = 2.49, p = .12, \eta_p^2 = .26$. Bonferroni-adjusted pairwise comparisons revealed thresholds at 1 cycle of modulation ($M = .01, SE = .001$) were significantly higher than both 2 ($M = .007, SE = .001; p = .004$), and 3 cycles ($M = .007, SE = .001; p = .005$), but there was no significant difference between 2 and 3 cycles of modulation ($p > .99$).

A repeated measures 2 (random phase, fixed phase) x 4 (observer slopes, HTT PS, SDT low PS, SDT high PS) factorial ANOVA was performed to investigate the effect of phase and slope on strength of integration for modulated lines. The assumption of sphericity was
violated for slope and the interaction, so a Greenhouse-Geisser adjustment was applied.

There was no significant main effect of phase, $F(1,7) = 2.56, p = .19, \eta^2_p = .39$, and there was no significant interaction effect, $F(1.22,4.86) = 0.74, p = .55, \eta^2_p = .16$. There was a significant main effect of slope, $F(1.74,6.96) = 21.46, p < .001, \eta^2_p = .84$ and planned comparisons indicated there was no significant difference between observer slopes ($M = -.49, SE = .07$) and probability summation estimates for HTT ($M = -.53, SE = .03; p = .71$) or SDT high ($M = -.54, SE = .05; p = .61$), however, the probability summation estimate SDT low ($M = -1.04, SE = .09$) was significantly steeper than observer slopes ($p = .008$). These results provide no evidence of global processing for either condition and are depicted in Figure 3.7 below. They also suggest the high channel number probability summation estimate is more appropriate than that derived assuming a low number of channels.

**Figure 3.7.** Geometric means and 95% confidence intervals for thresholds of 8 observers for fixed phase line (grey squares; left) and random phase line (black squares; right) stimuli. Thresholds are fitted by a power function with slopes of -0.44 (fixed phase; grey line) and -0.61 (random phase; black line). Probability summation estimates are represented by the dashed lines: HTT (red; -0.47 left; -0.48 right); SDT low (black; -0.73 left; -1.16 right); and SDT high (grey; -0.37 left; -0.64 right).
3.3.1. Summary

For the RF patterns there was a significant difference between the observer thresholds of the fixed phase and random phase conditions at 1 cycle of modulation, but not 2, or 3. There was strong evidence for global processing of the random phase RF pattern, with observer slopes significantly steeper than all probability summation estimates. The fixed phase RF pattern, however, demonstrated no evidence of global processing but was consistent with probability summation.

For the line stimuli, observer thresholds for the fixed phase were significantly lower than the random phase presentations. Observer thresholds at 1 cycle of modulation were significantly greater than at 2, and 3 cycles, but there was no difference between the observer thresholds at 2 and 3 cycles of modulation. Similar to the fixed phase RF pattern, these stimuli showed no evidence of global processing.

3.4. Discussion

The purpose of the current paper was to examine the effect of fixing the phase of stimuli (their rotation) on modulation detection thresholds for both RF patterns and modulated lines in order to interpret conclusions drawn from previous research regarding the evidence for global contour integration. By making the modulated sector of the line stimuli the same length as the circumference of the RF patterns we are able to compare the two stimuli in their integration of information along their respective contours. This gave both stimuli the same period of modulation (wavelength) across the surface of their respective patterns, which has been demonstrated to be important for both RF patterns (Loffler et al., 2003; Wilkinson et al., 1998), and modulated lines (Tyler, 1973). The results demonstrated strong evidence for the global processing of random phase RF patterns, but not for fixed phase RF patterns, fixed phase modulated lines, or random phase modulated
lines. These results showed that fixed phase presentation had a significant effect on the processing of RF patterns, but not modulated lines.

The current results do differ from those obtained with an RF3 by Loffler et al. (2003). They found only a slight decrease in thresholds for an RF3 with fixed phase compared to one with random phase. For the other two patterns they tested (RF5 and RF24) they found that thresholds for the fixed phase presentation appear to decrease more at 1 cycle of modulation than for the full cycle pattern. This is the same as the results of the current study, with thresholds converging when the fully modulated pattern is presented. The current study used 8 naïve participants whereas Loffler et al. (2003) only had 2 for their investigation of fixed and random phase. Thus individual differences may be a potential explanation for the difference in the results found. Additionally, when Loffler et al. (2003) tested the difference between fixed phase and random phase they used two data points for all 3 stimuli. For the RF5 and RF24 they employed either one cycle (RF5(1), RF24(1)) or all of the cycles (RF5, RF24), however, for the RF3 they tested at RF3(0.5) and RF3. The use of this half cycle (raised cosine function) is another potential explanation for the difference. Experiment 3 of Dickinson et al. (2012) found that using a cosine function in place of a sine function can have a significant effect on observer thresholds. Perhaps there is a feature created by the half cycle pattern which is not present for whole cycle patterns causing a different pattern of results.

Our results for fixed phase RF patterns are consistent with the interaction between local and global cues described in Experiment 3 of Dickinson et al. (2012). There was a significant difference between the detection of an RF3 at 1 cycle of modulation for a fixed phase pattern compared to a random phase pattern (see Figure 3.4). The fixed phase created a usable local cue through the knowledge of the location of deformation which was more salient than the global cue of the entire pattern for 1 cycle of modulation. This
resulted in a lower threshold of detection of this fixed phase pattern. As the global signal increased with 2, and 3 cycles of modulation the global cue became more salient than the local cue, resulting in the thresholds at 2, and 3 cycles of modulation decreasing at a very similar rate for both the fixed phase, and random phase presentation of an RF3. This interaction between the two cues causes the flattening of the overall integration slope found in the fixed phase pattern and the inability for this type of pattern to provide data which can reject probability summation explanations of the outcome.

This could explain the results obtained by Baldwin et al. (2016), as they used fixed phase presentation of the RF4 (both blocked and interleaved) and found they were unable to distinguish between observer thresholds and either additive summation or probability summation estimates modelled within the framework SDT. Similar to the current results (-0.54 for fixed phase RF), they would have experienced a salient local cue for the low cycles of modulation which would have flattened their integration slope (they obtained slopes of -0.18 for their blocked condition and -0.53 for their interleaved condition) and were unable to reject probability summation as an explanation for the steeper slope. The current findings agree with conclusions reached previously arguing for global processing (Bell & Badcock, 2008; Bell et al., 2007; Dickinson et al., 2013; Dickinson et al., 2012; Hess, Wang, & Dakin, 1999; Loffler et al., 2003; Tan et al., 2013; Wilkinson et al., 1998) albeit with a more appropriate probability summation estimate. Furthermore, the ability for the random phase presentation of the RF3 to reject all probability summation estimates (HTT and both SDT) can be considered strong evidence for the global processing of these patterns. It is, therefore, likely the conclusions of previous research using random phase RF patterns with a low frequency were correct in their assertion of global processing for these patterns.

Baldwin et al. (2016) suggest that there is no difference between the processing of their single RF condition and their quad RF condition. In other words, it does not matter
whether additional information is added on to the same RF pattern or a nearby RF pattern, it results in the same non-global processing. It is true that the slopes for the blocked and interleaved conditions are similar between the two conditions, however, there is a different pattern of results for the two conditions. Thresholds for the blocked and interleaved presentations of the single RF patterns diverge when information is added to the pattern, while the thresholds for the blocked and interleaved presentations of the quad RF patterns converge with each cycle of modulation added. This different pattern of results for their two stimuli implies a difference in the underlying processing.

We agree with Baldwin et al. (2016) that the convergence of the interleaved and blocked presentations of the quad RF condition is consistent with observers monitoring a single location on the contour. When all cycles are present the observers have a better chance of detecting the modulation at that location and when fewer cycles are present in the interleaved condition they will fail to detect the modulation when it is not at that location. The blocked trials produce essentially the same threshold for all stimuli because only a single, known location is being monitored. The extra cycles have no impact on performance because observers are not attempting to perform a global detection task.

The pattern of results are completely different for the single RF condition in Baldwin et al. (2016) and they are contrary to what is predicted by SDT probability summation estimates in Kingdom et al. (2015). The threshold for detection of the interleaved presentation is lower than the blocked presentation after 1 cycle of modulation. Probability summation cannot account for this decrease. If detection was purely based on local features then an observer would not be able to perform better (i.e. lower threshold) than in the blocked condition. This is because when there is only local processing and the observer knows exactly where to look, they achieve their best threshold for detection. The increase in sensitivity can only be accounted for by the integration of some of the local information.
around the contour of the single RF. Therefore, there is clear evidence in the data presented in Baldwin et al. (2016) that demonstrates evidence of global processing for single RF stimuli which (similar to additional evidence discussed below) does not rely on comparison to probability summation estimates modelled using either SDT or HTT.

Additional evidence for global processing also comes from Dickinson et al. (2013), where they used a two-by-two forced choice task in which they presented one of two possible RF patterns (an RF3 or an RF6) in one interval, and a circle in the other. Observers were required to identify which pattern was presented and in which interval it appeared. Their results showed that the thresholds for detection of modulation and the identification of the particular RF pattern were the same (Dickinson et al., 2013), indicating observers are able to make a necessarily global judgment about the RF pattern’s shape at its threshold for detection and that the two patterns were being identified by independent global processes (Watson & Robson, 1981).

Baldwin et al. (2016) suggest that an RF3 typically demonstrates steep integration slopes and it might be argued that our results might not generalise to RF patterns with a greater frequency (i.e. RF4 and above). We would suggest the contrary, as our results indicate the use of fixed phase provides a salient local cue which is used when the global cue is relatively weak. As the global cue of an RF pattern decreases in strength with increasing RF number, as evidenced by the decreased integration slope (Bell & Badcock, 2008; Loffler et al., 2003; Wilkinson et al., 1998), we would, therefore, expect this cue to have a greater effect on higher frequency RF patterns as their global cue is weaker than that of an RF3. Ultimately, researchers have found that detection of modulation in patterns with radial frequencies higher than 10 is local and changes in thresholds with increasing numbers of cycles are consistent with probability summation (Bell et al., 2007; Hess et al., 1999; Jeffrey, Wang, & Birch, 2002; Loffler et al., 2003; Schmidtmann et al., 2012; Wilkinson et al., 1998).
Baldwin et al. (2016) compared their results to a number of different probability and additive summation estimates. They were generated by either fixing the parameters $\tau$, $g$, and $\sigma$ in Equation 4 or allowing them to vary. Our study was concerned with the effect of fixed phase presentation on RF patterns and modulated lines and as such, we were changing the parameter “number of channels monitored”. Considering we were modifying this parameter experimentally, it was logical for us to create probability summation estimates which varied this parameter. As clearly shown in Kingdom et al. (2015), increasing the number of channels monitored results in a significant increase in probability summation threshold predictions when the number of channels are low.

We generated two SDT probability summation estimates: one where the number of channels was equal to the RF number, the number of stimuli was equal to the cycles of modulation (as employed by Baldwin et al., 2016), and is analogous to a fixed phase presentation; the other with the number of channels equal to 120 (the number of unique $1^\circ$ rotations an RF3(3) can make; see methods) and is analogous to a random phase presentation. An RF3 with random phase presentation was significantly steeper than both SDT estimates, meaning even when using an inappropriately conservative probability summation estimate, we were still able to find evidence of global processing for a random phase RF3. Given the slopes of probability summation estimates decrease with an increase in the number of channels monitored, it means our results would be able to reject probability summation estimates with 3 or more channels (assuming the other parameters are the same). Therefore, we saw no reason to add additional models, as altering parameters such as $\tau$, $g$, and $\sigma$ with a more appropriate number of channels would not produce probability summation estimates which were more conservative than our 3 channel model. The same reasoning holds for the fixed phase presentation of the RF3, the 120 channel model was inappropriately shallow (liberal) for a fixed phase presentation, however, the observer results were still not significantly steeper than those predicted thresholds.
Using an appropriate number of channels (e.g. 3) and varying other parameters would not have resulted in any other conclusion. Thus, we do not need any additional models as each model provides an appropriate estimate for one presentation and an inappropriate (ultra conservative or liberal) estimate for the other presentation.

Results from the line conditions are consistent with local processing of these patterns regardless of fixed phase or random phase presentation. Thresholds for detection of random phase presentation were significantly higher than fixed phase presentation, as we would expect with its comparative increase in spatial uncertainty and our pattern of results are similar to those of Tyler (1973) who also investigated sensitivity to sine wave modulation on a straight line with spatial certainty. Tyler (1973) found approximately a doubling of sensitivity when moving from 1 to 2 cycles of modulation for patterns with a spatial periodicity between 0.3 and 1 c/deg, but no improvement with additional cycles (see Figure 4 of Tyler, 1973). Our patterns with each cycle of modulation presented over 2.09° of visual angle approximate a spatial frequency of 0.5 c/deg. Therefore, our results replicate the findings with an approximate doubling of sensitivity when moving from 1 to 2 cycles, and no improvement when moving from 2 to 3.

This lack of improvement between 2, and 3 cycles of modulation for the line stimulus, combined with the lack of difference in the pattern of results displayed for the fixed phase and random phase presentations, highlights the difference between modulated lines and RF patterns. As suggested by Tyler (1973) there appears to be a spatial limit (approximately 2.5°) to the integration of information presented on a modulated line, whereas presentation of RF patterns with different radii (measured up to 4°) has minimal effect on observer thresholds measured as a proportion of radius (Bell & Badcock, 2008; Wilkinson et al., 1998). This is also evidence for different processing strategies for the two
types of stimuli (Dickinson et al., 2012) and the importance of period of modulation being a function of polar angle.

3.4.1. Conclusions

The current study looked at the effect of fixed phase and random phase presentation on RF patterns and modulated lines. We found strong evidence for the global processing of random phase RF patterns and evidence for an interaction between local and global cues for fixed phase RF patterns. This can explain the recent findings of Baldwin et al. (2016), with their inability to reject probability summation in their interleaved presentation of a single RF pattern being a result of their use of fixed phase stimuli that presented few potential locations for the cues even in interleaved conditions. We also replicated the results of Tyler (1973), finding an increase in sensitivity between 1, and 2 cycles of modulation, but not between 2, and 3 cycles of modulation. These results suggest RF patterns and modulated lines are processed differently by the human visual system.

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doi:[http://dx.doi.org/10.1016/S0042-6989(98)00039-X](http://dx.doi.org/10.1016/S0042-6989(98)00039-X)
3.5. Link to Chapter 4

The purpose of this Chapter was to investigate whether the use of fixed phase presentation by Baldwin et al. (2016) could explain the difference between their results and those found in Chapter 2 and previous literature (Dickinson, Han, Bell, & Badcock, 2010; Dickinson et al., 2012; Loffler et al., 2003; Tan et al., 2013). We found that fixed phase presentation of RF patterns creates a salient local cue which is used preferentially by the visual system when the global signal is weak. This causes a flattening of observer integration slopes, obscuring the global integration the researcher is attempting to measure. The use of random phase presentation removes this local cue, restoring the ability to accurately measure global integration. We also found evidence contrary to the suggestion that modulated lines and RF patterns are processed by a common mechanism (Mullen et al., 2011; Schmidtmann & Kingdom, 2017), as RF patterns displayed a different pattern of results when increasing the number of cycles of modulation and furthermore, the modulated lines were unaffected by fixed phase presentation. This suggests that closed contours (e.g. object outlines) are important to the visual system and it combines the information along the path of these shapes which result in sensitivities which exceed that of local element detection. Therefore, as the results of Chapter 3 have indicated a confounding factor within Baldwin et al. (2016), we revisited their paradigm in Chapter 4 to investigate whether, after the removal of the local cue through the use of random phase RF patterns, there was evidence for global integration both across and within RF patterns.
Chapter 4:
Integration of shape information occurs around closed contours but not across them

Robert J. Green, J. Edwin Dickinson, & David R. Badcock

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Keywords: Shape perception; global processing; signal detection theory; RF patterns; probability summation
Abstract

Scenery and complex objects can be reduced to a combination of shapes, so it is pertinent to examine if the integration of information found occurring around simple contours also occurs across them. Baldwin, Schmidtmann, Kingdom, and Hess (2016) investigated this idea using radial frequency (RF) patterns, distributing information around a single contour or across four contours. However, their use of a restricted number of locations for this information may have influenced their results (see Green, Dickinson, & Badcock, 2017). The current study revisits their paradigm using random phase (spatial uncertainty) presentation of RF patterns with 11 observers. Results provide strong evidence for the integration of information around single contours but not across them. These findings are contrary to the lack of integration found by Baldwin et al. (2016) within a single contour, but do provide support for their suggestion that improvement in performance when adding information to separate RF patterns is a function of probability summation. Similar to Green et al. (2017) it suggests the importance of using random phase RF patterns when measuring integration.

Keywords: Shape perception; global processing; signal detection theory; RF patterns; probability summation.
4.1. Introduction

The human visual system decodes the image presented to find appropriately arranged elements which may indicate the presence of an object. This is thought to occur through the combination of local orientation and corners (Dickinson, Cribb, Riddell, & Badcock, 2015; Persike & Meinhardt, 2017) into more complex objects (faces, houses etc.) and scenes (Van Essen, Anderson, & Felleman, 1992; Vernon, Gouws, Lawrence, Wade, & Morland, 2016). Spatial integration of adjacent local information can result in better sensitivities than predicted by the increased likelihood of detection that could arise simply from having more numerous local elements and has been used as one type of evidence of global processing. This integration has been shown to occur around, both, contours (Bell & Badcock, 2008; Cribb, Badcock, Maybery, & Badcock, 2016; Dickinson, McGinty, Webster, & Badcock, 2012; Hess, Wang, & Dakin, 1999; Loffler, Wilson, & Wilkinson, 2003; Tan, Dickinson, & Badcock, 2013) and textures (Tan, Bowden, Dickinson, & Badcock, 2015).

Radial frequency (RF) patterns (Wilkinson, Wilson, & Habak, 1998) have previously been used to examine the global processing of shapes. These patterns are circles that have had their radius sinusoidally modulated as a function of polar angle and they are, therefore, closed contours which can be varied in shape (see Figure 4.1) to mimic the bounding contours of some objects, making them a useful stimulus in the study of shape perception. They are defined by their RF number (number of wavelengths able to fit in 360°) and the number of complete sinusoidal cycles actually present in the pattern. Increasing the amplitude of the modulating sine wave increases the pattern’s deformation from circular, and therefore, increases the probability of the observer discriminating the RF pattern from a circle.

One method used for determining the presence of global processing in RF patterns is the comparison of the rate of reduction in observer thresholds, arising from increasing
numbers of cycles of modulation of a fixed wavelength on the contour, to the rate which
would be predicted by probability summation. Probability summation is the increased
chance of detection due to an increase in the number of local signals available on the
contour; a number which increases as more cycles are added. However, the way in which
probability summation was previously calculated has been called into question and will be
discussed below.

![Figure 4.1](image)

Figure 4.1. Example RF patterns. Top, left to right: an RF3(1), RF3(2), and RF3(3) (RF3 with 1,
2, and 3 cycles of modulation respectively); bottom, left to right: an RF4, RF6, RF8. All
patterns have an amplitude of \(1/(1+\omega^2)\), where \(\omega\) is the RF number and results in a pattern
well above threshold levels, but shown for clarity.

Complex scenes are made up of collections of objects which can be further reduced
to simple shapes and in turn local elements. Researchers have demonstrated the pooling of
discrete local elements in a wide range of contexts, including dot pairs (Badcock, Clifford, &
Khuu, 2005; Dickinson & Badcock, 2007; Dickinson, Broderick, & Badcock, 2009; Glass, 1969;
Glass & Pérez, 1973; Morrone, Burr, & Vaina, 1995), Gabor patches (Dickinson, Han, Bell, &
Badcock, 2010; Holmes & Meese, 2004; Tan et al., 2015), and both static (Baker & Meese,
2011; Meese, 2010; Meese & Hess, 2007) and moving gratings (McDougall, Dickinson, &
Badcock, 2016). There is also evidence for the visual system’s ability to extract group
statistics from low-level visual elements (Ariely, 2001; Burr & Ross, 2008) and more complex
scenes, such as determining the average emotion, gender, and identity from a crowd of
evidence, we might expect information from simple shapes, particularly those with shared parameters, to be pooled together across a surface by the visual system in a process similar to that used with local elements or a crowd of faces.

Baldwin, Schmidtmann, Kingdom, and Hess (2016) investigated the integration of information in two contexts. First when the information was spread around a single contour of an RF pattern (within) and, second, when the same amount of modulation was applied to more than one contour (across). They used 4 RF patterns in a diamond arrangement (quad RF condition) to examine detection thresholds across-RF patterns and compared these results to detection thresholds within a pattern (single RF condition). In their analysis they determined there was little difference in the summation across-RF patterns compared to within-RF patterns, a result consistent with detection of local features rather than global integration of information around contours. Furthermore, they found no evidence to reject probability summation, which is indicative of local feature detection, and therefore, they found no evidence of global processing either within or across the RF4s when assessed using their method.

Baldwin et al. (2016) were unable to reject probability summation within-RF patterns, a finding which is contrary to the conclusions of previous studies looking at integration of RF4 patterns (Dickinson et al., 2012; Schmidtmann, Kennedy, Orbach, & Loffler, 2012). These latter studies did argue for the global processing of RF4s, with observer thresholds decreasing faster than predicted by probability summation as more modulation cycles were added to a single contour. However, those studies did generate probability summation estimates using high threshold theory (HTT), a method which Baldwin et al. (2016) and Kingdom, Baldwin, and Schmidtmann (2015) argue against. Although it must be noted that there were some differences in methodology between the studies using HTT and Baldwin et al. (2016) which are also quite likely to have influenced the results.
Baldwin et al. (2016) used fixed phase (fixed orientation) stimuli for both the single RF and quad RF conditions, meaning the orientation of the pattern was the same between trials. They presented the stimuli in blocked trials (where the observer would know how many cycles were being presented and in which location the maximum deformation would occur) or interleaved trials (where, from trial to trial, the number of cycles was unknown and the orientation could be 1 of 4 known possibilities). When the stimulus presentation was blocked, Baldwin et al. (2016) found that thresholds were very similar to each other regardless of the numbers of cycles present. This is unsurprising as, with fixed phases, observers would know where deformation would be occurring in the pattern and would only need to monitor one location. Indeed it has been shown by Dickinson et al. (2012) that the presence of a known local cue (e.g. knowing where the deformation is going to occur) can result in stimuli being locally processed (poor integration) and the removal of the observer’s certainty in the location of deformation restores this indication of global integration for RF patterns.

The interleaved presentations of both the quad and single RF conditions used by Baldwin et al. (2016) served to create spatial uncertainty in the location of deformation, however, this is not analogous to the random phase (random orientation) presentation of an RF pattern as the deformation could appear only at 1 of 4 locations. This meant the observers could monitor those 4 locations and disregard the remainder of the pattern, a strategy which favours local processing. This could explain why, for the single RF condition, the integration slope obtained (-0.53) when fitting the improvement in threshold as a function of the number of modulation cycles was less than that found in Dickinson et al. (2012) who used random phase RF4 stimuli and obtained an average integration slope of -0.80. The integration slope is the index of the power function that describes the relationship between threshold and number of cycles of modulation. Linear summation with constant noise results in a slope of -1; additive summation by the ideal observer in a 2 interval task.
results in a slope of \(-0.50\) (Tyler & Chen, 2000); and probability summation varies across observers, but is typically between approximately \(-0.30\) and \(-0.50\) for HTT predictions (see Appendix A of Baldwin et al., 2016) and between approximately \(-0.30\) and \(-0.60\) (Green, Dickinson, & Badcock, 2017) for SDT using random phase RF patterns (depending on parameters used in the calculation, which is discussed below).

Although Baldwin et al. (2016) found both the single RF and quad RF interleaved conditions produced similar integration slopes, the pattern of results for the two stimuli were different. As the number of modulated cycles increased for the single RF condition, the thresholds for the blocked and interleaved presentations diverged from one another. Whereas increased cycles of modulation for the quad RF condition resulted in the thresholds of the blocked and interleaved presentations converging. This difference in the pattern of results found for the two stimuli may suggest a difference in the way they are being processed by the visual system or perhaps the strategy adopted by the observers (see Green et al., 2017 for a discussion of the possible strategies adopted by the observers).

Previously, researchers investigating global processing of RF patterns have modelled probability summation estimates using high threshold theory (HTT; Dickinson et al., 2015; Dickinson et al., 2012; Loffler et al., 2003; Schmidtmann et al., 2012; Tan et al., 2015; Tan et al., 2013), however, Baldwin et al. (2016) obtained receiver operating characteristics (ROC) curves to demonstrate that detection of RF patterns is better described by signal detection theory (SDT) than HTT and argued further that probability summation estimates should therefore be derived using the methods of SDT. We agree with them that the curved fit of signal detection theory (SDT) provided a better explanation for their ROC data than HTT and therefore also use SDT to generate probability summation estimates for RF patterns, however, HTT estimates are also included as a comparison to SDT to facilitate comparison with earlier studies.
4.2. Methods

4.2.1. Observers

Two of the authors and nine naïve observers participated in the current study. ED has a divergent squint and used a black opaque occluder (eye patch) to cover his left eye during testing. All subjects had normal or corrected-to-normal visual acuity which was assessed using a LogMAR chart. The research was approved by the University of Western Australia human research ethics committee and conforms to the declaration of Helsinki. All participants gave informed written consent.

4.2.2. Stimuli

The stimuli were radial frequency (RF) patterns (Loffler et al., 2003). An RF pattern has its radius modulated by the following formula:

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

where \( \theta \) is the angle created with the x axis, \( R_0 \) defines the mean radius (1° of visual angle in all conditions), \( A \) sets the amplitude of modulation (proportion of mean radius), \( \omega \) refers to the frequency of modulation (number of cycles per 2\( \pi \) radians) and \( \varphi \) refers to the phase of the sinusoidal modulation which controls the rotation of the pattern (randomised for each pattern for each trial). A first derivative of a Gaussian (D1) was used to ensure a smooth transition between modulated sectors and unmodulated sectors, replacing the first half and last half cycles of the train of modulation, as also employed by Loffler et al. (2003). Therefore, at 1 cycle, the modulated sector conforms solely to a D1, with a maximum slope and amplitude identical to that which would be produced by a sine wave (Loffler et al., 2003). The cross section of the luminance profile of the path conformed to a fourth derivative of a Gaussian (D4) with a frequency spectrum peaking at 8 c/deg (Loffler et al.,
Where \( f_{\text{peak}} = \sqrt{2}/\pi \sigma \) (equation 2 from Wilkinson et al., 1998), resulting in a sigma (\( \sigma \)) of 3.376′ of visual angle.

4.2.3. Apparatus

Stimuli were generated using a PC (Pentium 4, 2.4GHz) and custom software written in MatLab 7.2.0 (Mathworks, Natick, 2002). The observers viewed a CRT Sony Trinitron CPD-G420 monitor (100Hz refresh rate) which presented the stimuli from the frame buffer of a Cambridge Research Systems (CRS) VSG2/5 visual stimulus generator. Screen resolution was 1024 x 768 pixels and viewing distance was stabilized at a distance of 58.75cm using a chinrest which resulted in each pixel subtending a visual angle of 2′. An Optical OP 200-E photometer (head model number 265) and the CRS Desktop software were used to linearise the luminance response and to calibrate background luminance to 45 cd/m\(^2\) and maximum luminance to 90 cd/m\(^2\), resulting in a Weber contrast of 1. The minimum luminance was 17.14 cd/m\(^2\) which resulted in a Michelson contrast of 0.68 for our stimuli. Responses were signalled using the left and right buttons of a mouse. Observers were instructed to fixate on a square (6′ side length) in the centre of the screen where stimuli were presented, with the centre of the entire stimulus able to vary ± 6′ of visual angle in the horizontal and vertical directions. This was done to reduce retinal afterimages to the luminance profile whilst maintaining the same spatial relation between the individual RF patterns.

4.2.4. Procedure

A two-interval-forced-choice (2IFC) paradigm was used, with observers reporting which interval contained patterns most deformed from circular. One interval contained the reference stimulus, which consisted of 3 spatially separated circles (\( A = 0 \) in Equation 1). These circles were centred 3° of visual angle away from the centre of the stimulus, had a radius of 1° of visual angle, and their centres were distributed to fixed locations around a
circle and separated by an angle of 120° (see Figure 4.2). The other interval contained the test stimulus, using an identical layout to the reference stimulus with one or more RF patterns replacing one or more circles (depending on condition, explained below). The order of presentation was randomly determined for each trial and both the reference stimulus and the test stimulus (i.e. all 3 contours) were jittered ± 6′ of visual angle in the horizontal and vertical directions between trials, however, there was no movement of the circles relative to each other.

![Figure 4.2](image)

**Figure 4.2.** Three example stimulus presentations used in the experiment: left, a reference stimulus containing unmodulated circles ($A = 0$ in equation 1; letters shown for illustrative purpose only and were not present for testing); middle, a test stimulus with an RF3(1) at locations A and B; and right, another test stimulus with an RF3(2) at location C. Both the right and middle stimuli contain two cycles of modulation, however, they are presented on one and two contours respectively.

The current study investigated integration within RF patterns, i.e. when deformation is applied to a single contour; and across-RF patterns, i.e. when deformation is applied to multiple spatially separate contours. Our methodology is different to Baldwin et al. (2016), who used RF4s and when testing across patterns used 4 locations. As described below, we interleaved the within and across presentations of 1, 2, and 3 cycles of modulation. At 2 cycles of modulation, there were 6 conditions interleaved, requiring 30 mins of testing. To adequately interleave 4 locations using RF4s, an approximate 1 hour block would be required to test 2 cycles of modulation, which would likely result in significant observer fatigue. Therefore, we chose to use 3 spatial locations with RF3s as our test stimulus to
reduce the number of trials presented in a single block and these patterns also demonstrate
the steepest integration slopes, allowing the greatest chance for global processing across
patterns.

Every stimulus was presented for 160 ms, with a 300 ms inter-stimulus interval, as
used in our previous similar studies employing RF patterns (Bell, Badcock, Wilson, &
Wilkinson, 2007; Bell, Dickinson, & Badcock, 2008; Dickinson, Bell, & Badcock, 2013). Each
condition was tested in 3 blocks. In the first condition (1 cycle) an RF3(1; i.e. an RF3 with 1
cycle of modulation) was presented at either location A, B, or C. There were 150 trials per
location (450 total) and on each trial the contour containing deformation was randomly
selected. In the second condition (2 cycles) either 1 RF3(2) would appear at either A, B, or C
or 2 RF3(1)s would appear at AB, AC, or BC (see Figure 4.2). Again, within a block there were
150 trials per location (900 total) and locations were randomised between trials. In the third
condition (3 cycles) an RF3(3) would appear at either A, B, or C or 3 RF3(1)s would appear
(one at each location; ABC). As with the previous conditions, 150 trials per location (600
total) and locations were randomised between trials. Data was collected using the PSI
method (Kontsevich & Tyler, 1999), implemented using the Palamedes toolbox (Prins &
Kingdom, 2009, available at http://www.palamedestoolbox.org), which optimised a Quick
function (Quick, 1974; see equation 2) with a lambda value of 0.01. The parameters used in
the slope estimation for the PSI method incorrectly included values less than 1. This resulted
in a small number of the estimated psychometric slopes having values of less than 1 and
therefore, required reanalysis of the data using a weighted Quick function (as there was
unequal sampling of stimulus intensities). This reanalysis resulted in no psychometric slope
values less than 1 and for this small number of psychometric functions visual inspection
suggested what $R^2$ values confirmed, the weighted quick function provided a more accurate
fit of the data (e.g. for observer AP, RF3(1) at location B, the weighted function resulted in
$R^2 = 0.69$ compared to $R^2 = 0.36$ for the original fit). However, for the vast majority of data,
there was no noticeable difference between the threshold and slope values obtained using
the PSI method or the weighted quick function and therefore, this did not affect the
experimental outcome.

Probability summation estimates were generated using procedures from both high
threshold theory (HTT) and signal detection theory (SDT) to allow comparisons with earlier
studies. Psychometric functions were plotted using a Quick function (Quick, 1974) with the
formula:

\[ p(A) = 1 - 2^{-\left(1 + \left(\frac{A}{a}\right)^{\beta}\right)} \]  

(2)

where \( p \) is the probability of correct response, \( A \) is the amplitude of modulation as a
proportion of the radius on an unmodulated circle, \( a \) is the amplitude producing the 75%
correct response level (the threshold) and \( \beta \) controls the slope of the psychometric function.
Under HTT (when probability summation is in operation) the slope of the line indicating the
improvement in threshold as more cycles are added is estimated by \(-1/\beta\), where \( \beta \) is the
average of the slopes of the psychometric functions for all cycles of the RF pattern. As can be
seen in Figure 4.3 psychometric function slopes (\( \beta \)) did not decrease with increasing
numbers of cycles of modulation contrary to probability summation estimates modelled
using SDT (Pelli, 1985).
Following Baldwin et al. (2016) we estimated probability summation under SDT by calculating $d'$ using the routine PAL_SDT_2AFC_PctDP from Prins and Kingdom (2009). These values were used along with stimulus intensity to solve the following equation with respect to $g$ and $\tau$:

$$d' = (gA)^\tau$$

(3)

where $d'$ is internal strength of a signal, $g$ is a scaling factor incorporating the reciprocal of the internal noise standard deviation, $A$ is the stimulus intensity, and $\tau$ is the exponent of the internal transducer (which controls the rate at which the observer is converting increased stimulus intensity to increased proportion of correct responses).

Under SDT, the proportion correct estimated for probability summation is given by (see Kingdom et al., 2015 for further details):

$$Pc = n \int_{-\infty}^{\infty} \phi(t - d') \Phi(t)^{QM-n} \Phi(t) (t - d')^n dt ...$$

$$+(Q - n) \int_{-\infty}^{\infty} \phi(t) \Phi(t)^{QM-n-1} \Phi(t) (t - d')^n dt$$

(4)
where \( P_c \) is the proportion correct and set at 0.75, \( t \) is sample stimulus strength (amplitude), the heights of the noise and signal distributions at \( t \) are given by \( \Phi(t) \) and \( \Phi(t - d') \) respectively, \( \Phi(t) \) and \( \Phi(t - d') \) are the areas under the noise and signal distributions less than \( t \), \( Q \) is the number of monitored channels (defined below), \( M \) is the number of alternatives in the forced choice task (2 in the current study), and \( n \) is the number of stimulus components (discussed below). The fitting of this equation is also implemented in the Palamedes toolbox (for full details see Prins & Kingdom, 2009, available at http://www.palamedestoolbox.org). As the stimuli used are random phase RF patterns the observer is always uncertain of the location of deformation and therefore, we assume a fixed attention window (where the number of channels is greater than the number of local elements; see Kingdom et al., 2015, for a detailed explanation of fixed attention window paradigms).

### 4.3. Results

Figure 4.4 below shows the results for the within-RF pattern conditions and the across-RF patterns conditions. A 4 (A, B, C, across) x 3 (1 cycle, 2 cycles, 3 cycles) repeated measures factorial ANOVA was used to examine the effect of condition and number of cycles on detection thresholds. There was a significant main effect of both condition, \( F(3,30) = 21.07, p < .001, \eta^2_p = .68 \) and number of cycles, \( F(2,20) = 157.31, p < .001, \eta^2_p = .94 \). There was also a significant interaction effect, \( F(6,60) = 5.63, p < .001, \eta^2_p = .36 \). Pairwise comparisons revealed thresholds for 1 cycle of modulation were significantly higher than 2 and 3 cycles of modulation \( (p'\text{'s} < .05) \) and 2 cycles of modulation was significantly higher than 3 cycles of modulation \( (p < .05) \), which was irrespective of condition.

Because of the interaction effect 3 one-way repeated measures ANOVAs were performed to examine the effect of condition for each cycle of modulation. There was no significant main effect of condition at 1 cycle of modulation, \( F(3,27) = 0.02, p = .99, \eta^2_p = \).
.002. There was a significant main effect of condition at 2 cycles of modulation, $F(3,30) = 14.73, p < .001, \eta^2_p = .60$, with pairwise comparisons revealing the across-RF patterns condition had significantly higher thresholds than all 3 within-RF pattern conditions ($p$'s < .05). There was no significant difference between the three pattern locations for the within-RF pattern conditions ($p$'s > .05). At 3 cycles of modulation, there was also a significant main effect of condition, $F(3,30) = 16.35, p < .001, \eta^2_p = .62$, the across-RF patterns condition had a significantly higher threshold than the 3 within-RF pattern locations ($p$'s < .05), and there was no significant difference between the thresholds of the 3 within-RF pattern locations ($p$'s > .05). It is clear from the analysis and Figure 4.4 below that the amount of improvement in thresholds for the across-RF patterns conditions is less than for the within-RF patterns conditions with increasing number of cycles.

![Figure 4.4: Geometric means of 11 observers with 95% confidence intervals for the within-RF pattern conditions (red, location A; blue location B; and green location C) and the across-RF patterns condition (black dashed line).](image)

To determine whether there is any evidence of global processing, the slopes of the lines joining the thresholds were compared to the probability summation slopes predicted by both HTT and SDT. The HTT probability summation slope estimate was calculated by the simple formula described in the methods for both within-RF patterns and across-RF patterns. Probability summation estimates under SDT were calculated for a high and a low
number of channels \((Q)\). This method was used by Cribb et al. (2016) where the number of stimulus components \((n)\) is increased by 1 with each additional cycle of modulation added and the number of channels \((Q)\) was 3 for the “low” calculation and 120 for the “high” calculation. The number 120 is the number of 1 degree rotations (out of 360°) an RF3 with 3 cycles of modulation could make before the pattern was repeated. This was chosen as: the maximum difference in orientation (the zero-crossing of the sine wave; i.e. the difference between the pattern’s tangent and a circle’s tangent) is a very local feature which is detected first (Dickinson et al., 2012) in modulation detection tasks; random phase results in spatial uncertainty with regard to this feature; and therefore a large number of locations would need to be monitored assuming probability summation. This number is not critical to the current results, however, and is discussed in detail below.

As there are 3 RF patterns presented simultaneously, the number of channels the observer is required to monitor is obviously three times as great. Therefore, we will be using 9 channels for our “low” SDT probability summation estimate and 360 channels for our “high” SDT probability summation estimate. Kingdom et al. (2015) demonstrated that increasing the number of channels increases observer thresholds and also has the resultant effect of decreasing probability summation slopes. Therefore, increasing the number of channels makes it easier to reject probability summation and we believe that for 3 RF patterns in random phase 360 channels is an appropriate estimate. The 9 channel estimate is too conservative, as it assumes 1 channel per cycle which is only appropriate for fixed phase patterns (Green et al., 2017), but we have included it for comparison as a lower limit.

Analysis of the observer thresholds found no significant difference between thresholds for the within-RF pattern conditions (i.e. no difference in thresholds within a single contour at locations A, B, or C), but did find a significant difference in thresholds for the within-RF pattern conditions compared to the across-RF patterns condition. Therefore,
analysis of the observer slopes and their probability summation estimates will be split into within-RF patterns and across-RF patterns. Figure 4.5 displays the averaged observer thresholds for each of the 4 conditions along with the 3 probability summation estimates used to investigate global processing.

To examine the within-RF pattern conditions, a 3 (A, B, C) x 4 (observer slope, HTT PS, SDT 9 channels, SDT 360 channels) repeated measures factorial ANOVA was used to examine the effect of location and model type on slope estimate. There was no significant main effect of location, $F(2,20) = 2.98, p = .08, \eta^2_p = .25$, and there was no significant interaction effect, $F(6,60) = 0.28, p = .95, \eta^2_p = .03$. However, there was a significant main effect of model type, $F(3,30) = 58.35, p < .001, \eta^2_p = .87$. Planned comparisons revealed observer slopes (estimates given in Figure 4.5 caption) were significantly steeper than all probability summation slope estimates from HTT and SDT ($p's < .05$).

A one-way repeated measures ANOVA was used to examine the effect of model type on slope estimate for the across-RF patterns condition. There was a significant main effect of model type, $F(3,30) = 4.92, p = .007, \eta^2_p = .33$, and pairwise comparisons indicated there was a significant difference between the slopes of the SDT 9 and SDT 360 probability summation estimates ($p < .05$), but the observer slopes were not significantly different to any of the probability summation estimates from HTT or SDT ($p's > .05$).
Figure 4.5. Geometric mean for 11 observers with 95% confidence intervals for conditions A, B, C, and across patterns. Solid black lines show the integration slopes (-0.82, CI [-0.58, -1.07]; -0.84, CI [-0.62, -1.06]; -0.72, CI [-0.45, -0.99]; and -0.36, CI [-0.16, -0.57] respectively) and the dashed lines display the probability summation estimates (grey, HTT [-0.44, -0.43, -0.34, -0.38]; red, SDT 9 channels [-0.36, -0.36, -0.31, -0.57]; blue, SDT 360 channels [-0.20, -0.20, -0.18, -0.32] for [A, B, C, across] respectively).

4.4. Discussion

The purpose of the current paper was to examine the assertion that integration results reflect only local processing. This was done by distributing cycles of modulation either across multiple contours or around a single contour. The results demonstrate that in our study integration of information within a single RF pattern is significantly stronger than
across-RF patterns. There appeared to be no preference for the spatial location of the RF pattern, as there was no consistent increased sensitivity in the lower visual field (a result differing from that of Schmidtmann, Logan, Kennedy, Gordon, & Loffler, 2015, which is discussed below). Comparison of observed thresholds and those predicted by probability summation using both HTT and SDT showed strong evidence for the global processing within-RF patterns, but no evidence of global processing across-RF patterns.

As originally noted by Loffler et al. (2003) when introducing the method of changing number of cycles for a given RF number, the use of fixed phase RF patterns could potentially lead to localised attention with the observer concentrating on a fraction of the contour and disregarding global aspects. Dickinson et al. (2012) demonstrated that this can change the results substantially and we believe this explains the difference between the current results and those of Baldwin et al. (2016). Our use of random phase stimuli, coupled with uncertainty of whether the cycle/s of modulation would appear on one pattern or distributed across them (within and across), meant the observer was unable to anticipate the location/s of deformation. This required them to monitor the entire contour of each of the RF patterns and resulted in strong integration of information within discrete RF patterns, but not across them. Baldwin et al. (2016) used fixed phase stimuli, potentially introducing a highly salient local cue which resulted in decreased thresholds, particularly for the more difficult patterns to detect (1 and 2 cycles of modulation), which would result in a shallower slope and therefore, reduce the estimated strength of integration. The interleaving of conditions (1, 2, 3, and 4 cycles) in their study did not introduce enough spatial uncertainty as information could only appear in 1 of 4 possible locations. Therefore, observers were not required to monitor the whole pattern and were still able to use a local processing strategy.

Another potential explanation for the difference between the current results and those of Baldwin et al. (2016) is their 300 ms presentation time compared to the 160 ms of
the current study. The increased duration in Baldwin et al. (2016) allows the observer to make a saccade during presentation. This, again, allows the observer to utilise different strategies, potentially moving their focal point to different parts of the contour in an attempt to get more information.

Within the pattern of results obtained by Baldwin et al. (2016) there is evidence for a difference in the processing of the single RF condition compared to the quad RF condition. They found a difference in thresholds at 1 cycle of modulation for the interleaved and blocked presentations of the quad RF condition (see Figure 6 of Baldwin et al., 2016). This difference decreased with more cycles of modulation until they converged at 4 cycles of modulation. This pattern of results is consistent with that described in Kingdom et al. (2015) for probability summation when using a fixed attention and matched attention window. This suggests the observer monitoring 1 location as there is no improvement in thresholds within the blocked condition when more cycles are added.

For the single RF condition, the thresholds were the same at 1 cycle of modulation for the interleaved and blocked presentations, but they diverged with increasing cycles of modulation (Baldwin et al., 2016). This pattern of results cannot be explained using a probability summation model. At 1 cycle of modulation probability summation would predict that the spatial uncertainty created by the interleaved presentation would result in higher observer thresholds than for the blocked presentation (this is what is evident from their quad condition). The thresholds for the interleaved condition start at the same threshold for 1 cycle of modulation and then decrease faster than for the blocked condition. This means the performance for the interleaved condition (where the observer does not know the location of deformation) is better than for the blocked condition (where the observer knows exactly where deformation will occur). No probability summation model can explain this
result, as they necessarily predict the interleaved presentation could never achieve thresholds less than the blocked presentation (Kingdom et al., 2015).

Therefore, for the interleaved presentation of the single RF condition to have a higher sensitivity than the blocked presentation (Baldwin et al., 2016) there must have been integration of information around the contour. For the blocked presentation, the observers were able to monitor a single location which could explain the lack of change in thresholds found. The spatial uncertainty created by the interleaved presentation of the single RF condition likely caused the observer to monitor all 4 locations where deformation could occur. This enabled the integration of information from the other locations, resulting in a decreased threshold relative to those found for their blocked presentation, however, this integration was not enough to reject probability summation estimates as observers could still narrow down where the deformation would occur (1 of 4 possible locations). This created a local cue which interacted with the global cue to reduce the integration slope (see Green et al., 2017 where they demonstrate the effect of fixed phase on integration slopes of an RF3).

Habak, Wilkinson, Zakher, and Wilson (2004) used “nested” RF patterns to examine the interaction between patterns. In their study they created stimuli consisting of an RF pattern (target) with either a suprathreshold RF pattern inner ring, outer ring, or both. They were looking at the masking effect (decrease in sensitivity to the target) produced by the suprathreshold masking patterns. Among their results they found that the interaction between patterns had little to no effect outside of approximately 1°. The current study had RF patterns of 1° radius, 3° from the central fixation point, and spaced with a subtended polar angle of 120°. This resulted in the contours being approximately 0.8° apart at their closest point. This separation would suggest the RF patterns should have been able to
interact with each other so this is not a likely explanation for the lack of integration found between patterns (i.e. being on separate contours matters).

Observer slopes were compared to probability summation estimates from both HTT and SDT. Baldwin et al. (2016) examined receiver operating characteristic (ROC) curves for both of their conditions. They found evidence to suggest that HTT is not appropriate for the analysis of RF patterns as the straight line fit to the ROC predicted by HTT was significantly worse than the curved fit predicted by SDT. Therefore, we did not include HTT as a competing model, but rather to connect previous research with current theory. The current results show HTT to provide a more conservative estimate than the high number of channels (360) SDT estimate, which is consistent with Green et al. (2017). This was replicated across all conditions and support the suggestion of Green et al. (2017), that the previous studies finding evidence of global processing using HTT probability summation estimates would likely have reached the same conclusions using probability summation estimates modelled using SDT.

As outlined in the methods section, we used two estimates of probability summation from SDT, one with 9 channels (an overly conservative estimate but following the 1 channel per cycle used by Baldwin et al., 2016) and the other with 360 channels (a more appropriate estimate for random phase patterns). Statistical analysis supports what is readily apparent from Figure 4.5, that observers slopes for locations A, B, and C are significantly steeper than all probability summation estimates from both HTT and SDT, while the across-RF patterns condition was not significantly steeper than any probability summation estimates. As can be seen in Figure 4.5, increasing the number of channels decreases the probability summation slope. Some researchers may argue that 360 channels is too many, however, we were able to reject probability summation at 9 channels (which is
certainly too low for 3 random phase RF patterns) and therefore, would be able to reject it at any number greater than 9.

Our results highlight not only the importance of using random phase RF patterns, but also an appropriate number of channels when calculating probability summation estimates. Baldwin et al. (2016) used fixed phase RF patterns in their experiment, so using the RF number for the number of channels was correct (i.e. number of channels was equal to 4, although this assumes the participant is monitoring all 4 channels rather than monitoring a single channel), however, this severely limits the sensitivity of the test for global integration and what we have shown is this approach should not be taken for random phase patterns. Random phase patterns have spatial uncertainty in the location of deformation and using the RF number for the number of channels will produce probability summation estimates which are too conservative.

It was suggested by Baldwin et al. (2016) that RF3 patterns may be a special case in which integration occurs and this might not occur for higher frequency RF patterns (i.e. RF4 and above). They cite their steep integration slopes as evidence of their difference to other low frequency RF patterns, however, this is unsurprising as it has been noted that the integration slopes for RF patterns decrease with increasing RF number (Loffler et al., 2003), so an RF3 would be expected to have steeper integration slopes than patterns with higher RF numbers. Dickinson et al. (2012) suggested that the difference in thresholds for differing RF patterns is actually a result of the use of amplitude of modulation rather than gradient at zero crossing as the measurement of threshold (see Figure 7 of Dickinson et al., 2012). When they re-plotted results for 3 participants for an RF2, RF3, RF4, and RF6 using gradient at the zero crossing as a function of number of cycles of modulation, they found that thresholds across all 4 patterns were the same when they had the same number of cycles of modulation. This suggests that low frequency RF patterns are processed in the same manner
and an RF3 is not a special case to be considered separate from other low frequency patterns.

Observers were instructed to focus on the fixation point and as the presentations times were 160 ms, we are confident in the RF patterns being presented in the upper and lower visual field. As we found no significant difference in thresholds at location A, B, or C, our results are also contrary to those found by Schmidtmann et al. (2015) who also used RF3s and found a lower field visual preference for RF patterns. In their study, they looked at thresholds for detection of straight lines, curves, and RF patterns. For straight lines, and curves they found no visual field preference (i.e. there was no difference in thresholds between the upper, lower, right, or left visual fields), but for RF patterns they found a lower visual field advantage (i.e. thresholds for the lower visual field were significantly lower than for other areas). They note that previous studies have shown a lower visual field advantage for reaching and grasping (visuomotor) tasks (Danckert & Goodale, 2003; Previc, 1990; Rossit, McAdam, Mclean, Goodale, & Culham, 2013) and cite this as a reason for their investigation of these simple shapes and components and suggest this increased sensitivity in the lower visual field may be a result of the fact that humans typically manipulate objects in the lower visual field.

However, the results of Schmidtmann et al. (2015) are not consistent with those of Rossit et al. (2013), as although they did find a lower visual field preference when grasping for objects, this result was not found for passively viewed objects. The results of Rossit et al. (2013) are consistent with the idea that action and perceptual pathways are different (Goodale & Milner, 1991, 1992; Milner & Goodale, 2008), and therefore, may have differing visual field biases (Danckert & Goodale, 2003). Additional evidence also comes from Wilkinson, Haque, Or, Gottlieb, and Wilson (2016) who also find no difference in sensitivity to motion-defined RF patterns when presented in either the upper or lower visual field.
Although these patterns are defined by motion, the pattern of results for changes in frequency, radius, and cycles of modulation are highly similar to static RF patterns. This suggests a similarity in the processing of these two stimuli, which is supported by the results of Tanaka and Yotsumoto (2016) who found evidence that motion trajectories are being processed in the ventral visual stream. Thus the preference for lower visual field when grasping may not be the explanation for the results found by Schmidtmann et al. (2015) and it is clear that future research is required.

The results of the current study found evidence for the global processing within discrete RF patterns, but not across them, suggesting it reflects the processing of object contours, rather than the detection of replications of local features in an image. There was no evidence for any one of our eccentricity matched locations resulting in greater sensitivity to deformation in shape. Our results are consistent with previous models of global shape processing of RF patterns (Poirier & Wilson, 2006) and biological data suggesting coding for the location of curvature maxima and minima relative to an object’s centre (Pasupathy & Connor, 2002).

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Appendix A. Individual observer results for all conditions

Figure A1 shows the individual observer thresholds for all conditions. There is some variation within the data, but critically the pattern of results remains the same, with similar performance at locations A, B, and C and reduced performance across RF patterns.
Figure A1. Individual observer thresholds for location A (red), B (blue), C (green), and across (black). The same pattern of results is apparent across observers, with thresholds for across RF-patterns higher than within-RF patterns.
References


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Retinotopic to Shape Curvature Representations in Lateral Occipital Areas, LO-1 and LO-2. *Journal of Neuroscience, 36*(21), 5763-5774.


4.5. Link to Chapter 5

The purpose of Chapter 4 was to revisit the paradigm of Baldwin et al. (2016) using random phase RF patterns to investigate the integration of orientation information placed on a single contour or distributed across separate contours. Consistent with Chapters 2 and 3, we found evidence for integration of information within RF patterns, but not across them. This supports the findings of Chapter 3 which suggest the use of fixed phase presentation by Baldwin et al. (2016), created a salient local cue which was used preferentially by the visual system, obscuring the global integration they were attempting to measure. Following this result, we further hypothesised that a salient local cue would also explain differences between work from our lab and the results of Or, Thabet, Wilkinson, and Wilson (2011). My honours thesis in 2012 found no evidence for a change in integration of information around the contour of an RF3 viewed by a moving slit (for the presentation times tested; up to 4000 ms). Or et al. (2011) used a difference of Gaussian luminance-defined dot to trace out the path of an RF3 and found an integration slope which was significantly shallower than we have found in Chapters 2, 3, and 4 for RF3 patterns. Therefore, in Chapter 5 we investigated whether the removal of a potential local (change in speed) cue created by the dot’s motion at points of deformation could restore the measured strength of integration to the levels found in previous Chapters and during my honours project.
Chapter 5:
The effect of temporal displacement on the integration of shape information

Robert J. Green, J. Edwin Dickinson, & David R. Badcock


NOTE: Experiments 1 and 2 were presented as part of my Honours thesis. Experiment 3 was conducted as original work for my PhD thesis and follows on from my Honours research. It was necessary to include Experiments 1 and 2 for a coherent journal submission.

Keywords: Shape perception; global processing; signal detection theory; RF patterns; probability summation; slit viewing; temporal displacement
Abstract

Within a natural scene it is not uncommon for an object’s shape to be revealed over time. We investigated whether the same integration of shape information which happens around a fully visible contour, also happens when that information is distributed over time. In a two-interval forced-choice task observers discriminated between: a radial frequency (RF) pattern and a circle which were revealed either using an implicit slit or traced out by a dot’s motion; and a line and a modulated line which were either contour-defined or motion-defined.

Firstly, with presentation times of approximately 1 second, we found no difference in the strength of integration when comparing a freely visible contour to one which: moved behind a slit; was revealed by a moving slit; or revealed piecemeal by a slit appearing at random locations (Experiment 1). Changing the duration of presentation (250 – 4000 ms) had no effect on strength of integration or threshold for detection within the moving slit condition (Experiment 2). Considering these results, Experiment 3 revisited integration for a dot tracing out an RF path (Or, Thabet, Wilkinson, & Wilson, 2011) and found removal of a change in speed cue increased the strength of integration to that found in Experiments 1 and 2 of the current study. The pattern of results for modulated lines was different to RF patterns, however, within these conditions there was no difference in strength of integration between contour-defined and motion-defined stimuli. Our results suggest motion-defined patterns are processed as form from motion.

Keywords: Shape perception; global processing; signal detection theory; RF patterns; motion RF patterns; modulated lines; probability summation; slit viewing; temporal displacement.
5.1. Experiment 1 – Introduction

Detection and discrimination of objects are important functions of the visual system, but not all objects within a scene are freely visible. Previous research has suggested that spatial disruption of contour information of a simple shape increases that shape’s thresholds for detection (Hess, Wang, & Dakin, 1999; Loffler, Wilson, & Wilkinson, 2003) and that information cannot be integrated across discrete shapes (Baldwin, Schmidtmann, Kingdom, & Hess, 2016). It has been suggested that spatiotemporally tuned cells enable us to combine form information when an object moves behind a stationary slit (Burr & Ross, 2004) and indeed object recognition is easy under these circumstances (Yin, Shimojo, Moore, & Engel, 2002). However, there has not been much research on the effect of these viewing conditions on the integration of local orientation information around the contour of a simple shape.

The radial frequency (RF) pattern is a pattern which has frequently been used to assess integration of information around a simple contour. These patterns are derived from circles which have their radius sinusoidally modulated as a function of their polar angle. Their RF number is related to their wavelength, but usually defined by the number of cycles able to fill 2π radians. This is distinguished from the number of cycles (or lobes) present on the path, which is the number of complete sine waves within the pattern (see Figure 5.1 below). Increasing the amplitude of the sine wave increases the deformation and in turn, the probability of detection of the modulation.

Figure 5.1. An RF3 with one, two and three cycles of modulation (left to right). Amplitude (A = 0.1) of the patterns is well above threshold, but shown for illustrative purposes.
There have been a variety of studies examining a number of different constraints on abilities to perceive and code shape information using RF patterns: global integration (Bell & Badcock, 2008; Dickinson, Han, Bell, & Badcock, 2010; Dickinson, McGinty, Webster, & Badcock, 2012; Hess et al., 1999; Loffler et al., 2003; Schmidtmann, Kennedy, Orbach, & Loffler, 2012; Tan, Bowden, Dickinson, & Badcock, 2015; Tan, Dickinson, & Badcock, 2013), curvature (Dickinson, Cribb, Riddell, & Badcock, 2015), shape adaptation (Bell, Dickinson, & Badcock, 2008), polar angle between adjacent features (Dickinson, Bell, & Badcock, 2013), and size (Habak, Wilkinson, Zakher, & Wilson, 2004). In addition to these Or, Thabet, Wilkinson, and Wilson (2011) used a dot with a difference of Gaussians (DOG) luminance profile to trace out the path of a RF pattern over a period of 1 and 2 seconds. They concluded there was evidence for global integration of this motion RF pattern for both stimulus durations.

Evidence for global integration is determined by comparing the decrease in observer thresholds with increasing number of cycles of modulation to that predicted by probability summation (the increased likelihood of local feature detection due to the increase in number of local elements). The results of Or et al. (2011) suggest that global integration of shape information can occur over relatively long temporal periods, but it is unclear as to whether this is only possible for motion trajectories of stimuli or if it can also occur for a contour-defined shape presented over time. There is evidence from Schmidtmann et al. (2012) which may indicate simultaneous presentation of information is required, as they suggested that all cycles of modulation needed to be present to produce the reduction in deformation thresholds required for an RF pattern to demonstrate global processing. Their results, however, were not typical of previous research which finds a smooth decrease in observer thresholds with increasing cycles of modulation (Bell & Badcock, 2008; Dickinson et al., 2010; Dickinson et al., 2012; Loffler et al., 2003; Tan et al., 2013), not a “dog leg” as found by Schmidtmann et al. (2012).
Given that it is not uncommon for the natural scene to create a slit (an ajar door, two trees close together, long grass etc.) through which we view a distal object, we will initially employ the use of a single slit to create temporal displacement of our contour-defined RF patterns and investigate the effect of presenting form information over time on global integration for spatially, temporally, and spatiotemporally distributed information.

5.2. Experiment 1 – Methods

5.2.1. Observers

Five experienced psychophysical observers participated in the current experiment, three of whom were naïve to the experimental aims. All observers had normal, or corrected-to-normal visual acuity, which was assessed using a LogMAR chart. Observers viewed stimuli binocularly, except for ED who has a divergent squint and completed the experiments under monocular viewing conditions using an opaque occluder (black eye patch).

5.2.2. Stimuli

The stimuli used were RF patterns as defined by Wilkinson, Wilson, and Habak (1998):

\[ R(\theta) = R_0 \times (1 + A\sin(\omega\theta + \varphi)) \] (1)

where \( \theta \) is the angle created with the x axis, \( R_0 \) is the mean radius (30° of visual angle in all conditions), \( A \) is the amplitude of modulation (proportion of mean radius), \( \omega \) is the frequency of modulation (number of cycles per 2π radians) and \( \varphi \) is the phase of the sinusoidal modulation. Patterns containing less than the full 3 cycles of modulation used a D1 (first derivative of a Gaussian) function to replace the first half and last half cycle so they smoothly returned the contour to a circle (following Loffler et al., 2003). At 1 cycle of modulation, therefore, the modulated path conforms solely to a D1. The cross section of the
luminance profile conformed to a Gaussian with a sigma (σ) of 2′ of visual angle. Pilot testing found, after a number of trials, that observers had trouble maintaining the percept of an object in motion and, rather, perceived the stimulus as two points of light diverging and converging, a version of the aperture effect. To aid in their perception, a static textured pattern was applied to the stimulus by randomly choosing half the pixels every interval to be the same as the background luminance rather than that defined by the Gaussian luminance profile (see Figure 5.2). These pixels remained at the same spatial location on the contour during its presentation and gave the observer local cues which helped indicate the position of the contour over time and worked against the percept of smooth vertical motion of two dots.

5.2.3. Apparatus

Custom software in Matlab 5.3 (Mathworks, 1999) was used to create the stimuli which were drawn to the screen of a Sony Trinitron Multiscan G420 monitor, with a frame rate of 100 Hz, from the frame buffer of a Cambridge Research Systems VSG 2/3 graphics card, housed in a PC with a 400 MHZ Pentium II processor. A Cambridge Research Systems OPTICAL OP 200-E photometer (Head model number 265) performed the luminance calibration of the display. Background luminance was 45cd/m². The RF patterns had a maximum Weber contrast ([L_{max}-L_{background}]/L_{background}) of 1. Observer responses were made on a Cambridge Research Systems CB3 button box and a chin rest was used to set the viewing distance at 117.5cm from the monitor, such that each screen pixel subtended 1′. The observer was instructed to fixate on a square static fixation point, with 4′ side length, which remained in the centre of the screen during presentation of both intervals. The centre of each pattern was able to vary ±6′ of visual angle in the horizontal and vertical directions.
5.2.4. Procedure

A two-interval forced choice (2IFC) procedure was used, consisting of a test stimulus (RF pattern) in one interval and a reference stimulus (circle; i.e. \( A = 0 \) in equation 1) in the other. The order of presentation was randomised between trials and the observer chose which pattern appeared the most deformed from circular. Each interval consisted of 34 frames, with a frame duration of 40ms and an inter-stimulus interval of 500 ms.

There were 4 conditions in Experiment 1: conventional presentation – the entire stimulus was visible to the observer; moving slit presentation – a slit moved over the stimulus progressively revealing it; moving pattern presentation – the pattern moved behind a stationary slit; and random slit presentation – a slit appeared at random locations revealing the stimulus in a piecemeal fashion. The slit used in all of the slit conditions was 10’ wide and extended above and below the stimulus boundary. In the moving slit and moving pattern conditions, the slit and the pattern (respectively) advanced in 3’ steps on each frame. The slit itself was implicit, with the slit boundary producing an illusory contour (see Figure 5.2), which observers reported appeared to extend above and below the upper and lower extent of the stimulus.
Figure 5.2. Example of moving pattern presentation, the stimulus is progressively revealed as it moves behind the slit, lower contrast sections were invisible but are shown for clarity (left). The stimulus as it appears to the observer (right). Note, the stimulus does not take up all of the stimulus window generated, therefore, when the slit is within the outer black brackets, only the fixation point is visible.

The stimulus window was larger than the absolute size of the stimulus, allowing the stimulus centre to jitter randomly within a 6′ radius of the fixation point between trials and also to enable RF patterns of varying amplitudes. This extra space in the window (see black brackets in Figure 5.2) resulted in areas of the window which were purely background luminance (in other words, empty). This means that during the moving slit and moving pattern presentations, frames before and after the stimulus did not contain any contour information and thus the stimulus did not occupy the full 34 frames in each trial. As the stimulus was 60′ in diameter and the slit 10′ wide (advancing in 3′ intervals), a stimulus with an infinitely small edge would occupy 24 frames in each interval, however, due to the Gaussian luminance profile the stimulus occupied 25 frames. This resulted in 1000ms presentation times for the moving slit, and moving pattern conditions and 1360ms presentation times for the conventional and random slit conditions. We do not believe this difference in presentation times between the conditions had an effect on the results as changing the stimulus presentation time did not have any effect on thresholds or integration strength (see Experiment 2).
Observer psychometric functions were sampled using the method of constant stimuli (MOCS), using 9 amplitudes per block, 3 blocks per cycle of modulation, and 3 cycles of modulation per condition. Results were fitted using a Quick function:

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

(2)

where \( p \) is the probability of correct response, \( A \) is the amplitude of modulation as a proportion of the radius on an unmodulated circle, \( \alpha \) is the threshold at the 75% correct response level and \( \beta \) controls the slope of the psychometric function. Thresholds were plotted against number of cycles and compared to probability summation predictions.

Previous studies have used high threshold theory (HTT) to provide an estimate of probability summation, however, evidence from Baldwin et al. (2016) has suggested this is an inappropriate method for RF patterns. We have included it here to provide a comparison with previous works. Probability summation predictions under HTT were estimated by \( 1/\bar{\beta} \), where \( \bar{\beta} \) is the average of the slopes of the psychometric functions for all cycles of the RF pattern.

As an alternative to HTT, signal detection theory (SDT) has been used in recent publications to generate probability summation estimates. This was done by estimating d prime (\( d' \)) using:

\[ d' = (g A)^\tau \]  

(3)

where \( d' \) is internal strength of a signal, \( g \) is a scaling factor incorporating the reciprocal of the internal noise standard deviation, \( A \) is the stimulus intensity, and \( \tau \) is the exponent of the internal transducer (rate at which observer is converting increased stimulus intensity to increased perception). Under SDT the estimated percentage correct for probability summation was given by (Kingdom, Baldwin, & Schmidtmann, 2015):
\[
P_c = n \int_{-\infty}^{\infty} \phi(t - d') \Phi(t) Q^{M-n} \Phi(t - d')^{n-1} dt ... \\
+(Q - n) \int_{-\infty}^{\infty} \phi(t) \Phi(t) Q^{M-n-1} \Phi(t - d')^n dt \tag{4}
\]

where \(P_c\) is the percentage correct and set at 75%, \(t\) is sample stimulus strength, the heights of the noise and signal distributions at \(t\) are given by \(\phi(t)\) and \(\phi(t - d')\) respectively, \(\Phi(t)\) and \(\Phi(t - d')\) are the areas under the noise and signal distributions below stimulus strength \(t\), \(Q\) is the number of monitored channels, \(M\) is the number of alternatives in the forced choice task, and \(n\) is the number of stimulus components. This equation is implemented in the Palamedes toolbox (Prins & Kingdom, 2009, available at http://www.palamedes.toolbox.org).

The number of channels included \((Q)\) in estimates of probability summation under SDT have a large effect on the resulting predicted strength of integration. Previous research by Cribb, Badcock, Maybery, and Badcock (2016) has used both a “low” and “high” number of channels to provide an ultra-conservative estimate (low number of channels; \(Q = 3\); and consistent with Baldwin et al., 2016) and a more theoretically appropriate estimate (high number of channels; \(Q = 120\)). The same method will be employed by the current study.

\[5.3. \text{Experiment 1 – Results}\]

Figure 5.3 displays the thresholds for all 5 observers along with the averaged thresholds across the 5 observers for each condition. A repeated measures 4 (conventional, moving pattern, moving slit, random) x 3 (1 cycle, 2 cycles, 3 cycles) factorial analysis of variance (ANOVA) was used to examine the effect of condition and the number of cycles of modulation on observer thresholds. There was a significant main effect of cycles of modulation, \(F(2,8) = 43.72, p < .001, \eta^2_p = .92\) and there was also a significant interaction effect, \(F(6,24) = 15.65, p < .001, \eta^2_p = .80\). Mauchly’s test of sphericity was violated for
Condition, so Greenhouse-Geisser correction was applied, $F(1.24, 4.95) = 88.61, p < .001, \eta^2_p = .96$. Bonferroni adjusted pairwise comparisons revealed a significant difference between all cycles of modulation (all $p$’s < .05), with thresholds for 1 cycle larger than both 2, and 3 cycles and 2 cycle thresholds larger than 3 cycles. Bonferroni adjusted pairwise comparisons also revealed there was no significant difference between the moving pattern and moving slit conditions ($p > .05$), however, there was a significant difference between all other pairwise comparisons between the conditions ($p$’s < .05). As can be seen in the caption of Figure 5.3, the slope of the conventional condition (black dots with black line) is steeper than the other 3 conditions, driving the significant interaction effect.

![Figure 5.3](image)

*Figure 5.3*. Thresholds with 95% confidence intervals for each observer, along with the geometric mean for all observers (group) for: conventional condition (black circle; -0.92); moving pattern (blue open circle; -0.78); moving slit (red circle; -0.75); and random (green open circle; -0.76).

A repeated measures 4 (observed, HTT PS, SDT 3 channels PS, SDT 120 channels PS) x 4 (conventional, moving pattern, moving slit, random) factorial ANOVA was used to
examine the effects of the different slope estimates and condition on the strength of integration. There was no significant main effect of condition, $F(3,12) = 1.77, p = .20, \eta^2_p = .31$, and there was no significant interaction effect, $F(9,36) = 0.37, p = .94, \eta^2_p = .09$. There was a significant main effect of type of slope, $F(3,12) = 64.48, p < .001, \eta^2_p = .94$. Planned comparisons found observer slopes were significantly steeper than probability summation slope estimates by HTT and SDT, for both low and high number of channels (all $p$’s < .01). Figure 5.4 displays the mean observer slopes, and the mean probability summation slopes under HTT and SDT.

![Figure 5.4](image_url)

*Figure 5.4*. Results averaged across 5 observers with 95% confidence intervals. Observer slopes (blue) and probability summation slope estimates under HTT (red), SDT using a low number of channels (green), and SDT using a high number of channels (purple).

SDT predicts that stimuli for which thresholds are determined by probability summation will exhibit a decrease in psychometric slope with increasing number of local elements (Kingdom et al., 2015; Pelli, 1985). Figure 5.5 displays the mean psychometric slopes for all 4 conditions. There appears to be no decrease in psychometric slopes with increasing numbers of cycles of modulation for any of the conditions. No significant linear trends were found for any of the conditions: conventional, $F(1,4) = 0.03, p = .87, \eta^2_p = .01$; moving pattern, $F(1,4) = 0.08, p = .79, \eta^2_p = .02$; moving slit, $F(1,4) = 3.18, p = .15, \eta^2_p = .44$;
and random slit, $F(1,4) = 2.70, p = .18, \eta_p^2 = .40$. Although there is variation in the data, our results are consistent with Baldwin et al. (2016) and with other work from our lab which suggests no change in psychometric slopes with an increase in the number of cycles of modulation.

**Figure 5.5.** Psychometric slopes for all conditions with 95% confidence intervals: conventional (black circle); moving pattern (blue open circle); moving slit (red circle); and random slit (green open circle).

5.3.1. Summary

There was no difference between the thresholds of the moving pattern condition and the moving slit condition. Viewing an RF pattern under either of these conditions resulted in thresholds approximately 4 times greater than under conventional viewing conditions (i.e. a static, freely visible, contour-defined pattern). The random condition had thresholds slightly lower than the moving slit/moving pattern conditions, but were still approximately 3 times greater than under conventional viewing conditions.

Despite the difference in thresholds, there was no difference in the strength of integration between any of the conditions. In other words although there was a difference in
the observers’ sensitivities to contour information for some of the conditions, it did not affect their ability to combine that information around the contour. There was also evidence of global processing for all conditions under both HTT and SDT (for a high and low number of channels) and there was no evidence for a decrease in psychometric slope with increasing numbers of cycles of modulation.

5.4. Experiment 2 – Introduction

The visual system combines information over time to enhance sensitivity. Legge (1978) showed that contrast sensitivity measured using both “low” spatial frequency (< 1.5 cpd) and “high” spatial frequency (> 1.5 cpd) targets increased until the presentation time reached either 100 ms for low or 1000 ms for high spatial frequency, after which it asymptotes. Evidence for integration windows has also been shown for visual acuity using Landolt rings up to 400 ms (Baron & Westheimer, 1973) and global motion using dynamic Glass patterns up to 3000 ms (Burr & Santoro, 2001; Ross, Badcock, & Hayes, 2000).

Given the visual system is thought to be a hierarchy of visual processing stages, pooling information from lower levels of the visual pathway (Felleman & Van Essen, 1991; Van Essen, Anderson, & Felleman, 1992), we may expect that global integration of contour information also has a temporal limit, with all of the shape information needing to be presented within a specific time frame. Research presented by Bell, Sacks, and Burr (2015) suggested that there was no effect of presentation time (measured from 10-320 ms) on integration, but they did find that sensitivity improved with increased presentation time. Our results from Experiment 1 demonstrate strong evidence for global processing for presentation times up to 1360 ms. Therefore, for Experiment 2, we wanted to determine if, similar to Bell et al. (2015), changes in presentation time would result in changes in observer thresholds (sensitivity) and if our comparatively longer presentation times (4000 ms
compared to the 320 ms in Bell et al., 2015) were able to effect the integration of information around the contour.

5.5. Experiment 2 – Methods

The same observers, apparatus, stimuli and procedure from Experiment 1 were used in Experiment 2, however, only the moving slit condition (stationary RF pattern of random phase, progressively revealed by a moving implicit slit) was tested with 5 different presentation times. As outlined above there were 34 frames presented, however, only 25 contained stimulus information. For Experiment 2 the duration of each frame for the respective conditions were: 10ms; 20ms; 40ms; 80ms; and 160ms. This resulted in presentation times of 250, 500, 1000, 2000, and 4000ms per interval.

5.6. Experiment 2 – Results

Figure 5.6 shows the mean thresholds (5 observers) for each of the 5 conditions and all 5 conditions together. A repeated measures 5 (250, 500, 1000, 2000, 4000) x 3 (1 cycle, 2 cycles, 3 cycles) factorial ANOVA was used to examine the effect of presentation time and number of cycles on observer thresholds. There was a significant main effect of number of cycles, $F(2,8) = 57.70, p < .001, \eta^2_p = .94$, but there was no significant effect of presentation time, $F(4,16) = 1.44, p = .27, \eta^2_p = .27$, and there was no interaction effect, $F(8,32) = 0.72, p = .67, \eta^2_p = .15$. Pairwise comparisons revealed that thresholds for 1 cycle was significantly greater than 2, and 3 cycles and thresholds for 2 cycles was significantly greater than 3 cycles.
Figure 5.6. Results for moving slit condition with increasing presentation durations and individual data. Thresholds are the geometric means for 5 observers with 95% confidence intervals, observer slopes (solid black line), and probability summation estimates: HTT (red dashed); SDT 3 channels (black dashed); and SDT 120 channels (grey dashed). Lines of best fit for all slopes were $R^2 > .99$, with values of: -0.75 (250 ms); -0.86 (500 ms); -0.99 (1000 ms); -0.88 (2000 ms); and -0.95 (4000 ms). The grouped graph displays all 5 conditions: 250 ms (black); 500 ms (blue); 1000 ms (red); 2000 ms (green); and 4000 ms (purple).

A repeated measures one-way ANOVA was used to compare observer slopes with the slopes from the 3 probability summation estimates. There was a significant main effect for all conditions: 250, $F(3,12) = 15.00$, $p < .001$, $\eta^2_P = .79$; 500, $F(3,12) = 17.38$, $p < .001$, $\eta^2_P = .81$; 1000, $F(3,12) = 19.87$, $p < .001$, $\eta^2_P = .83$; 2000, $F(3,12) = 37.71$, $p < .001$, $\eta^2_P = .90$; and 4000, $F(3,12) = 37.62$, $p < .001$, $\eta^2_P = .90$. Planned comparisons revealed no significant difference between observer slopes and SDT 3-channels probability summation estimates for the 250 ms and 500 ms presentation times ($p’$s > .05). All other comparisons showed a significant difference between observer slopes and their respective probability summation estimates ($p’$s < .05).

Figure 5.7 displays the mean sensitivity (at 1 cycle of modulation) and integration slopes for the 5 observers. A repeated measures one-way ANOVA was used to examine the effect of presentation time on sensitivity. There was no significant main effect of
presentation time, $F(4,16) = 0.81, p = .54, \eta^2_p = .17$ and there was no significant linear trend, $F(1,4) = 0.03, p = .88, \eta^2_p = .01$. Another repeated measures one-way ANOVA was used to examine the effect of presentation time on observer slopes and indicated no significant main effect of presentation time, $F(4,16) = 1.02, p = .43, \eta^2_p = .20$ and there was also no significant linear trend, $F(1,4) = 1.97, p = .23, \eta^2_p = .33$.

![Graph 1](image1.png)  
![Graph 2](image2.png)

**Figure 5.7.** Geometric mean with 95% confidence intervals of the threshold at 1 cycle of modulation (left) and mean integration slopes with 95% confidence intervals (right) for 5 observers. There appears to be no effect of presentation time (duration) on strength of integration or sensitivity.

### 5.6.1. Summary

There was no effect of presentation time on observer thresholds nor strength of integration. There was strong evidence of global processing for the 1000, 2000, and 4000 ms conditions, with observer slopes significantly steeper than all probability summation estimates. For the 250 and 500 ms conditions observer slopes were steeper than both HTT and SDT for an appropriate number of channels (120 channels), but not significantly steeper than the extremely conservative SDT probability summation slope (3 channels) in which observers would be required to know where the deformation would occur (fixed phase). Therefore, we also interpret the data for the 250 and 500 ms conditions as evidence of global processing. Similar to Bell et al. (2015), we found no effect of presentation time on
integration slopes, however, we found no changes in sensitivity (see below for further discussion). Logically there must be a limit to which the visual system can integrate information around a shape’s contour, however, we have no indication from our data what that limit might be as there appeared to be no trend apparent and further investigation is required.

5.7. Experiment 3 – Introduction

As mentioned above, Or et al. (2011) used a difference of Gaussian (DOG) dot to trace out the path of an RF pattern over a period of 1 and 2 seconds (Figure 5.8). They found evidence for global integration of this motion RF pattern, with improvement in detection of trajectory modulation approximating a power function with a slope of -0.64. This result is not typical of static RF3 patterns, however, where slopes are generally steeper: -0.86 (Loffler et al., 2003); -0.75 (Almeida, Dickinson, Maybery, Badcock, & Badcock, 2010); and -0.92 (Tan et al., 2013).

Or et al. (2011) suggested the relatively shallow (for an RF3) integration slope was a result of the difficulty of the task, with presentation times of 1 and 2 seconds requiring the use of memory which in turn results in extra processing and, therefore, poorer integration. However, given our results in Experiment 2 demonstrated quite steep integration slopes at comparable durations (-0.99 for 1000 ms; -0.88 for 2000 ms; and -0.95 for 4000 ms) and had probability summation estimates under both HTT and SDT (3 channels) which were around -0.60, we decided to re-examine the results of Or et al. (2011) to determine if global processing was occurring for these patterns, why the integration around these patterns is comparatively poor, and whether there is any evidence for form processing of these stimuli.
One explanation for the decreased strength of integration is possibly the use of constant angular speed by Or et al. (2011). A dot tracing an RF pattern with constant angular velocity will have changes in retinal speed to allow for variations in the radius. This change in retinal speed could result in a local cue which is preferentially used at low numbers of cycles where the global signal is relatively weak. As each cycle is added to the pattern the global shape signal increases and can eventually become more salient than the local cue (see experiment 3 in Dickinson et al., 2012). This interaction between local and global signal would reduce thresholds for lower numbers of cycles selectively and thus give the result of a relatively shallow integration slope and potentially describe the results obtained by Or et al. (2011).

Or et al. (2011) did anticipate the possibility of this speed cue and examined observer thresholds as a function of radial frequency for patterns with constant angular velocity and constant retinal speed. They concluded there was no effect of the constant angular velocity, as there was no significant difference between the slopes nor y-intercepts of the fitted functions relating radial frequency to threshold for detection. However, this was done with complete RF patterns (i.e. RF patterns with all cycles of modulation present) and would likely have a strong global signal from the pattern. Therefore, they were likely correct in their conclusion that angular velocity does not have an effect on complete RF patterns, but they did not test the effect of angular velocity on incomplete patterns.
One of the main reasons for creating this motion RF stimulus was to analyse periodic motion with a view to assessing its contribution to the perception of biological motion (Or et al., 2011). Thus, Or et al. (2011) suggested these stimuli were processed in motion regions of the brain. Gorbet, Wilkinson, and Wilson (2012) and Gorbet, Wilkinson, and Wilson (2014), using fMRI, suggested their data supported the view that these patterns are processed in motion regions of the brain, however, they were unable to rule out the possibility that motion RFs were actually being processed as form information due to temporal integration of motion streaks.

The temporal integration of single neurons in V1 can result in object motion producing visual streaks of oriented information and this has been shown to aid the visual system in determining motion direction (Badcock & Dickinson, 2009; Geisler, 1999; Ross et al., 2000; Tang, Dickinson, Visser, & Badcock, 2015). Research has suggested this information is not only coded in V1 (Apthorp et al., 2013), but at multiple levels up to STS (Mather, Pavan, Bellacosa Marotti, Campana, & Casco, 2013) and that a considerable number of connections occur between the dorsal and ventral streams of the visual system (Takemura et al., 2016). Therefore, it is possible that these motion RF patterns are being processed within the ventral visual stream similar to static, contour-defined RF patterns, although there is reduction in sensitivity for the motion RF patterns due to the information being held in memory.

Previous behavioural studies support this hypothesis as the processing of motion RF patterns (Daar, Or, & Wilson, 2012; Or et al., 2011; Wilkinson, Haque, Or, Gottlieb, & Wilson, 2016; Wilson & Fung, 2016) show a similar pattern of results compared to static RF patterns when changing parameters such as radius, frequency, and cycles of modulation (Bell, Wilkinson, Wilson, Loffler, & Badcock, 2009; Loffler et al., 2003; Wilkinson et al., 1998). Furthermore, Gorbet et al. (2012) compared the results of motion RF patterns with those
obtained with open motion patterns (a sinusoidally modulated line pattern revealed by a dot with a DOG profile, tracing either two or three cycles). They found there was no difference in the activation of areas MT and STS when comparing motion RF patterns to these motion-defined modulated lines. We believe this lack of increased activation in motion areas during the motion RF condition is evidence that motion information is not being integrated within this region, but is instead being combined in the form regions.

Therefore, Experiment 3 will replicate the Experiment of Or et al. (2011) using constant angular velocity and also test the effect of constant retinal speed on observer thresholds but with a set of patterns that will allow the measurement of the complete integration function. We predict that fixed angular velocity will produce reduced observer thresholds for incomplete patterns, but not complete patterns because of the salient local cue provided by the retinal speed changes, reducing observer thresholds for these incomplete patterns. Following on from the open motion patterns (sinusoidally modulated lines traced out by a DOG dot) created by Gorbet et al. (2012) we will also compare observer thresholds of contour-defined modulated lines (sinusoidally modulated lines analogous to an uncoiled RF pattern; see Figure 5.9) with motion-defined modulated lines and predict that, similar to the results of the motion-defined and contour-defined RF patterns, these stimuli will also demonstrate the same pattern of results.

5.8. Experiment 3 – Methods

5.8.1. Observers

The two authors who participated in Experiments 1 and 2 and two naïve observers participated in the current experiment, all with normal or corrected-to-normal visual acuity which was assessed using a LogMAR chart. Informed written consent was given and conformed to both University of Western Australia ethics and the declaration of Helsinki.
In this Experiment a dot traced out an RF pattern over time \((t)\), at angular speed \((v)\), as defined by Or et al. (2011):

\[
r(vt) = r_0 \times \left(1 + A \sin(\omega vt + \varphi)\right)
\]  

where \(r\) is the dot’s polar location, \(r_0\) is the mean radius \((1^\circ\text{ of visual angle in all conditions to maintain consistency with Or et al., 2011})\), \(A\) is the amplitude of modulation \((\text{proportion of mean radius})\), \(\omega\) is the frequency of modulation \((\text{number of cycles per } 2\pi \text{ radians})\) and \(\varphi\) is the phase of the sinusoidal modulation. Another way to define this equation, so as to include polar angle into the function would be:

\[
r(\theta(t)) = r_0 \times \left(1 + A \sin(\omega \theta(t) + \varphi)\right)
\]

where the parameters are the same as for equation 5 and \(\theta(t) = 2\pi t / (F_r(F_n - 1))\), with \(F_r\) being the frame duration in ms, \(F_n\) is the total number of frames to display, and \(t\) is time in ms. The dot used was a difference of Gaussians (DOG), again identical to that used by Or et al. (2011):

\[
\text{DOG}(R) = 1.8 \exp(-R^2 / \sigma^2) - 0.8 \exp(-R^2 / (1.5\sigma)^2)
\]

where \(R\) is the radius of the DOG and \(\sigma\) was set to 7.1′ of visual angle. As in Or et al. (2011), the pattern is spread over several pixels with varying intensity allowing sub-pixel precision in the dot’s spatial position.

where \(R\) is the radius of the DOG and \(\sigma\) was set to 7.1′ of visual angle. As in Or et al. (2011), the pattern is spread over several pixels with varying intensity allowing sub-pixel precision in the dot’s spatial position.
In addition to the motion RF stimuli, line stimuli were also employed to see if the closed contour was critical to the outcome. The length of the modulated sector for all line stimuli was 6.28° of visual angle (the equivalent length of an uncoiled RF pattern with a 1° radius), with an additional 2.09° of visual angle (the equivalent length of 1 cycle of modulation) in which the modulated sector could begin (i.e. the starting location of the modulation varied randomly between trials), and another 1° of visual angle at the top and bottom of the lines to avoid positional cues between the line ends and the start of modulation (see Figure 5.9).

There were 3 line conditions: motion line; motion line fixation; and contour line. The purpose of the motion line conditions is to determine if, similar to the contour-defined results found by Green, et al. (2017), open motion patterns are processed in a different way to the closed contour motion RF patterns. The motion line and motion line fixation conditions consist of a DOG dot (as defined in equation 7) tracing out the path of a modulated line which was either by itself (motion line) or 1° of visual angle to the side of a solid black line (motion line fixation; the same distance as between the fixation point and the dot used for the motion RF patterns). The motion line fixation condition was created to enable the observer to use the fixation to aid in their judgement of the dot’s horizontal motion. This was designed to be analogous to the observer tracking the dot with their eyes in the motion RF conditions and using the fixation square to judge its change in radius and so observers were instructed to follow the dot’s motion with their eyes.

For the contour line condition and similar to conventional RF patterns (Loffler et al., 2003) and previous contour-defined modulated lines (Green et al., 2017), the cross section of the luminance profile of the path conformed to a fourth derivative of a Gaussian (D4) with a frequency spectrum peaking at 8 c/deg where $f_{\text{peak}} = \sqrt{2}/\pi \sigma$ (Loffler et al., 2003; Wilkinson et al., 1998) and obtained using a $\sigma$ of 3.376’ of visual angle.
Figure 5.9. Dimensions of the line stimuli used: (A) contour line; (B) motion line; (C) motion line fixation.

5.8.3. Apparatus

Stimuli were generated using a PC (Pentium 4, 2.4GHz) and custom software written in MatLab 7.2.0 (Mathworks, Nantucket, 2002). The observers viewed a CRT Sony Trinitron CPD-G420 monitor (100Hz refresh rate) which presented the stimuli from the frame buffer of a Cambridge Research Systems (CRS) VSG2/5 visual stimulus generator. Screen resolution was 1024 x 768 pixels and viewing distance was stabilized at 58.75cm using a chinrest which resulted in each pixel subtending a visual angle of 2'. An Optical OP 200-E photometer (head model number 265) was used to linearise the luminance response and to calibrate background luminance to 45 cd/m² and maximum luminance to 90 cd/m², resulting in a Weber contrast of 1. Responses were signalled using the left and right buttons of a mouse. A square fixation point (6' side length) was used to indicate the centre of the screen where stimuli were presented.
5.8.4. Procedure

For the motion RF stimuli, a two-interval-forced-choice (2IFC) paradigm was used for both conditions, with observers reporting which interval contained a dot tracing out the pattern which was most deformed from a circular path. One interval contained the reference stimulus, which consisted of a dot tracing out a circle \( (A = 0 \text{ in Equation 1}) \). The other interval contained the test stimulus, with a dot tracing out a circle with 1, 2, or 3 cycles of RF3 modulation. Order of presentation was randomised between trials. Each stimulus was presented for 1000 ms, with a 500 ms inter-stimulus interval. There were 25, 40 ms frames, with the first and last frames identical to each other (resulting in the dot finishing at its starting location). Each condition was tested in 3 blocks, one for each cycle of modulation (i.e. 1, 2, and 3 cycles) and these were randomised for each participant. For the **angular velocity** condition, the dot traced out a random phase pattern with a constant angular velocity \( (6.28 \text{ deg/s}) \), meaning the dot appeared every \( \pi/12 \) radians, starting and finishing at the 3 o’clock position (see Figure 2). For the **retinal speed** condition, the total path length was calculated and the dot then moved one 24\(^{th}\) the distance of the path each frame (again the phase of the pattern was random). As can be seen in Figure 5.10, the two conditions produce almost identical differences in radii (peak and trough) and have the greatest difference in dot locations occurring around the zero crossing of the modulation function \((180^\circ \text{ in figure})\).
Figure 5.10. Polar location of dot for constant angular velocity (red) and constant retinal speed (black) with the same amplitude (approximately threshold level) for an RF3(1). Y-axis displays the radial location in minutes of visual angle in relation to an unmodulated pattern ($A = 0$ in equation 5).

Observers were instructed to follow the dot with their eyes for the motion line fixation condition, but for the contour line and motion line conditions there was no fixation point, so observers were able to freely view the stimulus. Again, a 2IFC paradigm was used for all conditions, with observers reporting which interval contained a modulated line (contour line condition) or a dot which has traced the path of a modulated line (motion line, and motion line fixation conditions). To reduce total number of trials and participant fatigue data was collected using the PSI method (Kontsevich & Tyler, 1999), implemented using the Palamedes toolbox (Prins & Kingdom, 2009, downloaded 2015 from http://www.palamedestoolbox.org), which optimised a Quick function (Quick, 1974; see equation 2). One hundred and fifty trials were performed for each cycle of modulation for each condition.
5.9. Experiment 3 – Results

To examine the effect of condition and number of cycles on observer thresholds for an RF3 a repeated measures 2 (retinal speed, angular velocity) x 3 (1 cycle, 2 cycles, 3 cycles) factorial analysis of variance (ANOVA) was used. There was a significant main effect of condition, $F(1,3) = 67.92, p = .004, \eta^2_p = .96$, and a significant main effect of number of cycles, $F(2,6) = 63.66, p = .004, \eta^2_p = .96$. The interaction violated the assumption of sphericity and there was no significant interaction effect after Greenhouse-Geisser adjustment was applied, $F(1,3) = 9.09, p = .06, \eta^2_p = .75$. Pairwise comparisons indicated a significant difference between all cycles of modulation (all $p$’s < .05), with 1 cycle of modulation having the highest threshold and 3 cycles having the lowest. Table 1 displays the descriptive statistics along with paired sample t-tests comparing each condition at each number of cycles of modulation. A paired samples t-test found retinal speed slopes ($M = .80, SD = .11$) were, on average, significantly steeper than angular velocity slopes ($M = .70, SD = .14$), $t(3) = 3.64, p = .04, d = 1.82$. Although there appears to be slightly more variation at 1 cycle of modulation compared to 2 and 3 cycles, repeating the ANOVA using log transformed data did not yield different results.

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<td>$M$</td>
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<tr>
<td>1 Cycle</td>
<td>0.121</td>
<td>0.026</td>
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<tr>
<td>2 Cycles</td>
<td>0.078</td>
<td>0.019</td>
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<tr>
<td>3 Cycles</td>
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*p < .05
Figure 5.11 displays the ratio of observer thresholds for the constant angular velocity and constant retinal speed conditions. A linear regression of the data ($R^2 = 0.94$; slope = 0.79, CI[0.65, 0.93]) is significantly shallower than a slope of 1, $F(1,10) = 11.77$, $p = .007$. This data clearly shows what is described in Table 1, observers at 1 cycle of modulation are comparatively poor (below the dashed line) at the retinal speed condition compared to the angular velocity condition. This difference is reduced at 2 cycles and is absent for 3 cycles of modulation.

Figure 5.11. Plot of the ratio of observer thresholds with each observer as a different shape and their respective 95% confidence intervals. Coloured data points correspond to: 1 cycle (blue); 2 cycles (green); and 3 cycles (red). Red solid line represents a linear regression of the ratios ($R^2 = 0.94$), while the black dashed line represents a line with the function $y = x$.

To examine global processing, a one-way repeated measures ANOVA was used to determine the difference between the measured slope and those predicted by probability summation under HTT and SDT. For the angular velocity, there was a significant main effect of slopes (angular velocity, HTT PS, SDT 3 channels PS, SDT 120 channels PS), $F(3,9) = 11.23$, $p = .002$, $\eta^2_p = .79$. Planned comparisons revealed no significant difference between the angular velocity slope and those predicted by probability summation for all models and number of channels (all $p$’s > .05). Pairwise comparisons revealed the significant difference was a result of the difference between the two SDT probability summation estimates ($p < .001$).
For retinal speed, there was a significant main effect of slopes (retinal speed, HTT PS, SDT 3 channels PS, SDT 120 channels PS), $F(3,9) = 12.22, p = .002, \eta^2_p = .80$. Planned comparisons revealed a significant difference between retinal speed slope and all of its probability summation estimates for all models and number of channels (all $p$’s < .05).

Figure 5.12 displays the results averaged across 4 observers for the contour-defined and motion-defined modulated lines. A repeated measures 3 (contour line, motion line, motion line fixation) x 3 (1 cycle, 2 cycles, 3 cycles) factorial ANOVA was used to investigate the effect of conditions and number of cycles on observer thresholds. There was a significant main effect of both condition, $F(2,6) = 10.87, p = .01, \eta^2_p = .78$, and number of cycles, $F(2,6) = 25.63, p = .001, \eta^2_p = .90$. There was no significant interaction effect, $F(4,12) = 1.89, p = .18, \eta^2_p = .39$. Bonferroni adjusted pairwise comparisons found no significant difference between any of the conditions ($p$’s > .05) and a significant difference between both 1 and 2 cycles and 1 and 3 cycles ($p$’s < .05), but no significant difference between 2 and 3 cycles of modulation ($p > .05$).

Figure 5.12. Geometric means of the four participants with 95% confidence intervals. The grey squares (top) show the motion line condition (-0.50), the red open circles (middle) show the motion line fixation condition (-0.57) and the black triangles (bottom) show the contour line condition (-0.77).
To compare observer slopes (strength of integration) and the slopes of probability summation estimates a 3 (contour line, motion line, motion line fixation) x 4 (observer slope, HTT PS, SDT 3 channels PS, SDT 120 channels PS) repeated measures ANOVA was performed. There was no significant main effect of condition, $F(2,6) = 1.51, p = .29, \eta^2_p = .34$, nor probability summation estimate, $F(3,9) = 3.42, p = .06, \eta^2_p = .53$. There was also no significant interaction effect, $F(6,18) = 1.09, p = .41, \eta^2_p = .27$.

Only two of the observers from Experiment 1 participated in Experiment 3, so to compare observer thresholds between the moving slit, moving pattern, and constant retinal speed conditions, a 3 (1 cycle, 2 cycles, 3 cycles; within groups) x 3 (moving slit, moving pattern, retinal speed; between groups) mixed design ANOVA was used. There was a significant within subjects effect of cycles of modulation, $F(2,22) = 116.32, p < .001, \eta^2_p = .91$, but no significant between subjects effect of condition, $F(2,11) = 0.25, p = .79, \eta^2_p = .04$. There was also no interaction effect, $F(4,22) = 0.55, p = .70, \eta^2_p = .09$. Pairwise comparisons indicated a significant difference between all cycles of modulation (all $p$'s < .001) with thresholds at 1 cycle of modulation the highest and 3 cycles of modulation the lowest.

5.9.1. Summary

The results show that the angular velocity stimulus had significantly lower detection thresholds than the retinal speed stimulus at both 1, and 2 cycles of modulation. There was no difference at 3 cycles of modulation. The retinal speed stimulus had a significantly steeper integration slope than the angular velocity stimulus and there was also evidence of global processing of the retinal speed stimulus, but no evidence of global processing for the angular velocity stimulus. These results are consistent with the interaction between a salient local cue and global signal.
For the line stimuli, there was a significant difference in thresholds but there was no difference in the pattern of results (integration) for any of the conditions. Thresholds decreased only when moving from 1 to 2 cycles of modulation, but not between 2 and 3 cycles of modulation. There was also no evidence of global processing in any of the three conditions. Both the pattern of results and the comparison to probability summation estimates suggest that motion RF patterns are processed differently to motion line patterns. These findings support that of Green et al. (2017), but are contrary to those of (Schmidtmann & Kingdom, 2017) and is discussed below.

There was no significant difference in the observer thresholds for the moving slit, moving pattern, and retinal speed conditions. This suggests that it does not matter whether the shape of an RF pattern is revealed by a dot tracing its path or a slit progressively revealing its contour, an RF pattern presented over time results in the same observer thresholds within the limits tested here.

5.10. General Discussion

The results of the current study have been quite surprising. It appears to indicate that although presenting an RF pattern over time (whether through a slit or traced by a dot) decreases observer sensitivity, it does not significantly affect the strength of integration of information around the contour. Changing the duration of presentation also appears to have no effect on an observer’s ability to combine this information together.

For Experiment 1 we examined the effect of slit presentation of an RF pattern. For the moving slit condition (where a slit progressively reveals a stationary RF pattern) it could be argued integration over a 1 second presentation time could still be accounted for by low level effects. Perhaps visual aftereffects made the information available for enough time after the slit had moved past to facilitate integration. This kind of argument, however, cannot account for the moving pattern condition (where an RF pattern moves behind a
stationary slit), as all of the information falls on the same spatial location. Both the moving pattern and moving slit conditions produced the same thresholds and are, therefore, likely to use the same method of processing. This result was replicated across all observers making it unlikely to be coincidental and if they were not using the same method of processing we would expect different thresholds as one is spread across space and the other is not. We are unsure of the method involved, but it does not rely on retinotopic mapping and must involve some sort of visual memory storage.

It is interesting that the random slit condition (where a slit randomly reveals an RF pattern in a piecemeal fashion) produced lower thresholds than the moving slit and moving pattern conditions. A potential explanation for this is that for each successive frame in the moving pattern or moving slit conditions the slit progresses 3′ of visual angle. This results in 3′ of “new information”, but 7′ of “old information”. For the random slit condition, however, each successive frame is unlikely to be a slit which is immediately next to the previous slit. This results in more “new information” and less “old information”, meaning there would be more information available to the visual system about the pattern per unit time. Without the data from Experiment 2 this would seem like a reasonable explanation, however, given those results it would seem unlikely. Experiment 2 showed that changing the presentation time of the moving slit condition had no effect on observer thresholds. This would indicate that changing the amount of information present per unit time (in the time range assessed) does not effect sensitivity and therefore, is evidence against this potential explanation for the increased sensitivity to the random slit condition, suggesting that low-level visual effects cannot account for our data.

Another potential explanation could be the “early” identification of the object centre. Models of RF coding (Poirier & Wilson, 2006) and physiological data (Pasupathy & Connor, 2001, 2002) suggest the centre of an object is highly important in shape perception. The random slit condition results in a presentation where the observer is likely to see
portions of the stimulus which have significant spatial separation in quick succession. This presentation would result in an early and potentially more accurate identification of the object’s centre, compared to the moving slit and moving pattern conditions. This would enable more accurate polar coding of orientation information and could result in greater sensitivity for the random slit condition.

The results of Experiment 2 were extremely surprising as we were expecting to encounter a temporal integration window within the presentation times tested. We measured presentation times starting at 250 ms and doubled the duration for each subsequent condition until we reached 4000 ms. We were expecting to see either a continuous systematic change or step change in either sensitivity or integration slope when we compared across conditions. However, it is clear from the data that the presentation times tested had no effect on performance. Logically there must be a limit to the duration over which an observer can integrate contour information, however, we were not able to find any indication of what that duration might be.

Our results are contrary to some of those presented by Bell and Corke (2014). In their second experiment they displayed each third of an RF3 (with either 1, 2, or 3 cycles of modulation) one at a time and found evidence for global integration when all three parts were presented within a 200 ms window, but not for longer durations. However, our results have suggested global processing can occur up to 4000 ms and potentially longer. Research by Wilson and Fung (2016) provides a potential explanation. They investigated the effect of discontinuities on motion RF perception. They found that presenting a pattern as discontinuous segments increased observer thresholds by a factor of 2. Perhaps the discontinuity present in the stimulus used by Bell and Corke (2014) resulted in the visual system being unable to group the discrete segments together, disrupting global processing for longer presentation times.
Experiment 3 replicated the findings of the second Experiment of Or et al. (2011) using a dot to trace out an RF pattern with a constant angular velocity. We found that by removing the speed cue created by this constant angular velocity integration slopes became steeper and analogous to those found in Experiments 1, and 2. In fact, there was no difference between the thresholds for the moving slit, moving pattern, and constant retinal speed conditions. The current authors believe this to be evidence that the Or et al. (2011) stimulus is being processed as form rather than motion (discussed below).

Or et al. (2011) did compare thresholds for a constant retinal speed and constant angular velocity presentation of their stimulus, however, they only examined these effects on complete motion RFs (i.e. patterns with all cycles of modulation present) and correctly concluded that there was no significant difference in thresholds for these patterns. Our investigation of these effects extended to incompletely modulated motion RF patterns and suggest a result similar to that of Green et al. (2017), an interaction between a salient local cue and the global cue of the pattern. The salient local cue is detected first when the global signal is low, but as more cycles of modulation are added, the global signal increases and detection becomes a result of this global cue.

Further research using these dot stimuli has been conducted using fMRI (Gorbet et al., 2012) to compare the areas of activation of these stimuli (motion RF patterns) with static RF patterns, and “open motion” patterns (analogous to our motion line stimulus). They found increased activation for the motion RF patterns in areas V1, V2, V3, V3A, MT, and STS when compared to static RF patterns and increased activation for the motion RF patterns in V1-V4 (but not MT or STS) when comparing to the open motion patterns. Gorbet et al. (2012, p. 11) also find the patterns of activity in areas V2, and V3 are predictive of the shape of the motion RF being viewed and note that these areas are involved in both shape and motion processing (Hegdé & Van Essen, 2000; Ito & Komatsu, 2004; Op de Beeck, Torfs, & Wagemans, 2008).
The similarity in performance for the motion RF, moving slit and moving pattern conditions, suggests a common mechanism involved in the processing of these stimuli. Therefore, we considered a possibility suggested by Gorbet et al. (2014), in which “motion streaks” (Geisler, 1999) produce form information which is combined using the same mechanisms as those that underpin processing of contour-defined patterns. However, Wilkinson et al. (2016) provide evidence against this explanation, as they found no effect on observer thresholds when they changed the duration of presentation (i.e. the average speed of motion) or contrast of the dot used for their motion RF stimulus, both of which were designed to change the length of motion streaks. Therefore, it is unclear how the information is being processed early in the visual stream, but our results do suggest that integration of this motion-defined information occurs in the same manner as for contour-defined information. Perhaps, as suggested by Wilkinson et al. (2016), the motion RFs are providing a signal to higher levels of the ventral visual stream resulting in the similarity of results found between contour-defined RF patterns and motion-defined RF patterns found in the current study and by Wilkinson et al. (2016).

Evidence for the processing of both motion and static RF patterns in higher levels of the ventral visual stream comes from fMRI studies using RF patterns. Rainville, Yourganov, and Wilson (2005) found BOLD responses in lateral-occipital complex (LOC) increased with increasing deviation from circular (i.e. amplitude) for static patterns and suggested this was an indication of the integration of shape information in this region. Furthermore, Gorbet et al. (2014) found significantly more activation in LOC for low frequency RF patterns (which demonstrate global integration) than for high frequency patterns (which demonstrate local processing). This result was found for both static and motion RF patterns, which they suggested indicates a common area of processing (Gorbet et al., 2014).

There are, however, some differences in the processing of static RF patterns and motion RF patterns. Behavioural results from Gorbet et al. (2014) found that observers were
unable to discriminate between high frequency motion RFs (RF9 and RF10), but were able to do so for the same frequency static patterns. Additionally, Wilson and Fung (2016) investigated the effect of discontinuities on motion RF patterns. They found a significant increase in observer thresholds when compared to standard motion RFs of the same frequency. They presented each cycle of modulation for an RF3 and RF4 discontinuously. For example, instead of presenting the first, second, and third cycle of an RF3 in order, such that it created an unbroken presentation, they “jumped” from the end of the first cycle to the start of the third and from the end of the third to the start of the second, breaking up the pattern into components. There were two discontinuous conditions where, after presenting a full cycle of modulation, the dot jumped at either the point of maximum concavity or maximum convexity. Wilson and Fung (2016) found the greatest increase in threshold for the maximum concavity condition. This would suggest that points of concavity are more important for motion RFs than points of convexity. This result is contrary to Loffler et al. (2003) who found the largest increase in threshold when occluding points of maximum convexity.

Notwithstanding these results, there is evidence for the processing and integration of motion trajectories within the ventral visual stream. Tanaka and Yotsumoto (2016) used fMRI to investigate the areas activated when presenting motion trajectories which produced the “wriggling motion trajectory illusion”. Multiple dots with different straight line trajectories produce the illusion of a “wriggling” motion due to the contextual effects of neighbouring dots’ motion. Additionally, some dots are grouped by the visual system causing the illusory percept of synchronised rotation. This illusory condition was compared to a control condition in which the straight line trajectories of the dots were allowed to collide, maintaining the perception of the straight line motion. They found the condition containing illusory motion displayed significantly more activation bilaterally in the early visual cortex and in the right fusiform area than for the motion control condition. They suggested the
illusory motion trajectories were being processed in the ventral visual stream similar to continuous static contours (e.g. modulated lines). This may explain the similarity in observer thresholds for the motion RF, moving slit, and moving pattern conditions. Integration of the perceived orientation information for all 3 stimuli may have been occurring in the ventral visual stream and not in motion regions as originally suggested by Or et al. (2011).

For the modulated lines there was no difference in sensitivity or strength of integration for any of the conditions. Observer thresholds decreased significantly between 1 and 2 cycles, but not between 2 and 3 cycles of modulation. Tyler (1973) presented sinusiodally modulated lines (contour-defined) and found an improvement between 1 and 2 cycles of modulation but no improvement with additional cycles of modulation for patterns with a spatial frequency between 0.35 and 0.9 c/deg. Our modulated lines had a spatial frequency approximating 0.5 c/deg and therefore, our results replicate those of Tyler (1973). It appears, as suggested by Tyler (1973), that there is a spatial integration window for these patterns of approximately 2.5° of visual angle. As there appears to be no such spatial integration limit found for RF patterns (Jeffrey, Wang, & Birch, 2002; Wilkinson et al., 1998) and there was no evidence for global processing of any of the line stimuli, it appears that both motion-defined and contour-defined modulated lines and RF patterns are processed differently by the human visual system.

Schmidtmann and Kingdom (2017) suggested that a common mechanism exists for the detection of RF patterns and modulated lines. Although they report quite high goodness of fits for their model overall, they acknowledge that it underestimates some of the low RF patterns and therefore, it is likely the high frequency RF patterns are driving their goodness of fit values. This could explain the difference between their results and those of Green et al. (2017) who found evidence that low frequency RF patterns and modulated lines are processed differently by the human visual system. Low frequency RF patterns demonstrate global processing whereas high frequency patterns do not (Bell, Badcock, Wilson, &
Wilkinson, 2007; Hess et al., 1999; Jeffrey et al., 2002; Loffler et al., 2003; Schmidtmann et al., 2012). The majority of these globally processed low frequency patterns tested by Schmidtmann and Kingdom (2017) are not adequately described by their model and therefore, may not be generizable to globally processed RF patterns. This conclusion is consistent in predicting the same range of RF patterns that are different to modulated lines as first noted by Wilkinson et al. (1998).

Recent work has shown a number of similarities between motion RFs and static RF patterns (Wilkinson et al., 2016). They found that thresholds increase proportional to the pattern’s radius and thresholds decrease as a function of increasing RF number which conforms to a power-law relationship, both of which have been shown for static RF patterns (Wilkinson et al., 1998). This is consistent with the suggestion that the processing of the shape of motion RF patterns also occurs in the form areas, rather than motion areas of the visual cortex.

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Chapter 6:
General Discussion
6.1. Radial frequency patterns are globally processed

The purpose of this thesis was to examine critical features of global shape processing in the human visual system. At the outset there was a debate within the literature about whether the previous analysis (Bell & Badcock, 2008; Dickinson, Han, Bell, & Badcock, 2010; Dickinson, McGinty, Webster, & Badcock, 2012; Loffler, Wilson, & Wilkinson, 2003; Schmidtmann, Kennedy, Orbach, & Loffler, 2012; Tan, Dickinson, & Badcock, 2013) of the improvement in RF pattern detection as more cycles of modulation were added to the path was a result of integration of local information, or could more accurately be explained by probability summation (Baldwin, Schmidtmann, Kingdom, & Hess, 2016). Therefore, it called into question the validity of the conclusions of past research investigating global shape processing which used these stimuli. Previous researchers followed the methodology of the initial papers examining these stimuli and used probability summation estimation methods based on high threshold theory (HTT) in their analysis, however, Baldwin et al. (2016) provided evidence that signal detection theory (SDT) is a more appropriate theory to base such estimates on when examining deformation thresholds for RF patterns. They based their conclusions on data reflecting deformation threshold when using either a single RF4 pattern or a diamond arrangement of four RF4 patterns and found they were unable to reject probability summation estimates generated using SDT. However, their methodology of using either fixed phase (fixed orientation) or a small set of phases for patterns departed from that of previous studies. Therefore, Chapter 2 aimed to re-examine integration of information around low frequency RF patterns and investigate the different probability summation estimates modelled under SDT and HTT to determine whether incorrect conclusions regarding global contour integration had been drawn from the use of HTT in previous studies. The chapter also examined the critical factors in the use of parameters within SDT calculations.
In order to determine the presence of integration around RF patterns experimentally, we used a discrimination at threshold paradigm (Watson & Robson, 1981). To discriminate between two RF patterns, that task requires a judgement of shape and the combination of information from at least two points on the contour. This necessarily is the integration of at least some information and, therefore, would be evidence of non-local shape processing occurring around the continuous closed contour of the RF pattern.

Furthermore, to discriminate between two patterns at deformation detection threshold indicates “labelled lines” in the visual system for each of the patterns (Watson & Robson, 1981). These labelled lines are independent channels within the visual system for each of the RF patterns tested. Therefore, this test was able to indicate whether there was integration of information around the RF patterns tested and whether there were independent channels for the two patterns.

We chose two patterns, an RF3 and an RF5 to investigate using the discrimination at threshold paradigm. In five out of six of the previous studies comparing observer thresholds to HTT probability summation estimates (Bell & Badcock, 2008; Dickinson et al., 2010; Loffler et al., 2003; Schmidtmann et al., 2012; Tan et al., 2013), either one, or both of these patterns had been used and therefore, they are the most informative for answering whether these studies were incorrect in their conclusions. Additionally, it was suggested by Baldwin et al. (2016) that RF3 patterns, with their steep integration slopes, were the only patterns which would be able to demonstrate observer slopes steeper than those predicted by probability summation and perhaps were processed in a different manner to other low frequency patterns. Including an RF3 and RF5 allowed us to directly compare the RF3 to another RF pattern in the low frequency range and determine whether there is validity to this claim.
Our results, similar to those found by Dickinson, Bell, and Badcock (2013), demonstrated both the RF3 and RF5 patterns were able to be discriminated at the deformation detection threshold when there was more than 1 cycle of modulation on the pattern. Thus, observers were able to make a shape judgement which requires them to integrate, at minimum, more than one cycle of the information around the contour at their threshold for detection. Therefore, our results indicated strong evidence for the global processing of these two low frequency RF patterns.

Furthermore, the integration of information around partially modulated RF patterns (i.e. patterns containing sectors with unmodulated circular paths [e.g. RF5(3)]) questions a suggestion of Schmidtmann et al. (2012). They argued that integration only occurred around fully modulated RF patterns (e.g. RF5), although it should be noted they were using a different experimental paradigm, with the reference stimulus being an RF pattern with a smaller amplitude than the test stimulus. For partially modulated patterns, they found improvement in performance whilst adding cycles of modulation to the contour conformed to their probability summation estimates. They posited a mechanism which required all cycles of modulation to be present for information to be summed together (an AND gate). Our results are inconsistent with this, as we found evidence for integration around the path of both partially and fully modulated RF patterns and our data was well described by straight line, not a sudden change in thresholds when the final cycle was added (consistent with previous research; Dickinson et al., 2012; Hess, Wang, & Dakin, 1999; Loffler et al., 2003; Tan et al., 2013). This suggests information is combined around the path, regardless of whether the contour of low frequency patterns is fully modulated or is only partially modulated.

One potential explanation for the difference in results is their smoothing function. In this thesis (following Loffler et al., 2003) the first derivative of a Gaussian function was used to smoothly add the cycles of modulation to the unmodulated path. Schmidtmann et al.
(2012) did not use this function, potentially creating a local cue at the point where the modulated sector joined the unmodulated sector. This cue would have been present for partially modulated patterns but not for fully modulated patterns when there are no unmodulated sectors. This may explain why they found thresholds for partially modulated patterns conformed to probability summation and the fully modulated pattern exceeded probability summation predictions, because the salient local cue would have been detected preferentially by the visual system when the global signal was weak (see discussion of this below). This would have resulted in the observer thresholds being a combination of local cue detection and global integration, obscuring the mechanism they were intending to measure.

Note that this results in poorer integration not because thresholds are higher, but rather because thresholds are initially (i.e. at 1 cycle of modulation) lower than would be produced by a purely global cue. The presentation containing both the global and local cue (i.e. fixed phase presentation) end at the same point as the presentation containing only the global cue (i.e. the random phase presentation), as the global cue is stronger than the local cue for complete RF patterns. Therefore, the lower threshold at 1 cycle of modulation for the fixed phase presentation results in a lower “starting point” and a shallower integration slope than the random phase presentation.

We have provided compelling evidence in favour of global processing within this thesis, which begs the question of what is the underlying mechanism/s involved. Although we did not strictly model any such mechanisms, our results nevertheless do provide support for a significant feedforward component. Notwithstanding the minor issues noted within the General Introduction, we believe the model by Poirier and Wilson (2006) provides a good approximation of the combination of information as it moves through the ventral visual stream. This suggests that information is combined into convex and concave fragments which are coded in relation to the object’s centre. As mentioned in Chapter 5, the results for
Experiment 1 support the importance of object centre for detection of RF patterns as observer performance for the random slit condition was significantly better than the moving slit and moving pattern conditions.

There is evidence that the curvature signal provided by the early visual system which is globally integrated or pooled is done in a nearly perfect manner (i.e. linear integration). This thesis has consistently found integration slopes of approximately -1 for an RF3, which itself is evidence of linear integration, however, for the RF5 (as with previous research, e.g. Bell & Badcock, 2008; Loffler et al., 2003) the integration slope was less than -1. This is explained by Experiment 4 in Dickinson et al. (2012), where they displayed evidence that integration slopes for RF2, RF3, RF4, and RF6 fell on the same line if the dependent variable measured was gradient at zero crossing rather than amplitude. This may indicate that rather than global integration slopes reducing with increasing RF number, they remain the same, but it is our choice of measurement which may be obscuring the true strength of integration. This begs the question of whether there is a difference in processing of low and high RF patterns, an obvious direction for future research.

6.2. Probability summation estimates under high threshold theory and signal detection theory

After finding experimental evidence for the global processing of the two RF patterns, we investigated the probability summation estimates modelled under SDT and HTT (Chapter 2). We must note here that we have presented strong evidence for low frequency RF patterns being globally integrated and this likely occurs within a single labelled channel for each low frequency pattern (i.e. a channel for an RF3 etc.). However, if we are to use the difference from probability summation method in the future to determine whether there is the presence of global integration, then we need to accurately define the parameters used within the calculations.
Firstly, we examined the SDT probability summation estimates using the methodology of Baldwin et al. (2016). To generate probability summation estimates using SDT (Equation 8 from Kingdom, Baldwin, & Schmidtmann, 2015) they must define a number of parameters, one of which is the number of channels monitored (Q). They used the RF number to determine Q in their calculation, on the assumption that one piece of information came from each cycle of modulation. Probability summation estimates failed to provide an adequate account of the performance for the RF3, but it could account for the RF5. This indicates that the methodology applied by Baldwin et al. (2016) was too insensitive to detection integration, as the use of fixed locations for deformation and their low number of channels was not appropriate for these patterns. When random phase was used and values were more appropriate, analysis of observer thresholds using SDT produced results consistent with previous research and the experimental results of Chapter 2.

There is evidence in Chapter 2 against the number of channels monitored being equal to the RF number. Kingdom et al. (2015, p. 3) note that interleaving stimuli which require the observer to monitor different channels will have a detrimental effect on the observer thresholds of the condition which requires a lower number of channels to be monitored. In other words, if the number of channels monitored was equal to the RF number (Baldwin et al., 2016) then we would expect thresholds for the RF3 to increase when it is interleaved with the RF5 compared to when it is presented by itself. This is because there is additional noise in the extra monitored channels in the non-target interval. However, there was no significant difference in observer thresholds for either the RF3 or RF5 when they were interleaved within the same block of trials, indicating the number of channels monitored for random phase RF patterns cannot be equal to the RF number.

One reasonable question is whether or not there is enough difference in the predictions between 3 and 5 channel estimates to be measurable. Under SDT an increase
from 3 to 5 channels would have an approximate 12-15% increase in threshold for detection (this estimate is based on the data from Baldwin et al., 2016 and Chapter 2). An increase of this size would put the threshold at the upper limit of the 95% confidence intervals for the observers. As this was a within-subjects design an increase of this amount would likely have been statistically significant. However, there was no consistent elevation in threshold found. Two of the four observers in Chapter 2 show a non-significant decrease in detection threshold for the RF3 when interleaved with the RF5, while the other two display non-significant increases. Therefore, to produce probability summation estimates modelled within the framework of SDT appropriate for these patterns requires that we use a number of channels greater than the RF number. This number is either the same for both RF patterns (as there was no change in threshold for individual patterns when interleaving the RF3 and RF5 conditions) or it would need to be sufficiently large that changes to the number result in negligible effects on threshold estimates. Given the inability of SDT to correctly reject probability summation for an RF5 we would favour the latter.

We chose the number of channels to be equal to the number of unique one degree (of polar angle) rotations a fully modulated RF pattern (e.g. RF3) can make. This is because research suggests that removal of critical local features on the RF pattern has a significant effect on observer thresholds (Loffler et al., 2003) and that normal visual performance can resolve two points of light separated by 1 minute of visual angle (or smaller; Elliot, Yang, & Whitaker, 1995; Frisén & Frisén, 1981), which is the approximate distance on the contour between two points separated by one degree of polar angle on an RF pattern with a mean radius equal to 1 degree of visual angle (like those we have used). We calculated this using the circumference of the circle \(2\pi r\) where \(r\) is equal to 60 minutes of visual angle and therefore results in a circumference \(\approx 377\) minutes, which approximates 1 minute per degree of rotation. This results in the number of channels monitored being 120 for the RF3 and 72 for the RF5. After their respective number of 1° rotations the fully modulated RF3 or
RF5 pattern repeat themselves. Of course, partially modulated patterns will be able to make more 1° rotations, but we use these values to be conservative.

Using this method produced probability summation estimates that were significantly shallower than slopes derived from the observer’s data, resulting in the rejection of probability summation for both the RF3 and RF5 patterns. This does coincide with conclusions about the processing being global that were reached using discrimination at threshold. Therefore, we suggest that this is an appropriate way to estimate the number of channels monitored for random phase low frequency RF patterns.

We then compared HTT predictions of probability summation (used in previous integration studies; Bell & Badcock, 2008; Dickinson et al., 2010; Dickinson et al., 2012; Loffler et al., 2003; Schmidtmann et al., 2012; Tan et al., 2013) to those generated by SDT using the appropriate number of channels outlined above. The probability summation estimates generated by HTT were significantly shallower than observer thresholds for both the RF3 and RF5 patterns. Furthermore, they were also steeper (and therefore more conservative as a steeper probability summation integration slope is harder to reject) than SDT probability summation estimates when modelled using an appropriate number of channels. This suggests that previous studies using these particular patterns, and likely others with low frequency RF patterns, were conservative when concluding there was evidence for global shape processing occurring around the contour. It also suggests that significant differences between observer thresholds and probability summation for random phase patterns are not obtained when the RF number is used to define the number of channels monitored.

Another prediction within the SDT framework for stimuli conforming to probability summation is the reduction in the psychometric slope, relating deformation detection to level of deformation, with increasing number of stimulus elements or cycles of modulation.
in this case (Kingdom et al., 2015, p. 7). The reduction in the slope of the observer’s psychometric function is a result of a decrease in uncertainty with fewer channels contributing purely noise to performance (Pelli, 1985). Again, our results (Chapter 2, Figures 9 and 10) are contrary to this prediction, with neither the RF3 nor RF5 showing any evidence for a change in the slope of the psychometric functions with increasing numbers of cycles of modulation for any of the conditions. These results are similar to other previous research (Baldwin et al., 2016; Schmidtmann et al., 2012) who also found no evidence of change in the slope of the observer’s psychometric function, further evidence against observer performance from low frequency RF patterns conforming to probability summation.

Therefore, we concluded there was both strong evidence for global processing of the RF3 and RF5 patterns as observers were able to discriminate these patterns (Watson & Robson, 1981) when they have more than 1 cycle of modulation at their threshold for detection and there was strong evidence against performance being a result of probability summation, as results failed to conform to a number of predictions underlying probability summation when modelled under SDT. There also appeared to be no evidence to suggest that an RF3 is processed in a different manner to other low frequency RF patterns.

6.3. The effect of fixed phase presentation

It was reasonable for Baldwin et al. (2016) to assume the RF number was equal to the number of channels monitored as they were using fixed phase presentations of the pattern (although they did interleave different cycles of modulation to increase spatial uncertainty in two conditions; discussed below). However, it was this departure from the methodology used in previous studies (Almeida, Dickinson, Maybery, Badcock, & Badcock, 2014; Bell, Badcock, Wilson, & Wilkinson, 2007; Bell, Dickinson, & Badcock, 2008; Dickinson et al., 2010; Dickinson et al., 2012; Hess et al., 1999; Loffler et al., 2003; Schmidtmann et al., 2012; Tan et al., 2013) which likely resulted in their inability to reject probability summation.
in their study. It was noted by Loffler et al. (2003, p. 523) when examining the effect of increasing the number of cycles of modulation on observer thresholds that spatial certainty may localise the observer’s attention, potentially causing the global aspect to be disregarded. Therefore, the purpose of Chapter 3 was to investigate the effects of fixed phase and random phase presentations on the strength of integration of information around an RF3 to determine whether this was a plausible explanation for the results found by Baldwin et al. (2016).

Chapter 3 demonstrated that when presented with 1 cycle of modulation of an RF3, observer thresholds for fixed phase presentations were significantly lower than for random phase presentations. However, this difference was not maintained for 2 and 3 cycles of modulation. These results suggest an interaction of global and local cues as discussed in Dickinson et al. (2012) and alluded to by Loffler et al. (2003). The fixed phase presentation created a salient local cue which the observers used preferentially when the global cue was comparatively weak (i.e. at 1 cycle of modulation). This meant at one cycle of modulation the observer was using a global cue for the random phase presentation and a more salient local cue for the fixed phase presentation, resulting in a reduced threshold for the fixed phase presentation. This is because for the fixed phase presentation the observer was able to focus their attention at the location where deformation was going to occur, eliminating noise from other contour locations, thus achieving lower thresholds. As additional cycles of modulation were included on the pattern the strength of the global cue increased above that of the local cue, resulting in the observer preferentially using the global cue for detection. This would mean that the observer was using the global cue for detection of 2 and 3 cycles of modulation in both the fixed phase and random phase presentations, that could explain the failure to observe a difference in performance.
Baldwin et al. (2016) measured observer thresholds for both blocked and interleaved presentations of a single RF4 and a diamond arrangement (quad RF) of four RF4s. In the blocked presentation, the observers knew the fixed number of cycles of modulation and where on the contour/s they would appear. In the interleaved presentation, all the cycles of modulation (i.e. 1, 2, 3, and 4) for a single condition (e.g. the quad RF condition) were presented within the same block of trials. The interleaving of the cycles of modulation for each condition was done to increase the spatial uncertainty, however, this is not analogous to random phase presentation. This is because observers would still know the information would appear in 1 of 4 possible locations and could attend to these local areas (all near the fixation point). For the single RF condition as the number of cycles on a contour is increased, observer thresholds remain relatively unchanged for the blocked condition and they decrease for the interleaved condition (Baldwin et al., 2016). The lack of reduction in threshold in the blocked condition indicates the monitoring of a single location, as additional cycles of modulation had no effect on performance (i.e. neither probability summation nor global integration was occurring). The reduction in thresholds for the interleaved condition resulted in sensitivity which was greater than for the blocked condition. This is further evidence for the global processing of their RF4, as if the pattern was locally processed it would not be able to achieve thresholds lower than those found for the blocked condition, as the observer knows exactly where the deformation will appear on the pattern. Therefore, the results for the single RF condition of Baldwin et al. (2016) displays evidence of integration of information, unlike the results found for their quad RF condition.

In the quad RF condition, results for the blocked and interleaved presentations conformed to those predicted for probability summation by (Kingdom et al., 2015). Similar to the single RF condition, the blocked presentation displayed no change in observer thresholds with increasing cycles of modulation. For the interleaved presentation, thresholds at 1 cycle of modulation were significantly higher than for the blocked
presentation (as we would expect, performance is best when you know where the deformation will be). The difference between the thresholds of the two presentations converge until they are the same at 4 cycles of modulation. This is what would be expected by attending to a single location, as the certainty in the location of deformation increases (in the interleaved presentation), performances increases. Therefore, we can explain the results of Baldwin et al. (2016) as conforming to a rate that looks like probability summation for the quad condition and demonstrating some evidence of integration of information in the single RF condition, but because of their use of fixed phase presentation, integration was not significant when compared to probability summation.

Although the results from Chapter 3 for RF patterns provide a plausible explanation for the results found by Baldwin et al. (2016), they appear to be contrary to the results found by Loffler et al. (2003) when using an RF3. In their study, Loffler et al. (2003) found no effect of fixed phase presentation on observer thresholds for an RF3. This result, however, is different to the other two patterns they tested (RF5 and RF24) which demonstrated a significant reduction at one cycle of modulation and less of a reduction for the full pattern when comparing fixed phase to random phase thresholds. One possible explanation for the difference between our results and theirs may be the use of an RF3 stimulus with 0.5 cycles of modulation, rather than 1 cycle. This raised cosine function is not typically used in assessing global processing and it has been shown that using a cosine function (although not exactly the same as a raised cosine function) in place of a sine function can have a significant effect on observer thresholds (see Experiment 3 of Dickinson et al., 2012). Therefore, it may be that 0.5 cycles of modulation is causing a local cue which is used in both the fixed and random phase presentations, resulting in no observable difference between the two presentations at 0.5 cycles. This speculation was not directly tested in the thesis and may be an interesting avenue for future work.
The obvious question raised by the difference in performance when observing fixed and random phase RF patterns is how the visual system achieves lower thresholds when the observer knows where to look. We have already suggested that observers may be able to disregard some of the pattern and therefore, reduce the amount of noise presented to the visual system. Another possible explanation is the involvement of feedback connections which may increase shape detection in a similar manner to that described by Choi, Pasupathy, and Shea-Brown (2016; see review in Chapter 1). This would be an interesting avenue for future neuroimaging research.

6.4. Modulated lines: Are they processed differently to RF patterns?

Chapter 3 also investigated the effect of placing the cycles of modulation on the open continuous contour of a modulated line rather than the closed continuous contour of an RF pattern. Closure appears to be important in the integration of information around contours made up of discrete local elements (Kovacs & Julesz, 1993; Mathes & Fahle, 2007), so it would be logical to assume that this feature is also important in continuous contours. However, recently this assumption has been questioned (Mullen, Beaudot, & Ivanov, 2011; Schmidtmann & Kingdom, 2017) and, further, it was suggested the closed continuous contour of RF patterns and open continuous contour of modulated lines are in fact processed by a common mechanism in the visual system. Initially Wilkinson, Wilson, and Habak (1998) rejected this idea, comparing detection of deformation at different contrast levels for the two types of patterns. They found a different pattern of results for the two stimuli and suggested this ruled out a common mechanism processing both. Chapter 3 compared the integration of information along a modulated line to those found for RF patterns. Our results, using lines as patterns, showed that there was no difference between the outcomes for fixed phase presentation and random phase presentations; observers performed the same for modulated lines under both conditions, unlike the results found for
RF patterns. These results were similar to those of Tyler (1973) who found a significant decrease in threshold between 1 and 2 cycles of modulation on a line, but no difference between 2 and 3 cycles of modulation. He suggested that there was a spatial integration window of approximately 2.5° of visual angle. This is supported by our results as the length of a modulated line with 2 cycles in Chapter 3 was 2.09°, while for 3 cycles of modulation it was 3.14°. The third cycle falls outside the proposed window of integration and is therefore, not combined with the first two cycles, assuming Tyler’s estimate also applies in our study.

It has been argued that the information on the modulated line should be presented at a similar eccentricity as the RF pattern. The information presented on the modulated line in Chapter 3 was distributed across a length of 3.14°, whereas for an RF pattern with a radius of 1°, the information is all contained within 2° of visual angle. Schmidtmann and Kingdom (2017) presented the information across two spatially separated lines to decrease the area over which the cycles of modulation were distributed. Although this reduces the eccentricity of the information, it assumes that information will be integrated across the two lines. Currently there are no results demonstrating the integration of information needed across discrete contours and rather, the results of Baldwin et al. (2016) and those from Chapter 4 would suggest information is not integrated across contours. Ultimately it has been shown that thresholds for detection of RF patterns are largely unaffected by change in radius (Wilkinson et al., 1998) when expressed as amplitude (not physical offsets), whereas modulated lines can only integrate information over a discrete length. This suggests a difference in the underlying processing mechanism.

Furthermore, comparisons of observers’ data for modulated lines, in Chapter 3, to probability summation estimates from both HTT and SDT found that the observer thresholds were not significantly different to those predicted by probability summation for either model. This result, combined with the lack of change in performance for fixed phase
presentations for lines, but not RF patterns, provide strong evidence that RF patterns and modulated lines are in fact processed differently by the human visual system.

6.5. Integration across spatially separate radial frequency patterns

Because of concerns over the methods used in Baldwin et al. (2016) we next revisited the question of whether integration can occur across discrete spatially separate RF patterns. Therefore, in Chapter 4 we measured integration within and across RF patterns using a similar methodology to Baldwin et al. (2016), but modified to remove spatial certainty. We used random phase presentation of each of three RF3s presented simultaneously and interleaved the conditions such that the observer did not know which pattern/s would contain deformation. This stopped the observer from adopting a localised attention strategy, as from trial to trial they were unable to predict the pattern or location on the contours in which the information would appear. Our results provided support for the conclusion of Baldwin et al. (2016) on integration across RF patterns, as we also found no evidence for integration of information across multiple contours, but contrary to their findings, we demonstrated strong evidence for integration within RF patterns. This suggests that for orientation information to be integrated, it is required to be on the same contour and not distributed across multiple contours.

Again, analysis was completed using two methods for estimating probability summation, HTT and SDT. As with Chapter 2 and Chapter 3, the HTT estimates were more conservative than those generated using SDT when using an appropriate number of channels. Furthermore, as in the previous chapters, the integration of information within a random phase RF3 pattern was very strong, with slopes approaching that for linear summation. This steep slope has been consistent across observers and across experiments (Chapters 2, 3, and 4), suggesting we can be confident in the global processing of these low frequency RF patterns within a typical human visual system.
There were a number of reasons for choosing to use an RF3 for the test stimulus in place of a higher frequency pattern. We have demonstrated in Chapter 2 that an RF3 is not processed differently to other low frequency RF patterns and therefore, there would be no issue with the generalizability of the results. As noted in Baldwin et al. (2016) and evidenced by previous research (Dickinson et al., 2010; Loffler et al., 2003; Chapter 2; Chapter 3), the RF3 shows the strongest integration of information around the contour. Given we are investigating whether information is integrated across RF patterns, we chose the pattern which displays the greatest effect when altering the number of cycles of modulation. If we are unable to demonstrate integration across RF3s, then it is unlikely that patterns with weaker levels of integration would be able to demonstrate integration across their contours. Finally, as we were interleaving the conditions, the longest block of trials took approximately 30 minutes to complete. Using a higher frequency RF pattern would result in more trials, as we would need an equal number of contours as the RF number (e.g. 5 contours for an RF5) in order to compare within pattern results to across pattern results. Therefore, there would have been more conditions, as there are more combinations of locations which would need to be presented to maintain spatial uncertainty. Interleaving a large number of conditions would result in longer testing blocks. Nine out of the eleven participants were inexperienced observers conducting an experiment as part of their course requirement. The longer testing blocks would have increased participant fatigue, an important factor when testing inexperienced psychophysical observers and, therefore, the use of an RF3 in Chapter 4 was the most convenient and logical choice.

The 3 patterns in the display were distributed equally with centres at a distance of 3° of visual angle from the fixation point and set out with two patterns above the fixation and one below (see Figure 2 in Chapter 4). We were interested in not only the a comparison to the results of Baldwin et al. (2016) but also in investigating possible links between simple shape arrangements and face processing. Therefore we chose our layout as it approximates
the spatial distribution of two eyes and a mouth. Further pilot testing was done with additional RF patterns to approximate a nose and head, along with the periodic modulation of a face outline in an attempt to investigate integration of information at higher areas of the ventral visual stream involved in face processing which is often claimed to be holistic (Farah, Wilson, Drain, & Tanaka, 1998; Sergent, 1984; J. W. Tanaka & Farah, 1993). However, this pilot data found similar results to those found in Chapter 4, suggesting information is not integrated across spatially separate locations and has not been included since it adds nothing further to the current investigation.

6.6. Effects of viewing orientation information over time

Work conducted previously as part of my honours thesis found integration of information still occurs around an RF3 when viewed through an implicit vertical slit (represented as Experiment 1, Chapter 5; note, as stated in Chapter 5, Experiments 1 and 2 were reanalysed and included for a coherent journal submission but were the bulk of a previous Honours thesis, Experiment 3 in Chapter 5 was new research conducted and examinable for this doctoral thesis). The pattern was revealed in one of three ways. Either: the slit moved over a stationary RF3; the RF3 moved behind a stationary slit; or the RF3 was revealed piecemeal over time by a vertical slit appearing in horizontally randomised locations. All conditions demonstrated strong integration around the contour with no significant difference between them (mean slopes of -0.92 CI [-0.74, -1.09], -0.78 CI [-0.50, -1.09], -0.75 CI [-0.49, -1.03], and -0.76 CI [-0.54, 1.00] for the conventional, moving pattern, moving slit, and random slit respectively). There was also no change in the strength of integration nor the sensitivity when the duration of each interval in the moving slit condition was 250, 500, 1000, 2000, or 4000 ms (Experiment 2, Chapter 5). Therefore, the observed integration slope of -0.64 found by Or, Thabet, Wilkinson, and Wilson (2011), when they used a moving dot with a difference of Gaussian (DoG) luminance profile to trace the
contour of an RF3, was significantly less than what we had found for in Experiments 1 and 2 of Chapter 5. Given they had a similar duration of presentation for their intervals (1000 ms and 2000 ms), we theorised it might be a result of the interaction between a local and global cue similar to that described in Chapter 3.

Or et al. (2011) and subsequent studies using these motion RFs (Gorbet, Wilkinson, & Wilson, 2012, 2014) did acknowledge that the constant angular velocity of rotation used may create a change in local retinal speed which the observer could use as a cue in stimulus detection. Or et al. (2011) investigated this potential influence on detection thresholds for fully modulated RF patterns by comparing a constant angular velocity condition with a constant retinal speed condition. They concluded there was no effect of this cue on low frequency motion RF patterns when measuring fully modulated RF patterns. However, they did not measure thresholds for the two conditions using partially modulated RF patterns and thus could not compare integration slopes. Therefore, Experiment 3 of Chapter 5 examined the effect of removing this local change-in-speed cue for partially modulated motion RF patterns.

Our results suggested, that similar to Chapter 3, the change in speed at points of deformation created by the constant angular velocity, was a salient local cue which the observer used preferentially when the global cue available from the pattern was weak (for 1 cycle of modulation). As the strength of the global cue increased, the difference in observer thresholds between the constant angular velocity and constant retinal speed conditions diminished (2 cycles of modulation), until the strong global signal for the fully modulated pattern (3 cycles of modulation) showed no significant differences between the two conditions, replicating the results of Or et al. (2011).

Integration slopes and thresholds for the RF3 for the constant retinal speed condition were very similar to those found in Experiments 1 and 2 of Chapter 5. Analysis of
the results suggested no significant difference between the moving slit and moving pattern condition of Experiment 1 and the constant retinal speed condition of Experiment 3. To further investigate the similarity between motion-defined patterns and contour-defined patterns we tested observer sensitivity to modulated lines traced out by a DoG dot. We used the same contour-defined modulated line stimuli from Chapter 3 and compared the results the motion-defined modulated lines. As was found for the RF patterns there was a similar pattern of results between the contour-defined modulated lines and motion-defined modulated lines (although this pattern of results was different to those found for RF patterns). There was a reduction in threshold between 1 and 2 cycles of modulation but not between 2 and 3 cycles of modulation. Observers were also less sensitive to the motion-defined modulated lines than they were to the contour-defined modulated lines. Although there was a difference in processing of the modulated lines and RF patterns, their results across contour-defined and motion-defined stimuli suggest that contour integration can occur under a variety of conditions, but performance is optimal when the entire path is presented simultaneously.

This similarity in processing between the contour-defined and motion defined stimuli led us to consider one of the possible explanations proposed by Gorbet et al. (2014, p. 13) who used fMRI to investigate cortical activation during motion RF tasks. They noted that the dot motion may have produced motion streaks (Geisler, 1999) which are processed as form information. The relatively long presentation times used in Chapter 5, along with the ability to integrate information in the moving pattern (spatio-temporal displacement) condition suggest that information must be getting stored in memory during these temporal displacement tasks. Storing the information in memory degrades the strength of the signal, resulting in decreased sensitivity, however, our results suggest regardless of whether it is contour-defined or motion-defined stimuli, the information is combined in the same way by the human visual system. This is evidenced by the strength of integration and pattern of
results remaining the same across the presentation types. Prior research suggests that form information from motion streaks is processed at multiple levels of the ventral visual stream up to STS (Mather, Pavan, Bellacosa Marotti, Campana, & Casco, 2013; Ross, Badcock, & Hayes, 2000), however, this was directly tested by Wilkinson, Haque, Or, Gottlieb, and Wilson (2016) by changing the speed and contrast of the dot. They found no effect of these two parameters on observer thresholds and concluded motion streaks were not a sufficient explanation for integration of motion RF patterns.

However, recent research from R. Tanaka and Yotsumoto (2016) investigated areas of cortical activation whilst observers viewed illusory dot motion. The dots travelled in straight line trajectories, but the contextual effect of the other dots’ motion caused the percept of a “wriggling” motion, as well as grouped curved motion. They found, compared to a non-illusory motion condition, evidence of activation in the ventral visual stream. They suggested that these motion trajectories were being processed similar to static continuous contours, providing a potential explanation for the results of Chapter 5. Both the contour-defined and motion-defined RF patterns were being processed in the ventral visual stream. As such, they achieved approximately the same results as there was the same amount of information presented around the path. Although this helps to describe why we get the same results for RF patterns when viewed through slits or traced out by a dot’s motion, we are still unsure of the mechanism that converts the motion into form information, an obvious avenue for future research.

6.7. Conclusions

The current thesis examined critical factors in global shape processing. Firstly, we investigated whether there was evidence for integration of information around low frequency RF patterns (Chapter 2). We found strong evidence for the global processing of RF3 and RF5 patterns, suggesting that previous work had drawn the correct conclusions.
about finding evidence for global processing of these shapes. Both the RF3 and RF5 were able to be discriminated at their threshold for detection, indicating there was no difference in the processing of RF3s compared to other low frequency RF patterns. Chapter 3 investigated the explanation presented in Chapter 2 that fixed phase RF patterns were introducing a local cue which reduced the strength of integration of information around the contour. We found evidence for this explanation and further, for the difference in processing of RF patterns and modulated lines, suggesting these two stimuli are processed using different mechanisms. This supports the original finding of Wilkinson et al. (1998) and provides strong evidence against previous suggestions that RF patterns and modulated lines are processed by a common mechanism (Mullen et al., 2011; Schmidtmann & Kingdom, 2017). Chapter 4 found further evidence for global processing occurring within RF3 contours, this time presented three at once, but no evidence of integration of information across the patterns. This suggests that for information to be integrated, it is required to be on the same contour, it cannot be distributed amongst separate contours. Finally, to create a coherent journal submission, Experiments 1 and 2 of chapter 5 reanalysed data collected in 2012 as part of my honours project and extended it in Experiment 3. The three experiments suggest that similar to Chapter 3, a salient local cue was interacting with the global cue of the pattern of the motion RF. When this local speed cue was removed through the use of a constant retinal speed stimulus, it resulted in a restoration of the strength of integration to levels found for other temporally displaced RF patterns. The similarity in the results of the RF patterns viewed by an implicit slit or through a dot’s motion provided behavioural evidence that motion trajectories are processed in the ventral visual stream (R. Tanaka & Yotsumoto, 2016).

We demonstrated global shape processing does occur for low frequency RF patterns. We found a plausible value for the parameter “number of channels monitored” in SDT probability summation estimates and that using a low value for this parameter can
result in incorrect conclusions. Our findings suggest that the results of Baldwin et al. (2016) were confounded by their use of fixed phase presentation and that when using random phase patterns, observer thresholds were congruent with the previous literature regarding RF pattern integration, finding integration within a single RF pattern, but not across multiple RF patterns. Taken together, when low frequency periodic curvature information is presented on a single contour, the visual system combines all of the available information together around the path. A variety of settings can cause salient local cues which can obscure global integration of information. The integration of information can occur regardless of temporal and spatial displacement but only when the information is presented on a single contour as would be desirable when detecting discrete objects in natural scenes.


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