Size scaling compensates for sensitivity loss produced by a simulated central scotoma in a shape-from-texture task

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Studies of eccentricity-dependent sensitivity loss typically require participants to maintain fixation while making judgments about stimuli presented at a range of sizes and eccentricities. However, training participants to fixate can prove difficult, and as stimulus size increases, they become poorly localized and may even encroach on the fovea. In the present experiment, we controlled eccentricity of stimulus presentation using a simulated central scotoma of variable size. Participants were asked to perform a 27-alternative forced-choice shape-from-texture task in the presence of a simulated scotoma, with stimulus size and scotoma radius as the independent variables. The resulting psychometric functions for each simulated scotoma were shifted versions of each other on a log size axis. Therefore, stimulus magnification was sufficient to equate sensitivity to shape from texture for all scotoma radii. Increasing scotoma radius also disrupts eye movements, producing increases in fixation frequency and duration, as well as saccade length.

Keywords: texture perception, macular degeneration, scotoma, size scaling, cortical magnification, peripheral vision, eye movements


Introduction

The ability to resolve fine details drops off quickly as stimuli of constant size are moved from fixation (the fovea) to greater eccentricities (distance from fixation in degrees visual angle). For example, it is generally impossible to report more than a few words distant from the current point of fixation. There are many sources of this eccentricity-dependent sensitivity loss; some are retinal, others are cortical, some are anatomical, and others are physiological. All such sources are a result of progressive undersampling, of one sort or another, at points away from fixation. However, it has frequently been reported that an appropriate eccentricity-dependent magnification (size scaling) can compensate for many if not most of these eccentricity-dependent sensitivity losses (Vakrou, Whitaker, McGraw, & McKeefry, 2005; Watson, 1987).

For most tasks, performance at some eccentricity ($E$) can be made equal to that observed at fixation by setting the size of the peripherally presented stimulus to a multiple ($F_E$) of the size ($S_0$) of the foveal stimulus:

$$ S_E = S_0 \cdot F_E. \quad (1) $$

Furthermore, it has long been observed that many spatial thresholds increase linearly with eccentricity (Weymouth, 1958) and hence

$$ F_E = 1 + E/E_2, \quad (2) $$

defines a linear function that specifies the magnification ($F_E$) at each eccentricity required to elicit performance equivalent to a foveal standard ($\text{Levi, Klein, & Aitsebaomo, 1985}$). The free parameter $E_2$ is so named because it indicates the eccentricity at which stimulus size must double to elicit equivalent-to-foveal performance. So, not only does magnification compensate for eccentricity-dependent sensitivity loss but also the required magnification is frequently a linear function of eccentricity.

The parameter $E_2$ can be used to characterize the eccentricity dependence of a particular task using assumption-free methods (e.g., Watson, 1987). If performance is measured at range of sizes and eccentricities, then the performance-vs.-size functions at each eccentricity will be shifted versions of each other if the only change with eccentricity is the local scale of the mechanisms engaged (Watson, 1987). If this is the case, then all performance-vs.-size functions can be collapsed onto a single curve by dividing stimulus size at each eccentricity
by the appropriate $F_E = 1 + E/E_2$. The value of $E_2$ providing the best fit to the data can be established using numerical methods. Once $E_2$ is known, one can specify the magnification needed at each eccentricity to match foveal performance. For a wide array of tasks, such as orientation discrimination (Makela, Whitaker, & Rovamo, 1993; Sally & Gurnsey, 2003, 2004, 2007; Sally, Poirier, & Gurnsey, 2005), symmetry detection (Saarinen, 1988; Sally & Gurnsey, 2001), vernier acuity (Whitaker, Rovamo, MacVeigh, & Mäkelä, 1992), and grating acuity (Rovamo & Vírsu, 1979; Rovamo, Vírsu, & Nasanen, 1978), stimulus magnification is sufficient to compensate for eccentricity-dependent sensitivity loss. [It is worth noting, however, that there are many tasks in which a single magnification factor fails to compensate for eccentricity-dependent sensitivity loss (Chung, Li, & Levi, 2007; Chung, Mansfield, & Legge, 1998; Latham & Whitaker, 1996; Melmoth, Kukkonen, Mäkelä, & Rovamo, 2000; Pelli, Palomares, & Majaj, 2004; Poirier & Gurnsey, 2002, 2005; Strasburger, Rentschler, & Harvey, 1994).]

Although the study of peripheral vision is of fundamental theoretical interest, it also has direct implications for clinical conditions such as age-related macular degeneration (AMD). Degeneration of the macula robs its victims of the central 10 to 20 degrees ($^\circ$) of the visual field (Cheung & Legge, 2005). The consequences of a central 2$^\circ$ blind spot (henceforth scotoma) can be appreciated by considering how many words on this page can be read when you place your thumb on some text and fixate it at arm’s length. Studying peripheral vision in normal observers may therefore lead to insight into the expected information processing abilities in individuals with AMD.

There are three obvious connections between studies of peripheral vision and the practical consequences of AMD. First, studies of peripheral vision should provide some guidance with respect to the sensitivities participants might be expected to show after loss of foveal vision. In other words, this research should help us answer the question: What are the information processing abilities of peripheral vision? Unfortunately, the methods employed may make this connection tenuous. Standard size scaling tasks vary stimulus size and eccentricity to characterize the eccentricity-dependent limits on peripheral vision. However, as stimuli increase in size they become progressively less well localized. For example, in a recent study (Sally & Gurnsey, 2007) the largest stimuli presented at 10$^\circ$ subtended 16$^\circ$, meaning that it extended from 2$^\circ$ to 18$^\circ$ from fixation. Consequently, mechanisms close to the fovea may have contributed to performance, thus breaking the link to visual pathologies such as AMD. Therefore, there are many aspects of AMD that are not well captured by standard tests of peripheral sensitivity. In this paper, we examine peripheral sensitivity using simulated scotomas. To do so, we monitor participants’ eye fixations and update the monitor in real time so that the foveated region is obscured, i.e., a simulated scotoma is formed. Because the size of the simulated scotoma can be varied, this provides an alternative way to control eccentricity of stimulus presentation. Although a number of simulated scotomas are possible, in the present paper, we use a uniform, circular scotoma that occludes the fixated image region.

The second obvious connection between studies of peripheral vision and AMD concerns the limits of peripheral vision in processing the kinds of stimuli encountered in daily life. Past research on peripheral vision has addressed questions about orientation discrimination (Makela et al., 1993), vernier acuity (Levi et al., 1985), letter discrimination (Toet & Levi, 1992), contrast sensitivity (Rovamo et al., 1978), curvature detection (Whitaker, Latham, Makela, & Rovamo, 1993), and symmetry perception (Saarinen, 1988; Sally & Gurnsey, 2001) to name a few. Of course important questions can be answered using such 2D patterns, but these stimuli are a long way from those actually encountered in daily life, which are more likely the concern of those who have lost central vision. Several recent studies have turned from using simple 2D stimuli (of the sort just described) to behaviorally relevant stimuli that depict 3D objects. These studies have addressed face discrimination (Melmoth et al., 2000), perception of biological motion (Gurnsey, Roddy, Ouhnana, & Troje, 2008; Gurnsey, Roddy, & Troje, 2010; Gurnsey & Troje, 2010; Ikeda, Blake, & Watanabe, 2005), and the perception of structure from motion ($S/M$) and structure from texture ($S/T$; Gurnsey, Poirier, Bluet, & Leibov, 2006) across the visual field. The conclusion from this developing body of research is that size scaling can compensate for eccentricity-dependent sensitivity loss in these tasks.

The third connection between studies of peripheral vision and AMD concerns eye movements. Within normal vision, the eyes will move to points of interest in the visual field via saccades, in order to fix the points of interest onto the macula, which contains the fovea. When the macula is damaged, as in AMD, patients frequently learn to use their remaining peripheral vision by developing a pseudo-fovea, commonly referred to as a preferred retinal location (PRL; Fletcher & Schuchard, 1997). The PRL can act as a new fovea for many tasks (see Cheung & Legge, 2005 for a review) and is usually located on the boundary between the macula and the periphery where the highest density of undamaged photoreceptors remains. Of course, in comparison to the healthy fovea, the PRL is located in a region of the retina that is less dense in photoreceptors and accordingly there is a greater convergence of receptors, resulting in larger receptive fields and lower resolution.

Because portions of the stimulus being viewed can be obscured by the scotoma, especially at the larger scotoma radii, eye movements are needed to perform our task. However, it is unclear how changes in scotoma and image size would change the associated eye movement characteristics, and how these changes may reflect strategies to overcome the scotoma.
known to increase as the discriminability of the target from the background decreases (Hooge & Erkelens, 1999; Jacobs & O’Regan, 1987). As one may expect then, eye movements have been shown to be different within a search task in the presence of a scotoma, with increased fixation frequency and duration, and increase in the amplitude (length) of saccades with increased scotoma radius (Cornelissen, Bruin, & Kooijman, 2005; McMahon, Hansen, & Viana, 1991). From these findings, one would expect an increase in both the frequency of eye movement and duration of fixations in the presence of large simulated scotomas in the present task.

The present paper addresses two questions: (i) Can stimulus magnification compensate for sensitivity loss caused by a simulated central scotoma? and (ii) How do eye movements change in the presence of simulated scotomas? The stimuli are simulated 3D surfaces derived from the early work of Dosher, Landy, and Sperling (1989) and Landy, Dosher, Sperling, and Perkins (1991) and used more recently by Gurnsey et al. (2006). Figure 1A provides an example of such a stimulus. There are three locations on the simulated surface, each of which may contain a topographical feature: a hill, a valley, or a flat plane. The participant’s task is to report the features in the three locations. The stimuli provide a non-trivial challenge to the visual system but also have sufficient structure to make the analysis of eye movements tractable. Furthermore, very similar stimuli have been used before in a standard size scaling task and this allows us to compare peripheral sensitivity when eccentricity is controlled in the standard way (participant fixates steadily while a stimulus is presented to the periphery) and with a simulated scotoma.

**Methods**

**Participants**

The participants included one author (AJ) and four volunteers recruited from the vision laboratory at Concordia. Ages ranged from 21 to 45; three of the five participants were women. All participants reported normal or corrected-to-normal vision and wore the appropriate distance correction during testing. All participants were experienced psychophysics observers, with one having extensive experience in studies of peripheral vision. All participants were treated according to Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans (Medical Research Council of Canada, 2003).

**Apparatus**

Stimuli were presented and data collected using a Dell Quad-Core PC running Microsoft Windows XP. Participants viewed stimuli on a linearized video monitor (Viewsonic 19” CRT, 1024 x 768 pixel resolution, 100-Hz refresh rate). A chin rest was used to stabilize head position.

Eye position was acquired non-invasively using a video-based eye movement monitor (EyeLink 1000/2K, SR Research, Ottawa, Ontario). The EyeLink system recorded binocular eye position with a sampling resolution of 1000 Hz. Average delays from eye movement to position availability is 2.4 ms with heuristic filtering enabled and 1.35 ms with filtering disabled (manufacturer’s specifications for Eyelink 1000 with 2000 Hz upgrade). Consequently, to allow for the fastest repositioning of the artificial scotoma, the experiment was conducted with heuristic filtering disabled, and eye movement data were analyzed post-hoc. The stimulus computer was connected via a high-speed Ethernet connection to the EyeLink system. The 1.35-ms delay means that 86.5% of the time the screen will be redrawn 1.35 to 10 ms after the eye lands at a specific location and 13.5% of the time it will redraw 10 to 11.35 ms after the eye lands at specific location. Thus, on average the screen will be updated 6.35 ms after the beginning of a fixation. Although some information may be available during these brief intervals, our results show that in most cases very little use can be made of it.

**Stimuli**

Each stimulus consisted of three notional locations where there could appear hills, valleys, and plains (i.e., flat regions indistinguishable from the background of the stimulus). Figure 1A provides a sample stimulus with one valley and two hills. The three notional locations and three
possible features at each location make a total set of \(3^3 = 27\) different stimuli.

Stimuli were created by texture mapping a noise array onto a surface having 1 of the 27 possible topographies. The noise texture comprised 32 by 32 checks. Each check was 32 × 32 pixels having a uniform gray level drawn at random from a flat distribution. The noise image was then lightly blurred with a Gaussian filter having a standard deviation (\(\sigma\)) = 4 pixels. Each of the 27 surfaces was also defined as a 1024 × 1024 array. Hills, valleys, and planes were placed 241 pixels from the center of the array and separated by 120° on a notional circle. Hills and valleys were isotropic Gaussians with \(\sigma = 85.33\) pixels. The noise array was texture-mapped to the surface and projected orthographically to the image plane using the mesh function in Matlab. The camera angle had azimuth of \(-37.5°\) and an elevation of 25°. This means that the surface was rotated about the z-axis by 37.5° counterclockwise and then projected to a camera that was elevated 25° above the xy plane. The stimulus shown in Figure 1 provides an example of one such stimulus.

The largest (full size) image was contained within a 1024 by 768 pixel image. Six smaller versions of the full size image were created by progressively minifying the original image by a factor of \(\sqrt{2}\). This made for 7 stimuli whose relative sizes varied from 1 to 1/8 in equal logarithmic steps. All stimuli were created offline using Matlab (The Mathwork, Natick, MA). All aspects of stimulus presentation and data collection were under the control of Matlab and the Psychophysics and EyeLink Toolbox extensions (Brainard, 1997; Cornelissen, Peters, & Palmer, 2002; Pelli, 1997).

A gaze-contingent artificial scotoma was a circle set to mean gray luminance of the computer monitor with the edges blended with the underlying stimulus via a cosine taper (see Figure 1B). Position of the center of the circle was continuously modified on every screen refresh. Circle radius was varied between 0 (no scotoma), 0.5, 1, 2, 4, and 8 degrees of visual angle. The radius of the scotoma determined the distance from fixation of the nearest part of the stimulus.

The stimuli used here are structurally similar to those used by Gurnsey et al. (2006). However, those used by Gurnsey et al. had higher amplitude hills and valleys and the texture mapped onto the surface comprised a regular array of black disks on a white background. These two factors permitted participants to maintain high accuracy at very small sizes, which were achieved with large viewing distances. The eye tracker, essential to this project, cannot be used at the distances used by Gurnsey et al. Therefore, the present stimulus set was created to ensure that performance ranged from chance to 100% correct within the range of sizes (i.e., viewing distances) possible with the present equipment. In other words, the lower amplitude hills and valleys and the more complex grayscale textures used here limited the range of sizes within which above-chance performance was possible.

### Procedure

For most stimulus sizes, blocks consisted of 189 trials, i.e., 27 stimuli by 7 scotoma radii. For each scotoma radius, participants were presented with each of the 27 stimuli in a random order. Following the presentation of the stimulus, the participant entered a code to identify the stimulus. A valley was coded as a 1, a plain as a 2, and a hill as a 3. The arrangement of the three locations formed an inverted triangle (see Figures 1A and 1B), and participants reported the top two locations (left to right) followed by the bottom location. The appropriate response for the stimulus shown in Figure 1A would be [3,3,1] and [1,3,3] for Figure 1B. Participants were told to be as accurate as possible, and stimuli were presented until participants responded to all three positions.

The order of presentation of the independent variables (stimulus size and scotoma radius) was randomized between blocks and between participants. Each participant performed three replications of each block of trials, unless performance was on the ceiling or floor in the first block of trials, in which cases only 27 trials per condition were done. This means that for all combinations of stimulus size and scotoma radius participants provided between 27 and 81 responses. Before beginning the experiment, each participant was permitted sufficient practice to become familiar with the task and response coding.

For all scotoma radii except 0 (no scotoma), participants were seated 60 cm from the computer monitor. From this distance, the stimuli subtended 29.54, 21.84, 15.82, 11.33, 8.06, 5.72, and 4.05 degrees visual angle. For the no scotoma condition, sizes 29.54, 21.84, 15.82, and 11.33 were tested at 60 cm, 5.3953 at 90 cm, and 4.05 at 120 cm. In the latter three cases, the quarter-sized image (1024/4 = 256 pixels on a side) was used as a stimulus.

All stimuli were located at the center of the screen. To calibrate the eye tracker, a nine-point calibration routine was performed at the beginning of each block of trials, with a second 9-point calibration grid used to calculate the accuracy of the calibration. Calibration was repeated if the average spatial accuracy of all 9 points was worse than 0.5°. When averaged over all participants, the mean gaze error was 25 arcmin, with 19 arcmin at 0° eccentricity, and 27 arcmin at the calibration positions closest to the corner of the screen. No participants reported that the artificial scotoma appeared at a location different from their current fixation, and none reported any noticeable temporal delay between eye movement and the corresponding change in scotoma position.

In addition to the calibration, before the start of each trial, a single drift-correct target was presented at the center of the screen to revalidate the calibration and to provide a common starting location for the task. This required participants to fixate a target presented at the center of the screen and press a keyboard button. If spatial accuracy drifted by more than 0.5° from the initial calibration, then the participant repeated the calibration.
procedure before proceeding with trial. If the accuracy was below 0.5%, then the measured angle was used to perform an offset correction in the subsequent trial. The average offset correction over all participants and trials was 4 arcmin.

**Results**

**Psychophysical data**

The psychophysical results are summarized in Figure 2. The first five panels show the results of the five participants and the last (bottom right) shows the results averaged over all 5 observers. In all cases, accuracy increases with stimulus size and reaches asymptote—or nearly so—at 100% correct. The curves at each eccentricity are essentially shifted versions of each other; as the size of the scotoma increases, the size vs. accuracy curves shift to the right, although the curves at 0, 0.5, and 1° show very little shift. The overall similarity of the curves suggests that dividing each actual size by an appropriate magnification factor for each scotoma radius should shift each curve leftward onto the no scotoma curve. We assumed that each size vs. accuracy curve is well described by Gaussian integral in which proportion correct is a function of log(size). To collapse each scotoma curve onto the no scotoma curve requires dividing actual stimulus size, for a specific scotoma radius, by $F_R$. Assuming that the magnification needed is a linear function of scotoma radius ($R$), the function $F_R = 1 + R/R_2$ expresses the necessary scaling required for each scotoma radius. (Note that $R_2$ plays the same role in the present analysis that $E_2$ plays in the studies described in the Introduction section. $E_2$ refers to the eccentricity at which stimulus size must double to maintain equivalent to foveal performance and $R_2$ refers to the scotoma radius at which stimulus size must double to maintain equivalent to foveal performance.) This leaves the two parameters of the Gaussian integral (i.e., $\mu$ and $\sigma$) and $R_2$ to be determined. This was done using the `fminsearch` function in Matlab to minimize the sum of squared deviations from the predicted curve

$$pc = a + (1 - a)G(\log(x/F_R), \mu, \sigma),$$

where $pc$ is proportion correct, $a$ is the chance performance (in this case 1/27), $x$ is stimulus size, $F_R = 1 + R/R_2$, $\mu$ is the mean of the Gaussian, and $\sigma$ is its standard deviation.

The resulting fits are shown in Figure 3, along with the $R_2$ value providing the best fit and the proportion of variance ($r^2$) explained by the fit. In general, the fits were very good, explaining 94% of the variability in the data on average. The average $R_2$ value was 1.701 ($N = 5$, estimated $SEM = 0.2874$, 95% CI = 0.962 to 2.44). Therefore, size scaling eliminates most scotoma-dependent variability from the data. Of course, scotoma radius ($R$) is a stand-in for eccentricity because the radius of the scotoma determines the eccentricity of the non-occluded part of the stimulus.

Figure 2. (A–E) For each participant, the proportion correct responses as a function of stimulus size (conveyed on the x-axis) and scotoma radius (individual lines) are shown; the legend shows the scotoma radius. (F) The same as (A)–(E) but for the averaged data of the five participants.
It is interesting to note that Gurnsey et al. (2006) found $E_2 = 1.52$ ($N = 6$, estimated $SEM = 0.53$, 95% CI = 0.79 to 2.25) eliminated most eccentricity-dependent variability in a similar shape-from-texture task. Therefore, whether eccentricity is controlled by a simulated scotoma or by fixating away from the stimulus, very similar effects of eccentricity are seen.

Eye movement data

Although binocular data were recorded, only the right eye data were used for the purpose of this paper. Blink periods were identified using the SR Research heuristic filtering algorithm (Stampe, 1993), and the data removed. An additional 200 ms before and after each blink event were also removed to eliminate the initial and final parts of the blink, during which the pupil is partially occluded. In addition to using the SR Research algorithm, we removed portions of the data corresponding to very fast decreases and increases in pupil area (20 units per sample), plus the 200 ms before and after. Others have identified such periods as the consequences of partial blinks that do not fully occlude the pupil and are not detected by the SR Research algorithm (Martinez-Conde, 2006; Martinez-Conde, Macknik, Troncoso, & Dyar, 2006). After blink and partial-blink data cleanup, the remaining eye movement data were analyzed to detect saccades and fixations using the SR Research saccade detection algorithm: saccades were identified by changes in eye position in excess of 0.1°, with a minimum velocity of 30° s$^{-1}$ maintained for at least 4 ms. Fixations were defined as a period of no movement for a minimum duration of 20 ms. The initial fixation in each trial was defined as the fixation following the stimulus onset; thus the fixation from the pretrial drift correction was not included in the analysis. Once fixations and saccades were defined, the following eye movement statistics were calculated: number of fixations per trial, average fixation duration, and average amplitude of saccade. Maps of the fixation position and frequency at each stimulus and eccentricity size were produced using the SR Research data viewer.

Figure 4 presents the results for the three eye movement measures that we investigated: the first row shows the number of fixations, the second row shows fixation duration, and the third row shows saccade amplitude. In all cases, the x-axis represents stimulus size. Moving from left to right shows results for different scotoma radii (i.e., 0 to 8°; see insets in the top row). Within each panel, the average value of the dependent variable is plotted as a function of stimulus size for the condition with 0 features (i.e., no hills or valleys; blue dots), 1 feature (green dots), 2 features (red dots), 3 features (cyan dots), and the average value over all 27 stimuli (yellow dots).

It is extremely interesting to note that the values of the three dependent variable do not generally depend on the number of features in the stimulus. In most cases, the yellow dots (average values) fall on top of the remaining dots. The exception is the condition in which there were no features in the display (dark blue dots); in this case,
the response would be [2, 2, 2]. There is only one stimulus in the category so the data tend to be noisier than the other three categories; there are 6 stimuli in the one-feature category, 12 in the two-feature category, and 8 in the three-feature category. Therefore, the data are less noisy when they represent the average of these larger categories.

The number-of-fixations data were submitted to a 7 (stimulus sizes) by 6 (scotoma radii) within-subjects ANOVA conducted using SPSS (ver. 15); this and subsequent analyses collapsed across the “number of features.” In this and all subsequent analyses, we report partial eta squared ($\eta_p^2$) as an effect size measure,$^1$ and the reported p-values correspond to those obtained following the Greenhouse–Geisser correction for violations of sphericity (Greenhouse & Geisser, 1959). There were relatively large effect sizes for the main effect of scotoma radius, $\eta_p^2 = 0.567$, $F(5,20) = 5.245$, $p = 0.055$, and the interaction of stimulus sizes and scotoma radius, $\eta_p^2 = 0.504$, $F(30,120) = 4.06$, $p = 0.029$, but the effect size for the main effect of stimulus size was small, $\eta_p^2 = 0.106$, $F(6,24) = 0.474$, $p = 0.622$. It is the interaction between stimulus sizes and scotoma radius that is most interesting. For the two “smallest” scotomas (no scotoma and scotomas of radius 0.5°), the number of fixations is relatively independent of stimulus size. As scotoma radius increases to 1 and 2°, the number of fixations increases at small stimulus sizes but decrease as stimulus size increases. In other words, when the stimulus is small relative to the scotoma, participants make more fixations, but increases in stimulus size compensate for the loss of central vision, and consequently, fewer fixations are made. For scotomas of radius 4, the number of fixations is essentially independent of stimulus sizes, whereas for scotomas of radius 8, the number of fixations is low at small sizes and increases as stimulus sizes increase. For the 8° scotoma, very few fixations are made for the smallest stimuli, suggesting that participants simply give up because the stimuli are too small to resolve in the presence of a large central scotoma. However, more fixations are made for larger stimuli, suggesting that as stimulus size increases participants can extract usable information with peripheral vision and devote more time attempting to identify the stimulus.

The fixation durations were also submitted to a 7 (stimulus sizes) by 6 (scotoma radii) within-subjects ANOVA. There were small effect sizes for the main effect of scotoma radius, $\eta_p^2 = 0.132$, $F(5,20) = 0.61$, $p = 0.531$, and the interaction of stimulus sizes and scotoma radius, $\eta_p^2 = 0.204$, $F(30,120) = 1.025$, $p = 0.399$, and the effect size for the main effect of stimulus size was modest, $\eta_p^2 = 0.422$, $F(6,24) = 2.926$, $p = 0.155$. As shown in the second row of Figure 4, there is a modest decrease in average

![Figure 4](https://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/933485/ on 11/20/2018)
fixation duration with image size within each panel (representing different scotoma radii). Consistent with previous studies (Hooge & Erkelens, 1999; Jacobs & O’Regan, 1987) the more challenging (i.e., smaller) stimuli are, the longer participants will maintain fixation on a part of it. This is only partially true, however, because otherwise we would expect a larger effect of scotoma radius. Nevertheless, fixation duration seems to be largely determined by stimulus size; smaller stimuli tend to be fixated longer. It is interesting to note that fixation duration increases at small stimulus sizes between scotoma radii of 0 to 0.5. This may explain the similarity in the size-vs.-accuracy curves for these two conditions. Finally, saccade amplitudes were submitted to a 7 (stimulus sizes) by 6 (scotoma radii) within-subjects ANOVA. There were large effect sizes for the main effects of scotoma radius, $\eta^2_p = 0.645$, $F(5,20) = 7.256, p = 0.047$, and stimulus size, $\eta^2_p = 0.647$, $F(6,24) = 7.316, p = 0.033$, and the effect size for the interaction of scotoma radius and stimulus size was modest, $\eta^2_p = 0.293$, $F(30,120) = 1.654, p = 0.245$. As shown in the third row of Figure 4, saccade amplitude increased with stimulus size for each scotoma radius and there was a general increase in saccade amplitude across scotoma radii.

Although conventional characterizations of eye movements (e.g., fixation duration and number of fixations) are informative, they provide an incomplete picture of the strategies used to perform a task. This picture can be expanded by examining the spatial distribution of fixations. Maps of such distributions (i.e., fixation maps) were created by adding a 2D Gaussian blob with standard deviation ($\sigma = 0.5^\circ$) at the location of each fixation, combining the fixations of all participants. The summed values at frequently fixated regions will be larger than those at infrequently fixated regions. Intensity in the these maps range from red, indicating the highest frequency of fixation, to green, representing regions of few fixations. These color-coded fixation maps are superimposed on a sample stimulus in Figure 5; this stimulus has fixed size (21.84 degrees of visual angle) for this illustration. Each row depicts a different scotoma radius and each column corresponds to the number of features in the display. The results from the $0^\circ$ (no scotoma) condition (first row) show that participants distribute their fixations over the image in a manner independent of the number of features in the display. Furthermore, for scotoma radii of 0 to $2^\circ$ the fixations seem to be contained within roughly the same area. However, for scotoma radii of 4 and $8^\circ$ (last two rows) fixations extend beyond the confines of the stimulus. Of course, in these cases participants are forced to fixate away from a feature in order to identify it because of the scotoma. It is extremely interesting to note that the

![Figure 5](https://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/933485/) Spatial map of fixation frequency of all participants viewing a large stimulus (21.84 degrees of visual angle) with different sizes of scotoma. Red indicates most frequent fixation positions.
distribution of fixations expands mostly above the stimulus and to the sides. Clearly, participants found it more informative and/or more natural to have the stimulus fall in the lower visual field.

Figure 6 shows that the same pattern of results is also observed at different sizes of stimulus. Each row shows a different scotoma radius and each column shows stimuli of different sizes (relative image size of 1, 0.5, 0.25). When a scotoma less than 2° is present, the reduction of stimulus size does not change the spatial distribution of fixations. However, with a scotoma of 4° or 8°, there is increased variation in the spatial distribution of fixations, with most participants choosing to fixate above the stimulus.

To quantify the change in fixation distribution away from the center of the screen, the horizontal and vertical fixation positions were submitted to a 7 (stimulus sizes) by 6 (scotoma radii) within-subjects ANOVA. For the change in the average horizontal eye position (x-axis), there was a large effect size for the main effects of stimulus size, $\eta_p^2 = 0.651$, $F(6,24) = 7.476$, $p < 0.01$. As the image size increases, then participants move their eyes away from the center of the stimuli, and more toward the left of the stimulus (Figure 6).

For the changes in the average vertical eye position (y-axis), there were large effect sizes for the main effects of stimulus size, $\eta_p^2 = 0.823$, $F(5,20) = 18.587$, $p < 0.01$, and scotoma radius, $\eta_p^2 = 0.507$, $F(6,24) = 4.117$, $p < 0.1$, and a moderate effect size for the interaction of scotoma radius and stimulus size, $\eta_p^2 = 0.321$, $F(30,120) = 1.978$, $p = 0.199$. As shown in Figure 6, as the stimuli become more difficult to perceive, either due the increase in scotoma radii or decrease in image size, then the participants tend to fixate on the top of the stimulus.

Although the above analysis shows the average fixation location, it does not give a measure of how the stimulus and scotoma radius may influence the dispersion of the eye movements. As Figure 6 shows, a consequence of increasing scotoma radius is to increase the dispersion of fixations. Changes in horizontal and vertical fixation positions can be combined in a single score that describes for scotoma radius, $\eta_p^2 = 0.37$, $F(5,20) = 2.347$, $p = 0.176$, and the interaction of scotoma radius and stimulus size, $\eta_p^2 = 0.331$, $F(30,120) = 1.978$, $p = 0.199$. As seen in the first column of Figure 6 (relative image size = 1), as the scotoma radius increases then the average location fixated moves to the left of the stimulus.

![Figure 6](https://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/933485/)
the dispersion of fixations from the average point of fixation during the trial using the following equation:

\[ d = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left( x_i - \bar{x} \right)^2 + \left( y_i - \bar{y} \right)^2}, \]

where \( \bar{x} \) and \( \bar{y} \) are the mean \( x \) and \( y \) positions during a trial.

The value of \( d \) was measured on each trial for each participant and these values were then averaged for each participant, thus providing a measure of fixation dispersion for each participant for each scotoma radius and image size. These measures of dispersion were submitted to a 7 (stimulus sizes) by 6 (scotoma radii) within-subjects ANOVA. There were very large effect sizes for the main effects of stimulus size, \( \eta^2_p = 0.874, F(6,24) = 27.72, p < 0.001 \), and scotoma radius, \( \eta^2_p = 0.702, F(5,20) = 9.44, p < 0.001 \), but the effect size for the interaction of scotoma radius and stimulus size was weak, \( \eta^2_p = 0.109, F(30,120) = 0.49, p = 0.606 \). Generally, as scotoma radii and image size increased, there was a corresponding increase in the dispersion of fixations.

Although there were significant effects of image and scotoma radius, an examination of the dispersion data suggests individual differences within the 5 participants; in particular, participant GR’s data differ from those of the other 4 participants. Figure 7A shows the average dispersion data, as a function of stimulus size and scotoma radius, for all participants except GR (i.e., AJ, P1–P3). For small scotomas, the mean dispersion increased with stimulus size. However, as scotoma radius increases, there is an increase in dispersion, first at the smallest sizes and then across all sizes. Figure 7B shows the data for GR; these are clearly very different from the average of the remaining participants.

Figure 2 shows that participants produced very similar psychophysical results across image and scotoma sizes. Figure 7 shows that participants may differ quite a bit with respect to eye movements while eliciting similar performance. Figure 8 illustrates some of these differences in spatial terms. Each row of Figure 8 corresponds to a different stimulus size and each column corresponds to a subject. Each panel is a fixation map showing the distribution of fixations with a scotoma of 8° radius. When the image is large (last row), participants’ eye movements tend to be rather similarly distributed along the horizontal meridian. The most frequently fixated regions are offset from the locations of target features (red spots). However, as image size decreases, quite different strategies are revealed. AJ tends to fixate up and to the left of center, GR and P2 tend to fixate the center of the display (as though recognizing that the effect of the scotoma cannot be overcome with eye movements), P1 distributes eye movements along the horizontal meridian for all stimulus sizes, and those of P3 are much more widely distributed.

General discussion

The present study asked if size scaling would be sufficient to equate identification of shape from texture in the presence of simulated central scotomas having radii of 0 to 8°. The answer is clearly yes. We computed the scotoma radius (\( R_2 \)) at which stimulus size must double to match performance with no central scotoma. The mean \( R_2 \) value was 1.701.

A major motivation for the present study was to compare performance in the “scotoma task” with standard methods of assessing peripheral sensitivity. The radius of a circular central scotoma places a limit on the part of the peripheral retina that can contribute to the participants’ decisions. This limiting eccentricity can be treated as an analog of the nominal eccentricity of a stimulus presented in the periphery while a participant maintains central
fixation. The shape-from-texture task used here is similar in many respects to that used by Gurnsey et al. (2006). However, in that study, stimuli were presented for 350 ms in the right visual field. In the present study, participants could view the stimulus for up to 10 s using any part of the available visual field. Despite these differences in methodology, both studies reveal similar eccentricity-dependent sensitivity loss, characterized in the current study by a mean $R^2 = 1.7$ and in Gurnsey et al. by a mean $E^2 = 1.52$.

We noted earlier that the accuracy-vs.-stimulus-size curves for 0 to 1° scotomas are very similar. The same is true in the study by Gurnsey et al. (2006), which employed a standard peripheral vision method; participants fixated while the stimulus was presented at various eccentricities. In both cases, the same two possibilities exist: it may be that there is relatively little difference in performance across this range of eccentricities or there are failures of the scotoma (present study) or steady fixation (Gurnsey et al., 2006) to prevent foveal inspection of the stimulus. If the former is true, this implies that there is a modest non-linearity in the eccentricity-dependent resolution gradient. This possible non-linearity would be a challenge to quantify because accuracy shows a relatively gradual dependence on stimulus size. An $R^2$ of 1.7 suggests that size thresholds (sizes eliciting 64% correct in a 27 AFC task) should change by only about 60% for scotomas (or eccentricities) in the range 0 to 1°. However, this does remain a point for further investigation.

One of the interesting differences between the present study and that of Gurnsey et al. (2006) is the time available to identify the stimulus. In Gurnsey et al.’s study, stimuli were presented for about 350 ms, whereas in the present study, participants had up to 10 s to provide a response. However, as can be inferred from Figure 4, responses were typically provided within 2 to 4 s. Although the range of inspection times favors the present study, size thresholds (sizes eliciting 64% correct in a 27 AFC task) at fixation were much smaller in Gurnsey et al.’s study than in the present study. This difference is not unexpected because, as noted in the Methods section, the stimuli in the present study were designed to cover chance to perfect performance over a smaller range. Because the rate at which thresholds change with eccentricity in Gurnsey et al.’s study is about the same as the rate at which thresholds change with scotoma radius in the present study,
As noted in the Introduction section, a single magnification factor sometimes fails to eliminate eccentricity-dependent variation from a data set. For example, it is not uncommon for stimulus magnification to fail to equate peak sensitivity across the visual field (Chung et al., 1998; Melmoth et al., 2000; Strasburger et al., 1994). In these cases and others, two (or more) aspects of the stimulus must be scaled with eccentricity (Latham & Whitaker, 1996; Poirier & Gurnsey, 2002, 2005) in order to achieve equivalent-to-foveal performance. Figure 2 shows that ceiling level accuracy is achieved for all scotoma radii except, in some cases, for the 8° scotoma. It remains to be seen if further magnification would elicit ceiling level performance. Of course, reaching ceiling is not the same as matching sensitivity so it is not obvious that the present paradigm is sufficient to reveal a need for multiple scaling factors. The stimuli in the present experiment could be modified to address this question. Rather than fixing the amplitude of the hills and valleys they could be varied and threshold amplitude determined for each stimulus size and scotoma radius.

There has been a great deal of interest in crowding recently, and crowding is a classic example of the need for multiple magnification factors to compensate for eccentricity-dependent sensitivity loss. In this case, interference zones increase with eccentricity much faster than do the sizes of the mechanisms that encode the targets (Latham & Whitaker, 1996). In fact, the rapid increase in interference (crowding) with eccentricity explains why simple stimulus magnification is insufficient to equate reading rate (Chung et al., 1998) across the visual field. Such crowding effects have been well documented for tasks involving 2D stimuli (Latham & Whitaker, 1996; Pelli et al., 2004; Strasburger et al., 1994; Toet & Levi, 1992). It would be extremely interesting to determine whether or to what degree crowding principles apply to stimuli that depict 3D objects or structures, such as those used in the present experiment.

The use of simulated scotomas to remove central vision allows participants to choose the retinal location that they find most effective to perform the task. However, it was unclear at the outset how changes in scotoma and image size would change overt eye movements. Our participants behave to some extent like AMD patients with naturally occurring scotomas. Our participants tended to direct fixation to the left of the stimulus as scotoma size increased. Similarly, AMD patients tend to fixate the beginnings of words (Nilsson, Frennesson, & Nilsson, 2003), often to their disadvantage. Therefore, there may be a general disposition to fixate to the left of objects. On the other hand, we observe that as scotoma radius increases fixations tend to be directed above the stimulus, thus placing the stimulus on the lower visual field (see Figures 5 and 6). This contrasts with older AMD patients whose tendency to fixate left of—but not above—target words makes for a poor match to the requirements of reading. Nilsson et al. (2003) showed that when trained to place text below (or sometimes above) the scotoma reading rate improved substantially.

It seems that our participants adopted the fixate-above-the-stimulus strategy spontaneously. However, it is not clear whether the patients of Nilsson et al. would have had a leftward bias for the shape discrimination task that we used. It has been suggested that individuals may have several PRLs (Crossland, Culham, & Rubin, 2004), each serving a different function. It is also worth noting that younger patients with maculopathy (Stargardt’s disease) are more likely than older patients to develop a PRL that places the target above the scotoma (i.e., in the lower visual field). Therefore, this age difference may be reflected in the fixation strategies adopted by our participants.

The strategy of placing targets in the lower visual field may reflect how characteristics of the natural world shape the structure of the visual system. In the natural world, the lower visual field is more likely to contain features that must be navigated (trees, rocks), in comparison to the upper visual field (sky, clouds). Consequently, it would be advantageous that a feature detecting PRL be located above the scotoma. Furthermore, there are reports that the lower visual field is more sensitive than the upper visual field in a number of detection and discrimination tasks (Carrasco, Talgar, & Cameron, 2001; McAnany & Levine, 2007; Talgar & Carrasco, 2002), although in the absence of a scotoma sensitivity is greatest along the horizontal meridian (Carrasco et al., 2001). Thus, these simple differences in sensitivity may explain why participants choose not to fixate the lower part of the stimulus.

In the current study, we observe that as the size of the simulated scotoma increases there is an increase in the frequency of fixations and an increase in the amplitude (i.e., length) of saccades (see Figure 4). These results—obtained in a shape-from-texture task—are in agreement with other studies investigating how a simulated scotoma affects eye movements. Using a search task, Cornelissen et al. reported that the frequency of fixations required to find a target increased as they increased the size of a central artificial scotoma (Cornelissen et al., 2005). Others have also reported a similar effect of an artificial scotoma on fixation frequency during object recognition (Henderson, McClure, Pierce, & Schrock, 1997). Clearly, the introduction of a simulated scotoma disrupts the efficiency of eye movements. All participants come to the experiment with eye movement strategies that have evolved over a lifetime. The scotoma renders these strategies suboptimal so they must be revised. As with any learning experience, the execution of new actions is deliberate and slow rather than fast and efficient. The former are reflected in longer and more frequent fixations.

The finding that fixation frequency, duration, and saccade amplitude do not generally depend on the number...
of features in the stimulus is interesting. We would have predicted a relationship between these dependent variables and the number of stimulus features. Instead, we see that the eye movement measures (Figure 4) and the spatial distribution of fixations (Figure 5) were not systematically related. This may be because participants were instructed to be as accurate as possible in their responses, and stimuli were presented for up to 10 s. Because they were not asked to respond quickly, they may have felt there was a benefit to accuracy in performing additional eye movements. Indeed, when no scotoma was present, participants made about four fixations before deciding the stimulus type. In the presence of a scotoma, additional eye movements would also allow participants to recheck their initial perception of the stimulus features and check features that may have been ambiguous on the first viewing.

Impressive advances have been made recently in our understanding of eye movements. A sequence of recent papers has shown that eye movements in a visual search task approach those of an ideal observer that has knowledge of the target, potential target locations, and its own eccentricity-dependent “visibility map” and that updates the posterior probabilities of candidate locations after each fixation (Geisler, Perry, & Najemnik, 2006; Najemnik & Geisler, 2005, 2008, 2009). Different versions of the observer do a good job of predicting median number of fixations under various presentation conditions. Furthermore, some versions of the model can be ruled out because the spatial distribution of fixations is at odds with psychophysical results (Najemnik & Geisler, 2009). One may ask if a similar ideal observer model might be developed and applied to the present data set. The challenges in doing so would be many. The present stimuli depict 3D modulations and thus would require 26 or 27 3D templates, each of which would be computationally more complex than the simple cross-correlation mechanism required to match the Gabor signal used as a target by Najemnik and Geisler (2005), for example. Although our targets were always presented in the center of the display, determining an eccentricity-dependent visibility map would require measuring something like contrast sensitivity (e.g., depth modulation sensitivity) at a potentially unlimited number of retinal locations. Although none of these preconditions is impossible to establish, one would expect the ideal observer to produce eye movement statistics and spatial distributions of fixations that are common to all participants (as in Najemnik & Geisler, 2005).

In contrast to the eye movements of Najemnik and Geisler’s (2005) practiced observers, the eye movement data presented here show large individual differences, despite similar psychophysical performance. This is most evident in the analysis of the spatial distribution of fixations. As Figure 7B shows, GR shows similar fixation dispersion to the other participants when the scotoma radius is less than 2°. However, GR adopts an eye movement strategy that is unaffected by the increase in scotoma radius, except at the largest size (8°). Conversely, the other participants show increasingly erratic eye movements, with the dispersion of fixations increasing with scotoma radius (Figure 7A). As shown in Figure 8, GR chose to fixate near the center of the screen, whereas the other participants moved their eyes to many different positions of the screen in an effort to overcome the scotoma. Given that GR’s accuracy in the task is similar to that of the other participants, these very different eye movement strategies seem to have little effect on performance. This individual preference in eye movement strategy has also been shown in AMD patients. Indeed, reading performance has been shown to be better in patients that are not aware of eccentric viewing strategies that force patients to use a single PRL (Crossland et al., 2004).

Because of the high variability in our fixation maps, using the spatial distribution of fixations to distinguish between models would seem to be impossible for the present data set. This variability may reflect the relatively low degree of experience that participants had with the task. It would be very useful to track the evolution of eye movements over time as participants adapt to the scotoma. Were they to converge on a common strategy the construction of a model similar to that of Najemnik and Geisler (2005, 2009) might be possible.

**Conclusion**

The nice correspondence between this study and that of Gurnsey et al. (2006) suggests that the standard method of studying peripheral vision, although complicated by poorly localized stimuli, seems not to give a misleading answer to the question asked at the outset: What are the information processing abilities of peripheral vision? Whether limited by a simulated central scotoma or the non-central presentation of stimuli, we are clearly able to identify 3D structure in the periphery, and the rate of sensitivity loss is very similar in both cases. This seems like good news for a large literature on peripheral vision that has used non-central presentation of stimuli, i.e., stimuli presented away from the point of fixation.

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Footnote

1We are persuaded that the primacy of p-values is a bad thing for science and that measures of effect size should take their place (e.g., Cohen, 1994; Kline, 2004). Therefore, we report effect size measures (partial eta squared, \( \eta^2_p = \frac{SS_{\text{effect}}}{SS_{\text{effect}} + SS_{\text{error}}} \)) before the F ratios and their p-values. (Partial eta squared must not be confused with eta squared \( \eta^2 = \frac{SS_{\text{effect}}}{SS_{\text{total}}} \), which represents the proportion of total variability [in the dependent variable] explained by the effect in question; see Pierce, Block, and Aguinis (2004) for examples of mistaken use.) The advantage of effect size measures is that their expected values are independent of sample size. However, for a fixed \( \eta^2_p \) in the population the corresponding F ratio \( F = \frac{SS_{\text{effect}}/SS_{\text{error}} \times df_{\text{error}}/df_{\text{effect}}} \) increases with the number of degrees of freedom in the error term. Consequently, as oft noted, a trivially small effect size (\( \eta^2_p < 0.3 \)) becomes statistically significant with sufficient degrees of freedom. Conversely, relatively large values of \( \eta^2_p \) may not be statistically significant if there are insufficient degrees of freedom. Therefore, an estimate of the size of the effect stays closer to the data and is more meaningful. Partial eta squared is the standard effect size measure reported in SPSS for Analysis of Variance, which we used to perform our ANOVAs. Unfortunately, SPSS has not evolved to the point of providing confidence intervals for partial eta squared. We categorize our effect sizes as small (\( \eta^2_p < 0.3 \)), medium (\( 0.3 < \eta^2_p < 0.5 \)), large (\( 0.5 < \eta^2_p < 0.6 \)), and very large (\( \eta^2_p > 0.6 \)), but we acknowledge that this is somewhat arbitrary. However, because the effect sizes themselves are reported readers are free to judge whether they agree with our characterizations. As noted by Cohen (1988), whether a particular effect size is considered large or small depends on the relevant literature. It would be worthwhile to survey the literature in vision science journals to determine the range of effect sizes typically found. (Note, \( \eta^2_p = 1/[1 + (F \times df_{\text{error}}/df_{\text{effect}})^{-2}] \), which means that the effect size can be recovered from the F ratio if the degrees of freedom have been reported.)

References


