Shape discrimination in peripheral vision: Addressing pragmatic limitations of M-scaling radial frequency patterns

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A B S T R A C T

Peripheral worsening in shape discrimination (SD) can be compensated by size-scaling of peripheral stimuli. However, such scaling results in production of large stimuli that occupy a vast range of eccentricities. We used six proportionally decreasing spatial scales to address this pragmatic limitation and to explore how shape discrimination varies with radius in the nasal visual field. Five participants with normal vision discriminated circles and radial frequency (RF) patterns presented nasally to the fixation point at 5°, 10°, 15° and 20°. Stimuli were scaled with the nasal cortical magnification factor (nCMF) from a central stimulus in six spatial scales, which varied from 0.125 to 1, where 1 corresponded to 1.2° radius. Thresholds expressed in Weber fractions remained constant at eccentricities up to 20° regardless of the spatial scale. Weber fractions for the smaller spatial scales (0.125–0.5) were higher and more variable than for the larger spatial scales (0.75–1), yet still constant across periphery. The results provide evidence that peripheral shape discrimination is constrained by low-level properties, such as eccentricity, and can be predicted by the cortical magnification theory. However, above the peripheral modulation resolution limits, RF shape discrimination is based on the proportion between the modulation amplitude and the radius for larger scales (0.75–1), and demonstrates peripheral scale invariance for these stimuli. For eccentric shape discrimination tests, stimuli with low spatial frequency, high contrast, and radii corresponding to SS 0.75–0.875 should be used to ensure constant Weber fractions, small variability, and peripheral stimuli that are not excessively magnified.

1. Introduction

Performance for most visual functions is best in central vision and deteriorates progressively further in the periphery. This was observed for visual acuity (Riggs, 1965), contrast sensitivity (Rovamo, Virsu, & Näsinen, 1978), stereopsis (Prince & Rogers, 1998), orientation discrimination (Sally & Gurnsey, 2003, 2004, 2007), grating acuity (Rovamo et al., 1978; Rovamo & Virsu, 1979), two-dots separation, discrimination between mirror-symmetric forms, tumbling E (Rovamo & Virsu, 1979; Virsu, Näsinen, & Osmovilta, 1987), symmetry detection (Saarinen, 1988; Gurnsey & Sally, 2001), and shape discrimination of radial frequency (RF) patterns (Achtman, Hess, & Wang, 2000). The magnitude of this peripheral decrease depends on eccentricity, stimulus characteristics and level of its processing.

At first, the eccentricity-dependant decline in visual function happens in line with changes to the sampling density of retinal circuits (Curcio, Sloan, Kalina, & Hendrickson, 1990; Rossi & Roorda, 2010). Light information that reaches the retina is sampled by the photoreceptors, which is followed by a resampling of the signal by the retinal ganglion cells (Ahmad, Klug, Herr, Sterling, & Schein, 2003; Curcio et al., 1990; Kolb & Dekover, 1991; Young, 1971). The ganglion cell signal is transferred via the lateral geniculate nucleus (LGN). It was found in macaques that in the LGN there are four times more cells dedicated for foveal afferent ganglion cells than for peripheral cells (Connolly & Van Essen, 1984). This results in the further exaggeration of foveal input that is next transferred to the visual cortex where fewer than 100 neurons are dedicated for a LGN neuron transferring information from periphery, and nearly 1000 cortical neurons per central LGN neuron (Connolly & Van Essen, 1984). Thus, magnification of foveal representations in the cortex cannot be attributed only to the retinal ganglion cell topography, but also to a disproportional number of LGN and cortical neurons served by foveal photoreceptors (Azzopardi & Cowey, 1996).

This multi-step emphasis on foveal input results in approximately 40% of primary visual cortex processing information from the central vision (Hendrickson, 2005). It means that central retina has much larger

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representation over cortical surface than a similar area in the peripheral region where the amount of dedicated cortical space decreases steadily with eccentricity (Vitu, Casteau, Adeli, Zelinsky, & Castet, 2017; Daniel & Whitteridge, 1961).

This phenomenon is called cortical magnification and is defined as "the diameter in the primary visual cortex onto which 1° of visual field projects" (Daniel & Whitteridge, 1961). The amount of cortical volume dedicated to processing information from a given region of the visual field can be considered as its processing power (Strasburger, Rentschler, & Jüttner, 2011; Daniel & Whitteridge, 1961). It underlies the idea of M-scaling, where the cortical magnification factor (CMF) is used to scale peripheral stimuli to unify the processing power for peripheral and central stimuli. It improves the peripheral performance to the level of the foveal performance for measures of e.g. acuity (Virsu et al., 1987), letter recognition (Higgins, Arditi, & Knoblauch, 1996), symmetry detection (Saarinen, 1988), orientation discrimination (Sally & Gurney, 2003, 2004, 2007), grating acuity (Rovamo et al., 1978; Rovamo & Virsu, 1979) and RF shape discrimination (Achtman et al., 2000).

Comparisons of regional sensitivity of visual functions are important in examining progressive conditions, which occur non-uniformly in the retina, such as age-related macular degeneration (AMD) or glaucoma. The comparisons between peripheral and central sensitivities are hindered by the eccentricity-dependent variability in sensitivity. Visual tests with expected uniform performance in the peripheral and central vision provide an intra-individual level of comparisons for each patient, inform about a disease onset, and can serve as a predictor of the disease progression.

One of the factors that reflects changes in visual function in age-related macular degeneration (AMD) is shape discrimination of radial frequency (RF) patterns (Liu, Wang, & Bedell, 2014; Wang, He, Mitzel, Zhang, & Bartlett, 2013; Wang, Wilson, Locke, & Edwards, 2002). This task involves the discrimination between a circle and a radially modulated circular shape called a radial frequency (RF) pattern (Wilkinson, Wilson, & Habak, 1998). When using central vision or free gazed vision, AMD patients need bigger modulation than people with normal vision to identify the deformation (Liu et al., 2014; Wang et al., 2013, 2002).

In observers with normal vision, shape discrimination declines with increasing eccentricity when constant-size stimuli are used in eccentric presentation. However, scaling peripheral stimuli with the cortical magnification factor (M-scaling) is sufficient to equate central and peripheral thresholds when expressed as proportions of the radius (Weber fractions) (Achtman et al., 2000). Unfortunately, the M-scaling brings some pragmatic limitations when stimuli are displayed eccentrically to the fixation point. Firstly, it results in peripheral patterns being progressively less well localised and occupying a vast range of eccentricities. For example, a circle of 1.2° radius presented in central vision, once scaled with the nCMF will increase to 9.79° radius for a presentation at 20° in the nasal visual field. This means that the RF pattern will extend from 10° to 30° of the nasal visual field. Secondly, M-scaling takes into account the exact eccentricity of presentation. However, M-scaled peripheral stimuli cover a range of eccentricities, and some of their parts are under-scaled and others are over-scaled. Thus, measured thresholds may reflect peripheral pattern integration over a range of eccentricities rather than shape discrimination at a specific location.

In a pragmatic approach, the CMF is successfully used to estimate the just resolvable distance at a given eccentricity and to scale peripheral stimuli to optimally equalize central and peripheral performance (Schoening, Bouman, de Mesquita, & Slappendel, 1979; Strasburger et al., 2011). The CMF is a useful concept to counterbalance for the eccentricity-dependent loss in sensitivity, yet findings from physiological studies showing that magnification of foveal representations in the cortex cannot be attributed only to the retinal ganglion cell topography, question the CMF as a general principle of sensory representation in the cortex (Azzopardi & Cowey, 1996, 1995; Dow, Snyder, Vautin, & Bauer, 1981). The strong hypothesis of the CMF given by Rovamo and Virsu (1979) is also hard to defend in the light of tasks that are not successfully scalable (e.g. Tyler, 1999; Koenderink et al., 1978, see Strasburger et al., 2011 for a full review).

In our study, we address the pragmatic limitations of M-scaling by testing much smaller peripheral RF patterns than usually done in eccentric presentation (Schmidtmann, Logan, Kennedy, Gordon, & Loffler, 2015; Achtman et al., 2000). We investigate peripheral shape discrimination using stimuli in six spatial scales M-scaled according to the eccentricity of presentation. The spatial scales used for the M-scaling were derived from a central baseline radius (r) of 1.2° and were proportionally decreasing from 1r to 0.125r. This study provides a guidance on the sensitivity levels of peripheral shape discrimination in eccentric presentation in healthy observers across the nasal visual field, and explores whether these levels are size and eccentricity dependent to identify conditions for more precisely localised peripheral shape discrimination (SD) tests.

2. Materials and methods

2.1. Participants

Five healthy participants (M_age = 27.5 years old, SD = 1.51, 3 women, 2 men) with no ocular problems took part in the experiment. Four were naive observers and one was an author of this study. All participants had normal vision or corrected to normal using contact lenses, and observed the experiment monocularly with the right eye only in a dim room. The experiment was composed of four to six 40-min sessions and it took participants approximately 3–4 h to complete it. There was no remuneration provided. Participants gave informed consent prior to the experiment, which was approved by the Ethics Committee of the School of Health Professions, University of Plymouth and was conducted in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

2.2. Procedure and stimuli

2.2.1. Apparatus

Stimuli generation, presentation and data collection were under the control of MATLAB (MathWorks, Inc.) and the psychophysical Cambridge Research System (CRS) toolbox extensions. Stimuli were displayed via the ViSaGe (CRS) system in a calibrated cathode ray tube (CRT) NEC monitor. The resolution of the screen was 1024 × 768 with 19.8 pixels per degree at the short viewing distance (42 cm) and 32.5 pixels per degree at the long viewing distance (72 cm). Monitor refresh rate was 120 Hz and mean luminance was ~50 cd/m^2. Participants recorded their response by pressing on one of two active buttons on a wireless response box (CB6 from CRS).

2.2.2. Stimuli and presentation

Radial frequency (RF) patterns and circles were used to measure shape discrimination (SD). RF patterns are sinusoidally modulated circular contours, which consist of a 4th derivatives of a Gaussian (D4) with a cross-sectional luminance profile and are band limited in the spatial frequency domain (Wilkinson et al., 1998). Radii of RF patterns at a polar angle θ in radians are:

\[ r(\theta) = r_0(1 + \text{Asin}(\alpha \theta + \phi)) \]  

where \( r_0 \) represents the mean radius (size), \( \alpha \) the amplitude of radial modulations expressed as a Weber fraction (absolute modulation amplitude divided by the mean radius), \( \omega \) the radial frequency (number of cycles), and \( \phi \) the phase (orientation) of the pattern (Wilkinson et al., 1998), which changed from trial to trial. Circles (\( \alpha = 0 \)) were used as reference patterns. We used achronmic stimuli with spatial frequency (SF) of 1 or 5 c/deg, baseline radius of 1.2°, Michelson contrast of 60% and a radial frequency of 6 cycles (Fig. 1).

A stimulus with a baseline radius of 1.2° was displayed
displayed stimuli were presented in the nasal visual field with their centres concentrically to the fixation point to obtain a reference threshold and radii are 0.5 eccentricity-dependent decrease in shape discrimination when baseline (0.875, 0.75, 0.5, 0.25 and 0.125) of the 1.2 wider range of radii that were proportionally decreasing fractions (3).

2.2.3. Scaling of the baseline radius
Peripheral stimuli were scaled using the nasal cortical magnification factor (nCMF) from Rovamo and Virsu (1979):

\[(1 + 0.33E + 0.00007E^3)^{-1} \times M(0 < E < 60^\circ)\]  

(2)

where \(E\) represents eccentricity, and \(M\) the magnification for the central fovea (7.99 mm/deg). The baseline radius of 1.2 presented at 0° was multiplied by the reciprocal of

\[(1 + 0.33E + 0.00007E^3)^{-1}\]  

(3)

for each tested eccentricity (5°, 10°, 15° and 20°). It was already shown that up to 20° the M-scaling of peripheral patterns compensates for the eccentricity-dependent decrease in shape discrimination when baseline radii are 0.5° and 1° (Achtman et al., 2000). In this study, we used a wider range of radii that proportionally decreasing fractions (0.875, 0.75, 0.5, 0.25 and 0.125) of the 1.2° baseline radius. We refer to these fractions as spatial scales (SS). The values of the scaled peripheral radii are shown in Table 1. The peripheral stimuli were presented eccentrically to the fixation point as shown in Fig. 2 with spatial frequency of 5 cyc/deg for stimuli in small spatial scales (0.125 and 0.25) and 1 cyc/deg for larger spatial scales (0.5–1). The smaller spatial scales were displayed with SF of 5 cyc/deg because lower spatial frequencies would result in a thickness of the D4 contours being similar to the length of their short radii. Thus, patterns with short radii and low spatial frequencies would become deformed as their opposite contours would meet in the centre of the pattern. Our earlier experiment showed that thresholds for such bulky patterns were higher than for patterns where the thickness of the stimulus was much smaller than the radius (Zolubak & Garcia-Suarez, 2017). Lower SF were preferred in this experiment due to the peripheral processing being supported mainly by low spatial frequency channels. We also aimed to make this study comparable with an analogue experiment where red-green RF patterns were used and required low spatial frequency.

Additionally, at each of the tested eccentricities we presented stimuli with an unscaled, fixed radius of 1.2° and spatial frequency of 1 cyc/deg as a control condition.

2.2.4. Procedure
Modulation thresholds, expressed as ratio of absolute modulation to radius (Weber fractions), were measured using a 2-interval forced choice (2IFC) one-up/two-down staircase procedure. In each trial, one interval contained a RF pattern and the other contained a circle (Fig. 3). Participants indicated which interval contained the RF pattern by pressing a relevant button on the CB6 response box. The modulation amplitude was varied according to their answers and it was reduced after two correct responses by 25% on the first reversal and by 12.5% on subsequent reversals, and increased by 25% after each wrong identification. Each staircase measurement was repeated at least four times and terminated after six reversals. Average of the last 5 reversals and then average of 4 repeats, corresponded to approximately 71% of correct responses (Lu & Dosher, 2013).

During the experiment, the viewing distance was varied to account for monitor-size limitations and to display stimuli that subtend 0.8° to 20° of visual field. Thus, at the beginning of each testing slot,
participants were asked to adjust their chair position according to the viewing distance (‘short’ = 42 cm, ‘long’ = 72 cm) and press a button to start the experiment when they were ready. Participants were instructed to maintain their fixation at the black dot displayed on the right side of the screen, and less experienced observers (n = 3) hold their head on a chin and forehead rest. Stimuli were presented for 500 ms with the same-length inter-stimulus interval (Fig. 3). Auditory feedback was given after each registered button press, but no positive feedback was given for correct responses. Practice trials were run for all participants before the experiment commenced.

3. Results

3.1. Scaling effects on shape discrimination across the nasal visual field

Weber fractions for each spatial scale and unscaled stimuli are plotted against eccentricity of presentation in Fig. 4. For fixed size (unscaled) patterns sensitivity for detecting sinusoidal modulations decreases with eccentricity, whereas spatial scaling with nCMF neutralises this variation. To test for significant differences in thresholds between different eccentricities, we used a one-way ANOVA and post hoc Tukey tests. Weber fractions for M-scaled stimuli remain constant across the periphery in all spatial scales, while Weber fractions for unscaled stimuli differ significantly (F(4,20) = 121.75, p = 0.001) between all eccentricities except between 5° and 10° presentation. This finding is consistent with previous studies (Achtman et al., 2000; Schmidtmann et al., 2015; Feng et al., 2020a), which showed that spatial scaling of the stimuli compensates for the peripheral decrease in RF shape discrimination. Statistical findings for the SS 0.125–0.25 should be treated with caution due to the very high variability and small sample size.

3.2. Peripheral shape discrimination of scaled stimuli

3.2.1. Weber fractions in different spatial scales

Data presented in Fig. 4 show that Weber fractions are constant within a given spatial scale up to 20°; however, the performance differs between spatial scales. We used the averaged peripheral Weber fractions for each spatial scale to check for significant differences using one-way ANOVA. We found significant differences (F(5,114) = 6.6, p = 0.001) between smaller (SS 0.125 and SS 0.25) and larger spatial scales (SS 0.5, SS 0.75, SS 0.875 and SS 1) with average Weber fractions in SS 0.125 and SS 0.25 being significantly higher than Weber fractions in larger spatial scales. These significantly higher Weber fractions and variability in SS 0.125 and SS 0.25 could have overshadowed differences between larger spatial scales. A one-way ANOVA run only for the larger spatial scales (0.5–1) showed that there was a significant difference (F(3,79) = 12.01, p = 0.001) between SS 0.5 and larger scales (0.75, 0.875, and 1).
with significantly higher Weber fractions in SS 0.5. The findings indicate scale invariance for RF patterns in SS 0.75 to SS 1 up to 20°.

3.2.2. Variability

Inter-individual variability, expressed in standard error of the mean, was in general significantly higher (F(5,18) = 33, p = 0.001) for SS 0.125 and SS 0.25 than for larger spatial scales, and there were no statistically significant differences between the larger spatial scales. This higher variability in smaller spatial scales could be caused by the peripheral sampling limits on the higher spatial frequency used with SS 0.125 and SS 0.25.

Further analysis aimed to investigate regional sensitivity for peripheral shape discrimination, and whether the nCMF estimates it precisely.

3.3. Regional sensitivity for shape discrimination

To analyse regional sensitivity, we compared ratios of peripheral to central absolute modulation thresholds rather than Weber fractions (Fig. 5). The foveal thresholds were measured for a stimulus presented with a 1.2° radius. The average absolute modulation threshold found in this and previous studies for foveal stimuli with similar characteristics (Achtman et al., 2000; Dickinson, McGinty, Webster, & Badcock, 2012; Jeffrey, Wang, & Brich, 2002; Wang et al., 2002; Zolubak & Garcia-Suarez, 2017) was 10 seconds of arc.

The absolute modulation thresholds increase with increasing eccentricity (F(4,140) = 52.5, p = 0.001). At a given eccentricity of presentation, the elevation of absolute modulation thresholds is mainly alike regardless of the spatial scale. The exception is SS 1, which seems to result in higher absolute modulation thresholds than other spatial scales. However, the one-way ANOVA showed significantly higher thresholds in SS 1 only at 10° (F(6,28) = 8.12, p = 0.001) and 15° (F(6,28) = 4.13, p = 0.004). The absolute modulation thresholds are eccentricity-dependent and scale-independent (besides SS 1) within each eccentricity of presentation. The magnitude of elevation in peripheral thresholds closely corresponds to the ratio of the peripheral to foveal reciprocal of nasal cortical magnification (Rovamo & Virsu, 1979). However, the magnitude was in general smaller than the elevation in the reciprocal of averaged cortical magnification found for human V1 in clinical and neuroimaging studies (Wu, Yan, Zhang, Jin, & Guo, 2012; Duncan & Boynton, 2003; Engel, Glover, & Wandell, 1997; Grüsser, 1995; Sereno et al., 1995; Cowey & Rolls, 1974), although its pattern was similar to the elevation in the absolute modulation thresholds.

We used six spatial scales that differed by a factor of eight. This resulted in the presentation of stimuli with largely varying radii at each eccentricity (Table 1). The eccentricity of stimulus presentation was defined at the point in the centre of the stimulus. Although it was set to be at 5°, 10°, 15° or 20°, the actual defining features of the stimulus were located at different eccentricities depending on the stimulus radius. Thus, parts of some stimuli were falling closer to the fixation point than others. This limitation of eccentric presentation is addressed by plotting the absolute modulation thresholds against the eccentricity of the stimulus part that fell the closest to the fixation point (Fig. 6).

Fig. 6 shows that for any given eccentricity of presentation, the absolute modulation thresholds were similar and independent from the spatial scale (besides SS 1). It may suggest that shape discrimination is not performed based on the local information that is the closest to the fixation point. If a local cue of the closest part of the RF pattern was used, thresholds would increase with decreasing spatial scale within a given eccentricity of presentation. Uniform absolute modulation thresholds for a given eccentricity of presentation could reflect the integrating capability of the area surrounding this eccentricity. Larger absolute modulation thresholds in SS 1 resulted from overestimated radii in this scale. Absolute modulation needs to be 0.003 of the radius to be visible. Thus, absolute modulation thresholds that constitute 0.003 of long radii exceed the actual peripheral modulation resolution.

3.4. Cortical magnification theory and Weber fractions predict peripheral shape discrimination

The absolute modulation thresholds increase with eccentricity (Fig. 5) in a way that can be explained by the cortical magnification theory. The elevation in absolute modulation thresholds corresponds closely to the changes in the cortical magnification for the nasal visual field (Rovamo & Virsu, 1979) and is smaller, but follows changes in averaged cortical magnification for human V1 measured in clinical and neuroimaging studies (Wu et al., 2012; Duncan & Boynton, 2003; Engel et al., 1997; Grüsser, 1995; Sereno et al., 1995; Cowey & Rolls, 1974) (Fig. 5). Thus, peripheral modulation resolution can be estimated using the nCMF. In fact, peripheral thresholds estimated from the average central threshold (10 seconds of arc) found in this and previous studies (Achtman et al., 2000; Dickinson et al., 2012; Jeffrey et al., 2002; Wang et al., 2002; Zolubak & Garcia-Suarez, 2017) match the actual peripheral thresholds measured in our experiment (Fig. 7). Thresholds for SS 1 were excluded as they were significantly higher than thresholds for SS 0.125–SS 0.875.

In addition, significantly higher absolute modulation thresholds for the largest patterns (SS 1) show that the proportion between radii and modulations is also an important factor in RF processing. This proportion (Weber fraction) in previous studies that used similar parameters (Schmidtmann & Kingdom, 2017; Wang et al., 2002; Wilkinson et al., 1998; Zolubak & Garcia-Suarez, 2017) and in this study for larger scales, was about 0.003 and constant in the periphery.

The results show that shape discrimination for RF patterns depends on the spatial properties of the nasal visual field (modulation resolution), which are predictable by nCMF, and on the proportion between modulation amplitude and radius of the RF patterns. These two factors interplay together and determine peripheral shape discrimination, where the peripheral absolute modulation threshold (Mt peripheral) at a given eccentricity is:
\[ M_{\text{peripheral}} = \frac{M_{\text{central}}}{(1 + 0.33 \times E + 0.00007 \times E^3)^{-1}} \]  

where \( E \) is the eccentricity of presentation and \( M_{\text{central}} \) is the absolute modulation threshold measured in central vision and expressed in seconds of arc. This method is consistent with a pragmatic approach to using the cortical magnification factor, where a threshold at a given eccentricity is taken as a baseline to estimate thresholds at further eccentricities (Koenderink et al., 1978; Strasburger et al., 2011). Moreover, constant and uniform Weber fractions of 0.003 for the larger spatial scales suggest that once the peripheral absolute modulation thresholds are 0.003 of the radius, further increases of the radius do not benefit the peripheral performance. Hence, the central absolute modulation threshold and the constant Weber fraction can be used to calculate optimal size of peripheral stimuli using the equation:

\[ r = 333.3M_t + 110M_tE + 0.023M_tE^3 \]  

where \( r \) is the radius (seconds of arc) at a given eccentricity, \( E \) is the eccentricity of presentation (degrees) and \( M_t \) is the central absolute modulation threshold in seconds of arc.

### Table 2
Comparison between averaged (without SS 1) and estimated absolute modulation thresholds, and optimal peripheral radii calculated based on the estimated thresholds.

| Eccentricity (°) | Averaged absolute Mt | Estimated absolute Mt | Estimated radii |
|------------------|----------------------|----------------------|-----------------|
| 5°               | 23.8°                | 26.5°                | 2.5°            |
| 10°              | 37.9°                | 43.7°                | 4°              |
| 15°              | 60.7°                | 61.8°                | 5.7°            |
| 20°              | 93.5°                | 81.6°                | 7.5°            |
field may result in apparent preferences for certain visual functions in certain regions.

Table 2 compares averaged absolute modulation thresholds found in this study for SS 0.125–SS 0.875 with absolute modulation thresholds estimated from central thresholds using nCMF, and peripheral radii calculated based on these thresholds.

The optimal peripheral radii estimated from the estimated thresholds, correspond closely to the radii in SS 0.75 (Table 1). Interestingly, this spatial scale, which radii were 25% smaller than radii in the largest scale (SS 1), was characterised by small variability and consistent Weber fractions across the nasal visual field. Therefore, radii in SS 0.75 guarantee optimal conditions for peripheral shape discrimination where modulation amplitudes correspond to the peripheral modulation resolution and constitute 0.003 of the radius. If modulation amplitudes are smaller than the peripheral modulation resolution, Weber fractions increase (see SS 0.125–0.5). When modulation amplitudes constitute less than 0.003 of the radius they will be increased even beyond the peripheral modulation resolution until they are 0.003 of the radius (see SS 0.125). For example, the modulation resolution for a RF6 pattern displayed at 10° eccentricity is 37 seconds of arc, and it also needs to be 0.003 of the radius to be noticeable. Hence, an optimal stimulus presented at 10° would have a 3.4° radius. In the case of a larger stimulus, for example when r = 5°, a modulation of 37 seconds of arc would constitute only 0.002 of the radius. In such case it would not meet the requirement of 0.003 proportion, and the observer would not be able to identify the deformation. Thus, the modulation amplitude would have to be increased to be 0.003 of the radius and reached 54 seconds of arc as it happened in SS 1 at 10°. Fig. 8 shows that optimal conditions were achieved for stimuli in SS 0.75 and SS 0.875 (filled markers) where the Weber fractions were 0.003, and the absolute modulation thresholds corresponded closely to the peripheral modulation resolution.

4. Discussion

We examined shape discrimination for RF6 patterns with peripheral radii ranging from 0.4°–9.79° and their centres positioned at 5°, 10°, 15°, and 20° in the nasal visual field. In line with previous studies (Achtman et al., 2000; Feng et al., 2020a), thresholds for unscaled patterns were increasing with eccentricity. As for most visual functions (Strasburger et al., 2011), also in the case of the RF shape discrimination, the retinotopic organisation of the visual field is reflected in the psychophysical results. Decrease in peripheral performance is neutralised by spatial scaling with the cortical magnification factor (Feng et al., 2020b; Achtman et al., 2000). We investigated a wide range of stimuli sizes at each tested eccentricity, for which we found consistent absolute modulation thresholds. This non-dependence on the stimuli feature location may reflect integration processes over an area surrounding the tested eccentricity. Our data supports the notion that stimuli are processed in the same way with the same performance across all tested locations of the visual field when they are size-scaled appropriately to

![Fig. 8. A comparison of averaged (N = 5) Weber fractions (top left), absolute modulation thresholds (top right) and the difference between maximum and minimum curvature (bottom) plotted as a function of M-scaled stimulus size (radius in degrees) for four tested eccentricities (5°, 10°, 15° and 20°). Filled markers in top left graph show optimal conditions for a given eccentricity. The optimal condition is when the proportion between modulation and radius is 0.003 and modulation amplitude closely corresponds to modulation resolution at a given eccentricity. Maximum and minimum curvature was calculated as in Wilkinson et al. (1998).](image-url)
the eccentricity of presentation (Yu, Chaplin, & Rosa, 2015).

Akin to findings in other studies, using patterns with radial frequency between 5 to 8 cycles (Feng et al., 2020a; Schmidtmann & Kingdom, 2017; Wang et al., 2002; Wilkinson et al., 1998), Weber fractions for larger patterns (SS 0.75–SS 1) were around 0.003. This shows that the proportion between the modulation amplitude and the radius required to spot a deformation in low spatial frequency RF patterns is universal for a range of stimulus parameters, locations, and in concentric presentation (when the fixation point is in the centre of a stimulus) or eccentric presentations (when the stimulus is located to the side of the fixation point like in our experiment). For example, Weber fractions for eccentric presentations (when the stimulus is located to the side of the fixation point) or for a range of stimulus parameters, locations, and in concentric presentation were around 5 to 8 cycles (Feng et al., 2020a; Zolubak & Garcia-Suarez, 2017) were the same as Weber fractions found in our study for eccentrically displayed patterns with outer parts at the corresponding eccentricities (SS 0.75–SS 1).

However, Weber fractions in smaller spatial scales (0.125–0.5) were higher than 0.003, meaning that for smaller peripheral patterns, the proportion of 0.003 was not sufficient to discriminate RF patterns from circles. This is where the spatial properties of peripheral vision come into play. Testing a wider range of sizes than in previous studies (Achtman et al., 2000) and analysing changes in absolute modulation thresholds resulted in identifying peripheral modulation resolution limit for RF patterns up to 20 degrees in the visual field. The decrease in peripheral modulation resolution closely corresponds to the peripheral changes in the cortical magnification factor. For smaller spatial scales, the absolute modulation thresholds inferred from the 0.003 proportion would not meet this peripheral modulation resolution; hence, the modulation amplitudes needed to be increased until they reached it. For example, a modulation amplitude which is 0.003 of a 0.4° radius presented at 5° is 4.3 s of arc. Based on our measurements or the nCMF estimations, the modulation resolution at 5° is 24 s of arc (SEM = 3).

Thus, modulation of 0.003 of 0.4° radius is too small to be identified, and it will need to reach 24 s of arc, which will result in the Weber fraction elevated to 0.016 (SS 0.125). On the other hand, in SS 1 peripheral radii were overestimated and modulation amplitudes were increased until they were 0.003 of those long radii. Hence, in SS 1 the modulation amplitudes were higher than the modulation resolution at the tested eccentricities. It is worth mentioning that the modulation resolution for RF patterns cannot be explained by the minimal angle of resolution (MAR) (i.e. sampling limit of the retina) because the absolute modulation thresholds were within the hyperacuity range at all tested eccentricities. Peripheral resolution limit can affect RF shape discrimination when the spatial frequency of the contours is close or higher than this limit. At lower spatial frequencies there might be a modulation resolution limit at a higher level of the visual pathway, for example, related to more crowded modulation peaks in smaller scales.

Even though the modulation amplitude of 0.3% of a radius seems to be universal to discriminate RF patterns from circles, it is not exclusive and other properties of the stimuli, such as circular contour frequency (Feng et al., 2020a; Jeffrey et al., 2002), contrast (Feng et al., 2020a; Ivanov & Mullen, 2012; Wilkinson et al., 1998), and spatial frequency (Feng et al., 2020a; Baldwin, Meese, & Baker, 2012) need to be considered. In this study, we used a spatial frequency of 5 cyc/deg for SS 0.125–SS 0.25 and 1 cyc/deg for larger ones. These different spatial frequencies could have contributed to the higher Weber fractions and higher inter-subject variability in smaller spatial scales. Since the resolution for spatial frequencies decreases with eccentricity, stimuli with spatial frequency of 5 cyc/deg can be under-sampled at further eccentricities (15–20 degrees) (De Valois et al., 2002; Thibos, Cheney, & Walsh, 1987). Earlier studies suggest that lowering spatial frequency from 5 cyc/deg to 2.5 cyc/deg does not affect the peripheral fall in sensitivity (Achtman et al., 2000). However, in the Achtman et al. (2000) study, in eccentric presentation the averaged Weber fractions were around 0.02 for RF6 patterns similar in size to our patterns in SS 0.5 (where the averaged WF was around 0.004), and around 0.01 for patterns similar in size to SS 0.87 (with Weber fractions of 0.003). The only considerably different parameter in those compared cases was the spatial frequency that was much lower in our study. Small Weber fractions of 0.003 for RF6 presented concentrically were also found in studies, where low spatial frequencies of 0.45 cyc/deg (Feng et al., 2020a) and 0.625 and 1.25 cyc/deg (Achtman et al., 2000) were used. These varying findings could suggest that peripheral shape discrimination is SF dependent.

Scale invariance relates to the ability to encode a shape based on its proportion without reference to its exact size or retinal location (Ivanov & Mullen, 2012; Van Essen, Anderson, & Felleman, 1992). Our findings support scale invariance in eccentric presentation for high contrast RF6 patterns but only when the spatial frequency and absolute modulations are above the resolution limit. This explanation is in line with studies suggesting that shape discrimination is radius-invariant (Achtman et al., 2000; Wilkinson et al., 1998) as well as those showing dependence on the radius (Ivanov & Mullen, 2012; Mullen, Beaudot, & Ivanov, 2011; Mullen & Beaudot, 2002) because it demonstrates that size dependencies are noticeable when the modulation resolution at a given eccentricity is larger than 0.003 of the tested radius. When modulation amplitudes meet the peripheral resolution for RF shape discrimination and they are 0.003 of a radius, further increases of the radius size do not benefit the performance.

Besides SS 1, the absolute modulation thresholds within a given eccentricity of presentation were similar despite the most central parts of the stimuli falling at different eccentricities (Fig. 6). These findings may suggest that RF shape discrimination is not performed based on the local information provided by the part of the stimulus that is the closest to the fixation point, but reflect integration processes over a broader area. If performance was based on the local parts, absolute modulation thresholds would increase with decreasing spatial scale within a given eccentricity of presentation. These observations may support the view of global processing of RF patterns rather than local processing (Green, Dickinson, & Badcock, 2018, 2017; Kempgens, Loffler, & Orbach, 2013; Dickinson et al., 2012; Wilkinson et al., 1998; Jeffrey et al., 2002; Poirier & Wilson, 2006). However, in the light of contradictory evidence suggesting intermediate level of shape processing (Flynn & Jeffrey, 2019; Schmidtmann & Kingdom, 2017; Salmela, Henriksson, & Vanni, 2016; Schmidtmann, Gordon, Bennett, & Loffler, 2013; Schmidtmann, Kennedy, Orbach, & Loffler, 2012; Bell, Wilkinson, Wilson, Loffler, & Badcock, 2009) our findings should be treated only as a spur to further studies because our experiment was not designed to contribute to the ongoing debate over global contour integration versus local processing in shape discrimination tasks.

For patterns with the same radial frequency, the Weber fraction and radius determine their local curvature, which was suggested as a feature underpinning RF shape discrimination in various models where difference between maximum and minimum curvature underpins RF detection (Schmidtmann & Kingdom, 2017) or where maximum curvature information is used to encode a RF pattern by a global shape integration mechanism (Dickinson et al., 2012; Kempgens et al., 2013; Poirier & Wilson, 2006). We found that Max–Min curvature difference for larger spatial scales (SS 0.75–SS 1) plateaued out in the periphery (Fig. 8), which suggests that curvature was scale and location independent. However, the Max–Min curvature difference for smaller spatial scales was several times higher at corresponding eccentricities. These largely elevated Max–Min curvature differences for SS 0.125–SS 0.5 could indicate that curvature crest (elevation in contour created by a radial modulation) is a factor that limits the performance, i.e. absolute modulation resolution. This is in agreement with findings of increasing Max–Min curvature with increasing radial frequency of RF patterns (Schmidtmann & Kingdom, 2017) where, possibly, an absolute modulation amplitude and its proportion to radius remain constant, and the increasing number of radial modulations steepens the local curvature. This observation further demonstrates that RF shape discrimination in the periphery is limited by low-level factors.
Absolute modulation resolution decreases in the periphery in a close accordance with the ratio of peripheral to foveal cortical magnification for human V1. This suggests that RF shape discrimination is limited by cortical magnification in V1, but scale and location non-dependence for stimuli with supra-threshold modulations suggest curvature-based and integration mechanisms at higher stages of shape processing.

Two mechanisms involved in processing RF patterns in smaller and larger scales could be also suggested in the light of the circular contour frequency (CCF). Jeffrey et al. (2002) found that the number of cycles per degree of unmodulated contour length, called CCF, is an important factor in determining modulation thresholds of RF patterns. The authors showed that the absolute modulation thresholds were alike at a given CCF with no effect of radius or radial frequency (Jeffrey et al., 2002). In our study, radial frequency was constant (RF = 6), hence CCF changed with radius. It was higher in smaller spatial scales and lower in larger spatial scales for which the absolute modulation thresholds were found to be the same (beside SS1). However, it cannot be ruled out that the absolute modulation thresholds for two of the larger SS (0.75, 0.875) happened to be similar to thresholds in the smaller SS, and the small difference was not captured in the statistical analysis. Such interpretation is based on the higher absolute modulation thresholds observed in SS1, slightly elevated thresholds for the larger scales, and an observation that the function in Fig. 6 would correspond to a function of the absolute modulation thresholds and CCF. In a such case our data could be interpreted in terms of two processing mechanisms. First, it would be an integration mechanism for larger SS where Weber fractions are constant and absolute modulation thresholds increase with increasing SS. A second mechanism would be a thresholding mechanism for smaller SS where Weber fractions increase with decreasing SS, but absolute modulation thresholds remain consistent. This interpretation would bring a plausible explanation to an apparent paradox of constant Weber fractions and consistent absolute modulation thresholds in larger SS. To fully grasp these mechanisms in the periphery, stimuli same in size but different in CCF should be examined in future studies.

This paper aims to bring practical indications for the growing body of literature and applications of shape discrimination tasks in clinical populations (Vazquez, Harding, Heimann, Czanner, & Knox, 2018; Ku, Milling, Vazquez, & Knox, 2016; Vazquez & Knox, 2014; Wang et al., 2013; Liu et al., 2014), especially in peripheral vision. Firstly, we provide expected levels of peripheral sensitivity in healthy observers for low spatial frequency and high contrast stimuli of various spatial scales. We also demonstrate scale- and location-invariant performance for a range of sizes and eccentricities. This constant performance across periphery makes shape discrimination a useful task to monitor visual changes in conditions that heterogeneously affect the retina. Higher Weber fractions in certain parts of the retina would reflect deterioration in visual function rather than effects of eccentricity. Furthermore, the ability to estimate thresholds at different eccentricities provides an intra-individual level of comparisons for each patient where performance at healthy retina serves as a reference point for a given patient. This results in more precise monitoring of visual changes in different quadrants of the visual field and more adequate comparisons on an intra-individual level (healthy vs diseased retina) rather than referring to general norms. Larger spatial scales are suitable not only for these intra-individual comparisons, but also for inter-individual comparisons where age- and disease-specific norms can be established. In addition, we demonstrate that peripheral shape discrimination thresholds in the tested conditions are robust to small changes in size and location. These findings indicate that shape discrimination tasks with high contrast and low spatial frequency stimuli are promising tests for monitoring vision at conditions that heterogeneously affect the retina. Higher Weber fractions in certain parts of the retina would reflect deterioration in visual function rather than effects of eccentricity. Furthermore, the ability to estimate thresholds at different eccentricities provides an intra-individual level of comparisons for each patient where performance at healthy retina serves as a reference point for a given patient. This results in more precise monitoring of visual changes in different quadrants of the visual field and more adequate comparisons on an intra-individual level (healthy vs diseased retina) rather than referring to general norms. Larger spatial scales are suitable not only for these intra-individual comparisons, but also for inter-individual comparisons where age- and disease-specific norms can be established. In addition, we demonstrate that peripheral shape discrimination thresholds in the tested conditions are robust to small changes in size and location. These findings indicate that shape discrimination tasks with high contrast and low spatial frequency stimuli are promising tests for monitoring vision at home, where viewing distance and position are not strictly controlled.

Finally, to present peripheral stimuli in different quadrants of the visual field authors sometimes tend to spatially scale one of the dimensions of a central stimulus; for example, its radius or length (Achtman et al., 2000; Schmidtmann et al., 2015; Rousselet, Husk, Bennett, & Sekuler, 2005), which we also did in our study. This procedure may result in very large peripheral stimuli subtending a vast range of eccentricities especially when a central stimulus is well above threshold. To address this limitation when using scale-invariant stimuli, a pragmatic approach (Roedentink et al., 1978; Strasburger et al., 2011) should be used. A central absolute threshold should be measured, M-scaled, and used to estimate an optimal size of peripheral stimulus. The size of the peripheral stimulus should be estimated based on the constant proportion between stimulus dimensions, and the M-scaled central absolute thresholds. The M-scaling should involve a cortical magnification factor adequate for the tested principal half-meridian as listed in Rovamo and Virsu (1979). This is not a new approach, but rather a reminder to scale absolute central thresholds rather than a chosen dimension of a stimulus. For example, when M-scaling RF patterns, a central absolute modulation threshold should be scaled instead of a central radius. This way, peripheral shape discrimination can be tested in a more localised way, which is especially important when monitoring for non-homogeneous deterioration in visual function.

5. Conclusions

The results provide evidence that peripheral shape discrimination is limited by the spatial properties of the peripheral retina suggesting that it is constrained by low-level properties, such as eccentricity. However, once the peripheral absolute modulation resolution is reached, the discrimination of RF patterns from circles is based on the proportion between the modulation and radius. Our findings also suggest that SD task in eccentric presentation reflects integration of peripheral information over a range of eccentricities that relates to the intermediate and higher levels of processing RF patterns. Findings from this study can be used in designing RF shape discrimination tests for clinical conditions, which non-uniformly affected retina, such as age-related macular degeneration and glaucoma. For tests up to 20° of presentation, we recommend using low spatial frequency, high contrast stimuli with peripheral radii corresponding to values in SS 0.75–0.875 to achieve constant Weber fractions characterised by small variability, and peripheral stimuli not excessively enlarged.

CRediT authorship contribution statement

Anna Zolubak: Conceptualization, Data curation, Formal analysis, Methodology, Investigation, Project administration, Writing - review & editing. Luis Garcia-Suarez: Conceptualization, Funding acquisition, Software, Methodology, Resources, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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