Using AMD-like Simulated Scotomata in Young and Old Healthy Adults: Effects on Eye Movement Patterns and Fixation Efficiency

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ABSTRACT

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Age-related macular degeneration (AMD), a leading cause of legal blindness, causes irreversible visual impairment within a central scotoma (blind spot). Patients with AMD therefore use extrafoveal (not in the center of vision) locations for fixation, with a cost of increased fixation instability and reduced viewing efficiency. The clinical symptoms of AMD are varied. To investigate the degree to which observers with different types of AMD could retain residual visual functioning but without pathological complications, we studied eye movement (EM) patterns with a shape identification task with 4 types of simulated central scotoma (Relative, Absolute, Distorted, Warped) with young normal observers in Experiment 1. Results showed that the Relative scotoma (reduced contrast) was the least disruptive form. A complete loss or a distortion of central visual input (Absolute, Distorted, Warped) led to greater reduction of response efficiency and more severely altered EM patterns. There was a preferential horizontal fixation shift away from the targets toward the right visual field, with little shift along the vertical. Generally, there was a marked improvement with practice. Larger scotomata always led to larger changes, except for the Relative type. Since AMD affects mostly older people, we compared young and old healthy adults in Experiment 2. The results showed that old adults were less efficient than young adults, tended to have larger fixation shifts along the X- and Y- axes, but with a smaller angular change, and were slower to adapt. Large

scotomata were especially disruptive. Our results suggest that when using simulated scotomata, one needs to adjust the properties of the scotoma to the kind of AMD studied. It is also preferable to use old adults, since their response appears to be different in many ways from that of young adults. This novel perspective might suggest new requirements for low vision training.

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Introduction

Percepts arise from sensory inputs from our surroundings. The retina, lying on the back of the eye, is the place where the incoming light is absorbed, converted into neural events and processed for an initial extraction of visual information. A healthy and functional retina therefore plays a crucial role in visual perception. Any structural disruption of the retina can have a devastating effect on visual performance, as well as daily lives. The present thesis deals with a particular form of a compromised retina, namely the malfunctioning of the central part of the retina. A quick review of retinal architecture will provide a frame of reference for the impact of central malfunction.

Retinal architecture

At various levels of the early human visual system (notably retina and primary visual cortex), there are continuous anatomical and physiological changes with eccentricity (distance from the center). The changes comprise photoreceptor kind, photoreceptor density and size, ganglion cell density, and the amount of convergence at various retinal layers, as well as in the cortex, which determines receptive field size of the neurons involved (Anstis, 1998; Roorda & Williams, 1999). There are two types of light sensitive photoreceptors in the retina: rods and cones. The total number of rods in the human retina (92 million on average) far exceeds the number of cones (about 4.6 million; Curcio, Sloan, Kalina, & Hendrickson, 1990). As a result, the density of rods is much greater than that of cones throughout the retina, except the fovea. The fovea, about 1.2 mm in diameter, lies at the central retina, which contains the highest concentration of cones. The increased density of cones in the fovea is accompanied by a sharp decline in

the density of rods. The central 350 μm of the fovea (1.25 deg) is totally rod-free, and cones are densely packed together (Curcio et al., 1990).

Further, a special connectivity with cortical areas based on less convergence results in small receptive field sizes (Schiller, Slocum, & Weiner, 2007), and leads to a situation where a small retinal area (corresponding to a small visual field area) is represented by a large area in the cortex (magnification factor). Thus, the unequal distribution of photoreceptors and ganglion cells in the retina is maintained in their projections to the lateral geniculate nucleus (LGN; an intermediate stage of the pathway in the thalamus) and primary visual cortex. In fact, the central 5 deg of the retina have been shown to occupy 40% of striate cortex (area V1) in the macaque monkey (Levay, Connolly, Houde, & van Essen, 1985). This means that roughly 0.3% of the visual field projects to 40% of V1 surface area, and the remaining 99.7% projects to 60% of V1.

The topographic distribution, size, and packing geometry of photoreceptors contribute to the functional grain of the retina, which is strongly biased in favor of the small fovea over the large periphery, and this is also true for the visual cortex. The fovea, with the highest density of cone receptors, mediates high visual acuity and spatiotemporal sensitivity (Midena, Angeli, Blarzino, Valenti, & Segato, 1997; Tolentino, Miller, Gaudio, & Sandberg, 1994). Cone density declines by a factor of three from the fovea to 10 deg eccentricity, as does visual acuity and contrast sensitivity (Fiorentini & Berardi, 1991; de Valois & de Valois, 1988).

To compensate for this structural limitation of the anisotropic distribution of the retina, we therefore constantly generate saccadic eye movements, which are rapid and ballistic eye movements that quickly align the fovea with particular parts of the visual

scene. In between saccades there are fixation periods, during which aspects of the visual scene are computed and detailed visual information can be obtained. In order to see details and identify objects during scene perception, it is beneficial to have a functioning fovea engaging in information processing, so that we can reach the highest visual performance (Henderson, McClure, Pierce, & Schrock, 1997). However, certain ocular disorders specifically affect the central foveal region of the retina and deprive the patient of the proper use of the foveal processing and therefore of vital visual information. The present thesis deals with simulations of a group of particular retinal disorders, namely Age-related Macular Degeneration (AMD).

Age-related macular degeneration

Age-related macular degeneration is a leading cause of registered legal blindness among those aged over 65 in the United States, Western Europe, Australia, and Japan (Klein, Klein, & Linton, 1992; Mitchell, Smith, Attebo, & Wang, 1995). It is a disorder in which the macula progressively atrophies or neovascularizes, leading to irreversible visual impairment (Quillen, 1999). The macula, about 5 mm in diameter, is located in the center of the retina, which contains the fovea, and corresponds to the central 15 to 20 deg of the visual field. The pathological change of the macula has a profound detrimental effect on visual performance. Consequently, many patients with AMD eventually lose the ability to perform daily activities, such as reading and driving. With the increasing size of the aging population in Western and other societies, it is an urgent matter to scrutinize the visual and behavioral characteristics among those with AMD to help them regain residual visual function and improve their quality of life, as well as subjective well-being. The understanding of the variety of adjustments in the visual performance and eye movement

patterns among people without a functioning fovea is therefore of particular interest in the current study. It is therefore necessary to briefly examine the physiological differences that result in different types of AMD.

Physiology of Age-Related Macular Degeneration. There are two major forms of AMD: Geographic atrophy (GA, dry AMD) and neovascular lesions (wet AMD) of the retinal pigment epithelium (RPE). Geographic atrophy refers to confluent areas of RPE cell death accompanied by overlying photoreceptor atrophy (Green & Key, 1977). Neovascular lesions result from the development of new blood vessels beneath the retina. These abnormal blood vessels may break into the retinal cell layers. The leakage of fluid and protein from these vessels causes scar formation throughout the macula, which ultimately results in a deterioration of central vision. Neovascular lesions include choroidal neovascularization (CNV) and disciform scar. Choroidal neovascularization results from the subretinal hemorrhage due to the bleeding from choroidal neovascularization. Disciform scar occurs because of subretinal fibrosis (Gehrs, Anderson, Johnson, & Hageman, 2006). Both forms of AMD lead to retinal damage, which results in a central scotoma.

Characteristics of Central Scotomata. A scotoma is an area of reduced light sensitivity in the retina. In the early stages of GA, contrast sensitivity is reduced, but the affected area of the retina still has some residual light sensitivity (therefore Relative scotoma). Patients often complain that objects are "vanishing", or "are having blurry parts" (Gehrs et al., 2006). In the advanced stage, atrophic macular areas coalesce, creating an Absolute central scotoma (a blind spot) in the central visual field, in which light and contrast sensitivity diminish completely. Patients subjectively feel that objects

are "jumping out of nowhere". Individuals with wet AMD commonly present with visual distortions, in which straight lines appear crooked (Gehrs et al., 2006).

Most central scotomata in patients with advanced AMD have a diameter of 10 to 20 deg, however, the scotomata in the early stages are usually smaller with a diameter of 10 deg or less (Guez, Le Gargasson, Rigaudière, & O'Regan, 1993; Sunness et al., 1999). The degenerative effects on the acuity, contrast sensitivity, and distorted stimulus appearance most noticeably occur in the macula, while the peripheral visual field typically preserves its function in both forms of the disease. Because of the anisotropic structure of the retina, the size of the central scotoma is an important determinant of the residual functionality, which must depend on capabilities of the periphery, and these depend on eccentricity.

Eccentric viewing

Many observations indicate that patients with a central scotoma can develop an extrafoveal retinal location for fixations. In that case, they adopt a different fixation angle that displaces the central fixation, which would be within the scotoma, so that targets fall onto the peripheral unaffected retinal region (von Noorden & Mackensen, 1962; Cummings, Whittaker, Watson, & Budd, 1985). Eccentric viewing or fixation is an effective adaptive mechanism, which naturally and reliably occurs when the foveal areas in both eyes are no longer functioning (Schuchard, 2005).

For example, Cummings et al. (1985) studied viewing patterns and retinal locations for fixations among patients with AMD in a reading task. Thirty-six eyes of patients with a central scotoma were examined. Among those, 72% showed a single strongly preferred viewing angle. Case data revealed that patients rather readily placed

the target image onto intact and unaffected retinal loci, which were outside of the scotoma. The use of extrafoveal retinal locations for fixations gained wide recognition in the last two decades. Now, researchers prefer to use the term "preferred retinal location" (PRL) to describe the shift of fixation onto a peripheral retinal area (Cummings et al., 1985).

The question remains, however, whether eccentric viewing that necessarily uses peripheral visual functions is comparable in some way with foveal visual functions? A large body of psychophysical evidence shows that the size-versus-threshold (i.e., accuracy, contrast sensitivity or other perceptual properties) functions at each eccentricity differ only by a shift along the log size axis. That is, the change from center to periphery is best characterized by quantitative, rather than qualitative changes. The processing principles usually remain the same, as long as appropriate size scaling is applied. Stimuli in the periphery have to be magnified by a factor that is a function of the stimulus distance from the center (i.e., eccentricity). Therefore, it is usually possible to achieve a performance level, which is comparable to central performance (Gurnsey, Poirier, Bluett, & Leibov, 2006; Vakrou, Whitaker, McGraw, & McKeefry, 2005; Levi, Klein, & Aitsebaomo, 1985).

As mentioned above, the anisotropic nature of the retina requires the use of saccadic eye movements to bring objects of interest into the fovea for optimal processing. If fixation is eccentric, rather than foveal, as in patients with AMD, these eye movements will have to be made to some eccentric area (e.g. PRL). It is important therefore to examine the eye movement patterns when use of the fovea is not possible.

Eye movements without a fovea

It is certainly true that we can perform certain visual tasks in the absence of foveal information (Henderson et al., 1997). However, the efficient use of a PRL requires careful eye movement control. In normal observers, fixation stability, defined as an area that contains 68% of all fixations, ranges from about 100 to 650 min arc squared, which is equivalent to circular areas of about 0.2 to 0.5 deg in diameter (Crossland & Rubin, 2002). Fixations with PRLs in patients with a central scotoma are substantially less stable than normal fixations. Fixation stability is about 2 to 15 times lower than in normal observers (e.g., a range of 1 to 9 deg; Fletcher & Schuchard, 1997). Although through adaptation, patients with a central scotoma were able to use preferred areas for fixation outside of the central scotoma, fixation stability, however, decreased as scotoma size increased (Whittaker, Budd, & Cummings, 1988). One study compared foveal fixation stability to peripheral fixation stability in normal observers, which showed that fixation was 3 to 4 times less stable with peripheral fixation (Sansbury, Skavenski, Haddad, & Steinman, 1973).

The presence of a central scotoma during visual search also leads to increased fixation duration, especially for large scotoma sizes (Cornelissen, Bruin, & Kooijman, 2005; McMahon, Hansen, & Viana, 1991). Moreover, patients with AMD showed a prolonged visual search duration while performing a tranditional visual search task (Liu, Kuyk, & Fuhr, 2007). This was also true for a simulated central scotoma (Bertera, 1988). Hallett (1978) also reported elevated saccadic latency among people with a central scotoma, and suggested that it could be due to the cancelation of the habituated foveating saccades (foveating saccade refers to the retinal null point that is the fovea). Different

saccadic eye movement patterns and reduced fixation stability in patients with AMD might affect their performance on a behavioral level.

Behavioral characteristics without a fovea

Behaviorally, Cummings et al. (1985) compared patients' reading rate (no magnification aid) with that of normal participants. They found that patients with AMD had a reduction in reading rate when scotoma size increased, but this was not the case for reading accuracy. Patients were able to recognize word symbols accurately even with a central scotoma of up to about 20 deg in diameter. In contrast to the accuracy results reported by Cummings and collegues, Rayner and Bertera (1979) found that readers reported fewer than 10% of words in a sentence when an artificial scotoma masked the central 2 deg of vision.

Henderson et al. (1997) compared observers' performance on an object identification task using an artificial central scotoma. In the absence of foveal information, they also found that the accuracy of object identification was as good as in the normal condition during a free-viewing process. Without foveal information during scene perception, observers engaged for a longer time in extrafoveal analysis. Observers moved their eyes around more and looked longer at the displays when foveal information was not available. Therefore, the researchers suggested that additional extrafoveal processing could compensate for the loss of foveal information. They concluded that foveal information is beneficial for visual information processing but not necessary for object encoding.

This result regarding accuracy was contrary to Rayner and Bertera's findings. Henderson et al. suggested that the difference might be task-dependent: reading versus

object identification. To identify letters and symbols required high spatial frequency information, for which foveal stimulation might be more important, whereas objects could be identified on the basis of lower spatial frequency contour patterns.

The reason for the different results for response accuracy in the studies by Cummings and Rayner is still not very clear. A possible reason may be that observers in Cummings's study were real patients and had a long history of a central scotoma, while participants in the Raynor and Bertera study had normal vision with an artificial central scotoma. Some patients, whose macular disease was longstanding, reported that positioning eyes such as to image the target nonfoveally became associated with the sensation of looking directly at the target (von Noorden et al., 1962). Therefore, patients with longstanding macular disease might have benefitted from the longer periods of practice, with the result that the best remaining visual sensitivity was at their preferred nonfoveal locus. This might in turn have improved their response accuracy.

These examples of psychophysical and behavioral evidence suggest that eye movements with an extrafoveal retinal location are effortful. Although it might be practically possible to achieve a performance level that is comparable to central performance, this might be associated with decreased fixation stability and excessive extrafoveal exploration, requiring an increased amount of effort.

Present study

The present study was designed to address several points that were not or not adequately addressed in the existing literature:

First, to date, many previous studies on central vision loss most often used reading and 2-dimensional stimuli as testing conditions. As mentioned above, reading

with central vision loss could generate distinct visual performance and eye movement patterns, as compared with other types of visual tasks. Moreover, in the real world, 3-dimensional layouts are usually encountered. The major task of our visual system is to reconstruct a 3-dimensional visual scene from a 2-dimensional image that impinges on the retinal surface. Thus, it would be more informative to test object identification ability with 3-dimensional stimuli. The present study therefore used a 3D shape-from-texture identification task where gradients of visual texture from a pattern of random polka dots, combined with a pattern of surface contours, defined the stimuli (Todd, 2004; Gurnsey et al., 2006).

Second, the manifestations of central visual field deficits of AMD are not uniform. Many studies carefully examined visual performance with participants either having a Relative or an Absolute scotoma (e.g., Cornelissen et al., 2005). There are, however, other and perhaps intermediate presentations of central scotomata in AMD. For example, patients often complain about seeing distortions when they have wet AMD. Due to the disciform scar from subretinal fibrosis and CNV, the central macular region has uneven luminance and contrast sensitivity. Few studies examined eye movement patterns under these different types of central scotoma, which is a missing puzzle in the eccentric viewing research.

Thus, one of the main themes of the present research (Experiment 1) was to study eye movement patterns and visual performance when normal participants were presented with the following 4 types of simulated central scotoma: 1) Relative scotoma: Reduced contrast in the central visual field corresponds to the early stage of GA; 2) Absolute scotoma: Diminished central visual function with no visible contrast or brightness

corresponds to the advanced stages of GA and CNV; 3) Distorted scotoma: A static distortion with uneven luminance and contrast corresponds to disciform scars from wet AMD (Gehrs et al., 2006); 4) Warped scotoma: Distortion with dynamic visual inputs corresponds to a particular stage of the CNV form of central visual field deficits.

In all these cases, we were interested to know the degree to which peripheral regions of the retina were able to obtain perceptual information about 3-dimensional shape-from-texture during free viewing. We therefore studied the temporal and spatial characteristics of eye movements in normal observers with different types of central scotoma, while they were solving the visual task. To quantify the contribution of different retinal regions to scene perception, we have brought together observations of visual behavior, and eye movement patterns with different types and sizes of scotoma. We were also interested in how efficiently observers could solve tasks under various central scotoma conditions. We therefore measured response latency and accuracy, as well as the duration of regressive fixations (re-fixating previously fixated regions) and number of fixations, which could serve as an index of fixation stability and efficiency. We made a special effort to scrutinize the degree to which observers shifted their eye positions with a central scotoma. This allowed us to find out to what extent observers needed to displace the central scotoma to use a peripheral retinal locus and toward which direction this displacement occurred. All these pieces of information together gave us a complete representation of visual functions with various central scotomata.

The second theme of the present study was to examine the age effect with a central visual field deficiency (Experiment 2). Even though a version of AMD exists for younger ages (Juvenile MD or Stargardt's Disease; Sunness, Applegate, Haselwood, &

Rubin, 1996), the vast majority of central scotomata occur among older people. Since it is easier to study younger participants with simulated scotomata, it would be very helpful to know whether and to what extent different age groups differ in their response to a central scotoma. Therefore, in addition to the above-mentioned variables of interest, we also varied observers' age, which allowed us to assess visual functioning differences between different age groups. This could be an informative component for low vision training plans. Younger observers might have greater plasticity, so they might respond more accurately and adapt quicker when the central visual field is not available. However, it is not clear from the existing literature, to which degree the visual function is affected differently due to age, and what kind of eye movement patterns and visual performance aspects are unique to older observers with a central scotoma. We therefore compared eye movement patterns between old and young normally sighted observers, using a Distorted type of central scotoma.

The use of normal observers with a simulated central scotoma minimized complications that may be present with the patient population, such as general health, other ocular disorders, and potential cognitive abnormalities. AMD is a progressive disease. Some patients may not be aware of the presence of a central scotoma at the early stage. Therefore, the adaptation time course is hard to determine among patient populations. Using simulated scotomata may remove this potential confound in research on visual performance and eye movement patterns.

Experiment 1

Rationale

In Experiment 1, we compared temporal and spatial characteristics of eye movements and response efficiency while a simulated central scotoma moved seamlessly with the movements of the eyes by using a gaze-contingent real-time simulation technique in normally sighted young adults with a 3D shape-from-texture identification task. Previous studies have shown that patients with macular scotomata deliberated longer about the identity of the search target. Therefore, patients with a macular scotoma will have impaired visual search ability in addition to the inability to see targets located inside the scotoma (Schuchard, 2005). Therefore, in Experiment 1, we expected an overall decline in response efficiency and visual performance when a central scotoma was present (*Hypothesis 1*).

Here, the index of response efficiency was defined by response latency and response accuracy. The temporal and spatial characteristics of eye movements were measured through the analyses of several variables: 1) X and Y fixation shifts; 2) preferred eccentric viewing angle; 3) regression path fixation duration; 3) overall trial duration; 4) total number of fixations. These variables will be described in detail later.

In order to study the degree to which observers could use their residual visual function, we varied scotoma size (0, 2, 4, 8 deg) and scotoma type (Relative, Absolute, Distorted, and Warped). A size of 0 means that there was no scotoma (i.e., normal vision), and this served as a normal control condition within the same observers. All conditions were given to each observer 3 times in random order. This allowed us to learn about the extent and the speed of adaptation to the various scotoma conditions. According

to the existing literature, people with a central scotoma could learn rather quickly to adopt an eccentric viewing position (Whittaker, Cummings, & Swieson, 1991). We hypothesized that:

Hypothesis 2. When the scotoma size increased, observers would have greater difficulties to respond quickly. In terms of response accuracy, we expected they would not make a large number of errors across conditions, which would be consistent with previous research findings, unless the novel stimulus type would have a special effect (Henderson et al., 1997). In addition, response efficiency would improve as a function of replication.

Hypothesis 3. Due to the increased fixation instability resulting from the use of peripheral retinal locations for fixation, observers had to engage in an increased amount of extrafoveal exploration to solve the task. Therefore, we expected a pronounced positional shift (i.e., X- and Y- fixation shifts, eccentric viewing angle, and regression path fixation duration). In addition, this change would increase as a function of scotoma size, but decrease as a function of replication.

Hypothesis 4. Since the use of peripheral retinal locations for visual search added additional load for locating a proper retinal locus, we expected there would be an overall increase in trial duration and the number of fixations. Moreover, overall trial duration and number of fixations would increase as a function of scotoma size, but decrease as a function of replication.

Hypothesis 5. The Relative scotoma with only reduced contrast was expected to be the least detrimental condition among the 4 types of scotoma. There was still a residual visibility in the Relative scotoma condition. Therefore, observers would be able

to perform better with this scotoma type than with the other scotoma types on each measurement index. Due to the complete loss of central visual field and distorted perception of the target in Absolute, Distorted, and Warped scotomata, observers would have greater difficulties to identify objects efficiently. They would have to generate larger eye movements to locate objects of interest and bring them onto the retina, but outside the scotoma.

Method

Participants. Twenty-four observers participated in Experiment 1 (Age range 21-30, $M = 24.04$, $SD = 2.31$), 6 for each scotoma condition (i.e., Relative, Absolute, Distorted, and Warped scotoma). All were university students who participated for a class credit or were paid $10 to participate in an 1 hr session, and were treated according to the *Tri-Council Policy Statement*: Ethical Conduct for Research Involving Humans (Medical Research Council of Canada, 2003). All observers were naïve to the purpose of the experiment. Informed consent was obtained from every participant. Before the experiment, participants were tested for visual acuity with the ETDRS chart (Early Treatment Diabetic Retinopathy Study; Bailey & Lovie, 1976; see Appendix B) at a distance of 2 m with a letter-by-letter scoring method. The average visual acuity was 0.301 logMAR (20/40 or better). Therefore all had normal or corrected-to-normal vision. We also roughly assessed their visual field with a Damato 60-point campimeter (Precision Vision) chart to detect visual field loss caused by eye disorders. None were found.

Stimuli. We used a 3D shape-from-texture stimulus (Gurnsey et al., 2006). There were three shape locations on a flat surface positioned in 3-D space with a certain

inclination with respect to the observer. At each location the shape could be a hill, a valley, or a plain. There were 27 possible combinations, defining 27 different topographies of stimuli. Most size measures in this thesis are given in pixels. The conversion to degrees of visual angle for the particular monitor screen and observer distance was: One pixel equals 0.03134 degrees of visual angle. For example:

10 pixels = 0.3134 deg;

50 pixels = 1.567 deg;

100 pixels = 3.134 deg;

500 pixels = 15.67 deg;

1000 pixels = 31.34 deg.

Each stimulus was created by texture mapping a 64 x 64 array of dots (each of which was defined within a 14 x 14 pixel window and had a diameter of 11 pixels) onto an 896 x 896 surface. The resulting surface was orthographically projected onto the image plane. The horizontal extent of each stimulus was 896 pixels, corresponding to 28.08 deg of visual angle (see Figure 1). The mean luminance of each stimulus was 37.9 cd/m^2. The luminance of the polka dots was 0.85 cd/m^2.

Four types of simulated central scotoma formed 4 experimental conditions:1) Relative scotoma: Reduced contrast with a mean luminance of 33 cd/m^2, and a Michelson contrast of 0.48 (as compared to 0.97 without the scotoma). 2) Absolute scotoma: An area with no transparency and a mean luminance of 15.3 cd/m^2. 3) Distorted scotoma: A static distortion with a mean luminance of 33.8 cd/m^2. 4) Warped scotoma: A central distortion with a dynamic visual input, which had a mean luminance of 37.2 cd/m^2. All were varied in size: 0, 2, 4 or 8 deg in diameter (see Figure 2).

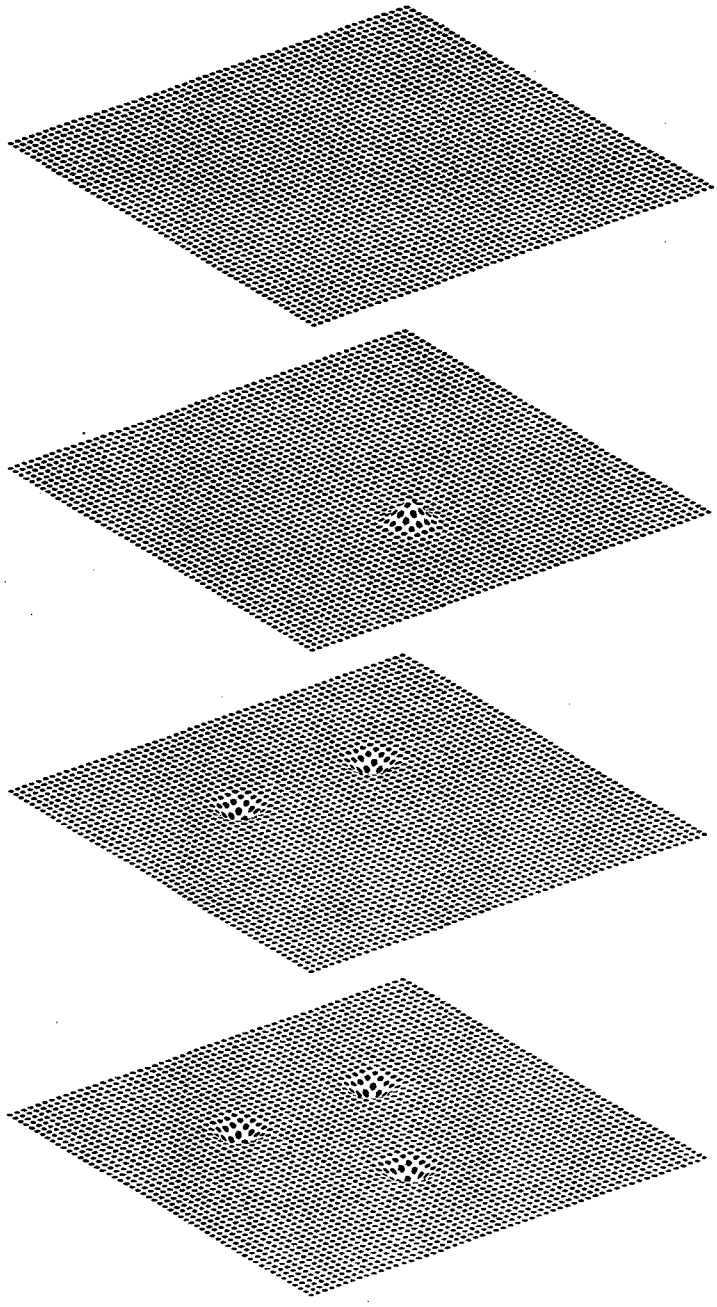


Figure 1. Example stimuli used in Experiment 1 and 2. In all four examples, each represents a stimulus with no shape, one shape, two shapes, and three shapes, respectively.

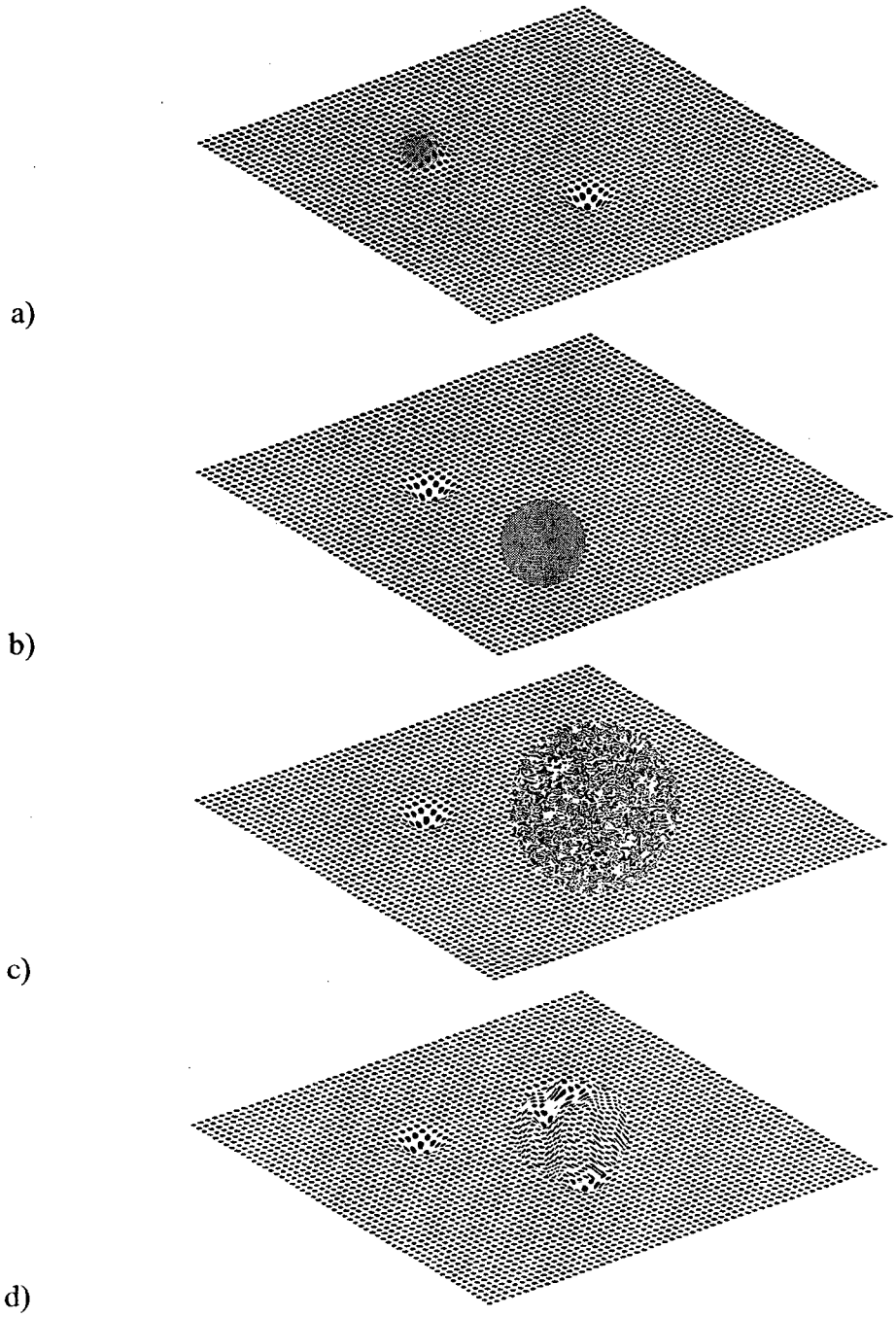


Figure 2. Example scotomata and scotoma sizes. a) a 2 deg Relative scotoma; b) a 4 deg Absolute scotoma; c) a 8 deg Distorted scotoma; d) a sample display of Warped scotoma.

Apparatus. The stimuli were presented on a 21-inch color monitor (ViewSonic G225f) at a frame rate of 120 Hz with a spatial resolution of 1024 x 768 pixels. A head-mounted eye tracker (EyeLink II; SR Research: http://sr-research.com) was used to record observers' eye movements with a sampling rate of recording at 250 Hz. X- and Y-coordinates of observers' eye positions determined the gaze contingent position of the scotoma in a continuous fashion. An adjustable chinrest served to reduce the size of head movements. A MATLAB software package (2007a; MathWorks Ltd.) and the Psychophysics Toolbox (version 3; Brainard, 1997; Pelli, 1997) were used to generate and present the experimental stimuli and to record observers' time to first response and response accuracy. The latency between the detection of eye movements with the eye tracker, and when the simulated scotoma appeared on the screen was 13.3 msec when measured with a photo-diode.

Design. In Experiment 1, there were four experimental conditions: Relative central scotoma, Absolute central scotoma, Distorted central scotoma, and Warped central scotoma. The central scotomata were varied in size (0, 2, 4 or 8 deg), and repeated three times each in a different random order for three replications. In total, each condition consisted of 12 blocks of 27 randomized trials. A group of six of the 24 observers experienced one type of central scotoma. Observers' task was to identify the three shapes on the stimulus displays by pressing the mouse buttons. The Left button was programmed to match the "Hill" shape. The scroll wheel was set to match the "Plain" shape. The Right button was defined to match the "Valley" shape. A correct response was defined as all three button clicks in one display correctly matched to the real shape in the display; otherwise, it was counted as an error response. Before the experimental conditions,

observers were given 10 to 20 practice trials with a 0 deg scotoma condition (i.e. normal vision), which familiarized them with both the targets and the response method.

Procedure. As a screening procedure, all participants were checked for visual acuity and visual field functioning before starting the experiment. Each participant was given instructions indicating that their task was to identify the three shapes on the stimulus display. They should use the mouse buttons to make their responses in a clockwise direction starting from the leftmost shape. Explicitly, they were required to respond first to the shape on the left, followed by the shape in the upper-middle and finally to the lower and right-most shape. This was important to assess their eye movement patterns and strategies. They were instructed to make their response as accurately as possible and as quickly as possible. Participants were also advised to fixate on the center of the screen before stimulus onset. When the stimulus appeared, they were allowed to freely explore the display as needed to solve the visual task. Participants were seated in front of the computer screen with their heads rested in a chinrest. The viewing distance was 70 cm. After the calibration of the Eyetracker, participants were given 10 to 20 practice trials without a scotoma. When they were familiar with the testing procedure and the response method, the actual experiment started. The 27 displays were presented in random order. Each participant experienced all scotomata with diameters of 0 , 2, 4, and 8 deg, and the different sizes of the scotomata were repeated for each participant three times. The scotoma size and replication orders were all counterbalanced among participants.

Results & discussion

Response Latency. The response latency was defined as the time interval between the onset of the stimuli and the time of the first response. The mean response latency was computed for each participant as a function of within-subjects factors: scotoma size (0, 2, 4, 8 deg) and replication (3), and a between-groups factor: scotoma type (Relative, Absolute, Distorted, and Warped), and then entered into a mixed-model factorial analysis of variance (ANOVA).

Response latency analysis revealed a main effect of scotoma size, $F(3, 60) = 38.61, p < .01, \eta^2_p = 0.66$. As expected, observers took longer to initiate the first response when the scotoma size was increased. There was also a main effect of scotoma type, $F(3, 20) = 4.25, p < .05, \eta^2_p = 0.39$, and an interaction of scotoma size and type, $F(9, 60) = 4.86, p < .01, \eta^2_p = 0.42$, showing that response latency was significantly increased when observers had an Absolute ($M = 2.00$), Distorted ($M = 2.21$), or Warped ($M = 1.67$) central scotoma at 8 deg (the largest size) as compared with the Relative scotoma ($M = 0.96$). The Relative scotoma did not detrimentally influence observers' response time due to the only partially reduced contrast within the scotoma. Observers were therefore still able to identify shapes within the region of the central scotoma without shifting their eyes too much as compared with other types of scotoma. Therefore, the response latency of the Relative scotoma was significantly lower than for other types of scotoma, especially when compared with the Distorted scotoma (with a mean difference of -0.57 sec, $SE = \pm 0.17$), and the size of the Relative scotoma did not affect the response latency. There was also a main effect of replication, $F(2, 40) = 51.27, p < .01, \eta^2_p = 0.72$. All observers improved and responded quicker as a function of replication (see Figure 3).

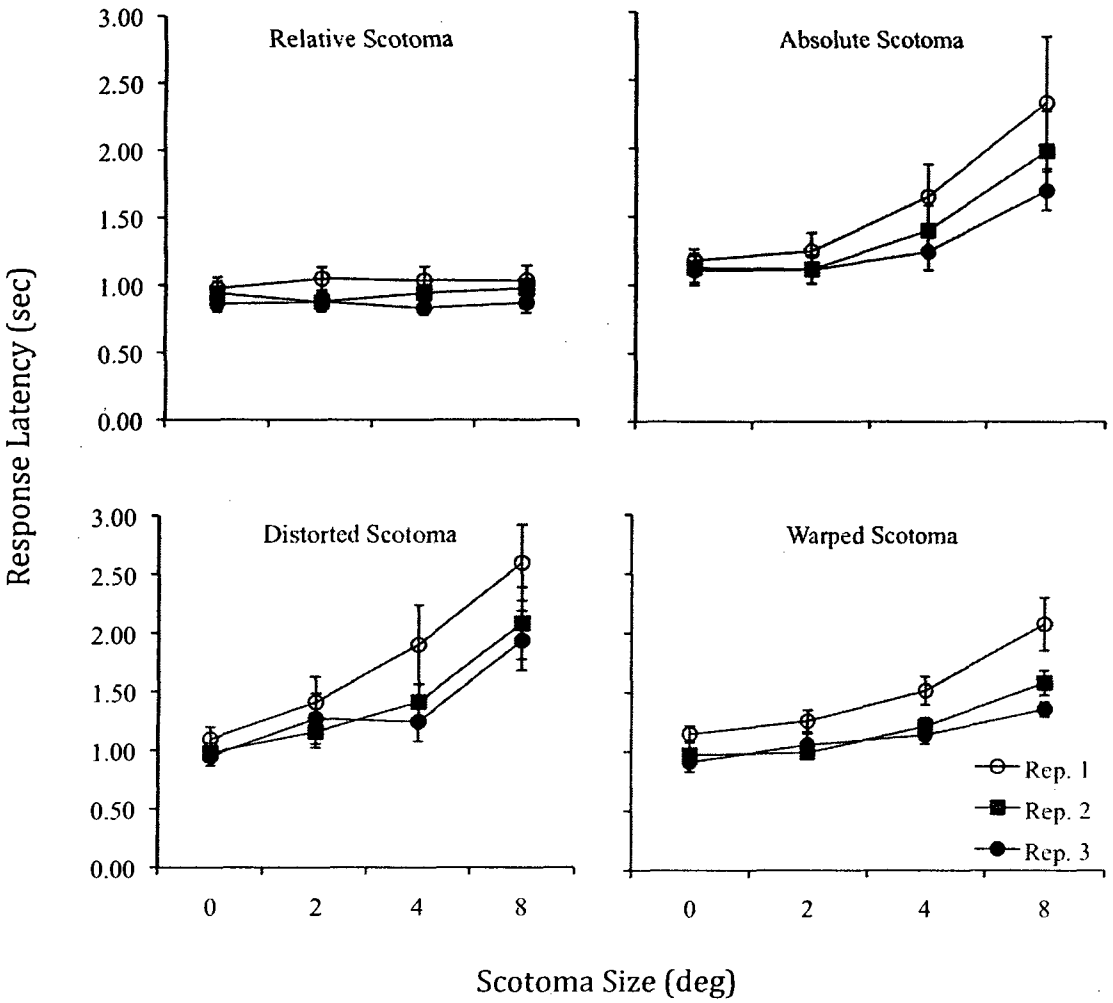


Figure 3. Mean response latency (in sec) across participants (n = 24) increased as a function of scotoma size, decreased as a function of replication, and there was an interaction of scotoma size and type in Experiment 1. Response latency was significantly increased when observers had an Absolute, Distorted, and Warped central scotoma at 8 deg as compared with a Relative scotoma. Error bar refers to the standard error of the mean.

Response Accuracy. There was a possibility of 27 correct responses in total. Observers had to identify 3 shapes (hill, valley, and plain) in one display by clicking the mouse buttons (left, right, and middle roll), respectively. Only if all three responses for one display matched with the given shapes, it was counted as a correct response. Otherwise, it would be considered as an error response.

The number of correct responses was submitted to the same mixed-model factorial ANOVA as the response latency data. This revealed a main effect of scotoma size, $F(3, 60) = 6.10, p < .01$, $\eta^2_p = 0.23$ (see Figure 4). Observers made more errors when scotoma size increased. Twenty-seven was the ceiling for correct responses. The average number of correct responses was *26.08, 25.53, 25.44,* and *24.54* for the 0, 2, 4, and 8 deg scotoma conditions, respectively. The error rate was significantly higher for the largest scotoma size (i.e., 8 deg). There were no significant effects of scotoma type and replication. The means of correct responses for Relative, Absolute, Distorted, and Warped scotomata were *25.49, 25.28, 25.58,* and *25.25*, respectively, showing that observers performed almost equally well on the different types of scotoma, and close to the ceiling. The means for the 3 replications were *25.07, 25.65*, and *25.48*, which were also statistically equal. Although we were expecting that observers would get better for later replications, the absence of a practice effect on response accuracy was probably due to a ceiling effect. The relatively few errors in all central scotoma conditions are consistent with Henderson et al.'s result (1997). Although the response latency increased as a function of scotoma size and type, the response accuracy was not affected. It suggests that observers engaged in more extrafoveal exploration to compensate for the loss of the central visual field. However, the response accuracy decreased as a function of

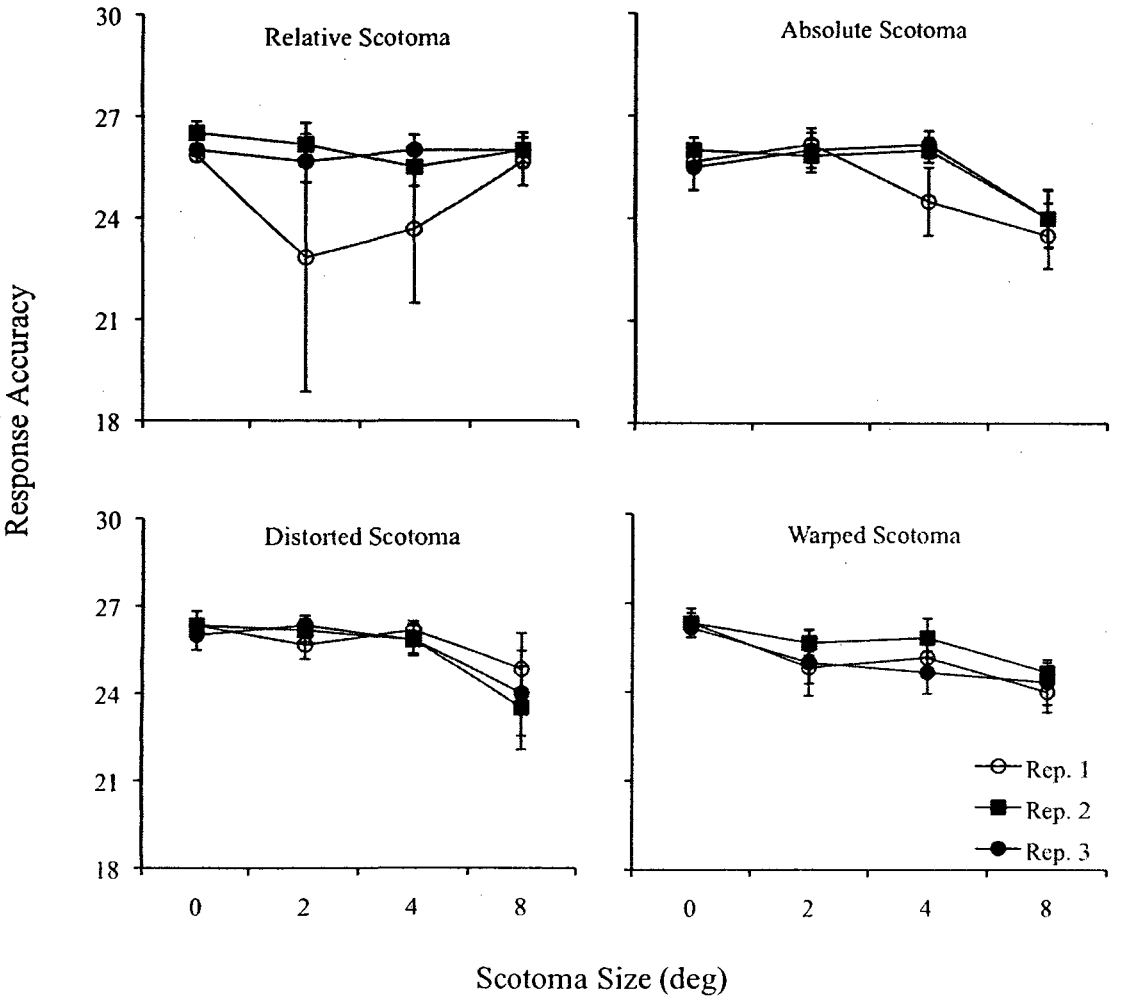


Figure 4. Mean response accuracy across participants (n = 24) decreased as a function of scotoma size (0, 2, 4, 8 deg) in Experiment 1. Error bar refers to the standard error of the mean.

scotoma size. This suggests that when the extrafoveal area became smaller as the scotoma size increased, the compensation became more demanding. Therefore, the size of the residual visual area might be a predictor for the degree to which people can regain their visual functioning.

Statistical Analysis for Eye Movement Data. We defined 3 interest areas (IAs), each of which contained one of the three shapes (see Figure 5). The sequence of IAs and shapes was defined in accordance with the observer's response sequence: starting from the left shape in a clockwise direction. On a 1024 x 768 display screen, the central X and Y positions for each shape were: Shape 1 (378, 378); shape 2 (530, 318); shape 3 (570, 416) in pixel units. The calculation of the X and Y positional shifts and viewing angles for eye fixations were all IA-based. Specifically, we compared the characteristics of fixations belonging to the same IA, so that information loss while averaging across all fixations in one stimulus display was minimized.

In order to simplify the analyses, we divided the 27 stimuli into 4 categories based on the number of shapes in each display (see Table 1). For a more detailed analysis, we chose Category 4 (i.e. there were always three shapes present). We argued that in these cases observers might have to do more eye movements and thus might provide us with more general information about changes in eye movement patterns. We therefore report here eye movement results based on the analysis of Category 4. There were in total 8 stimulus displays in Category 4.

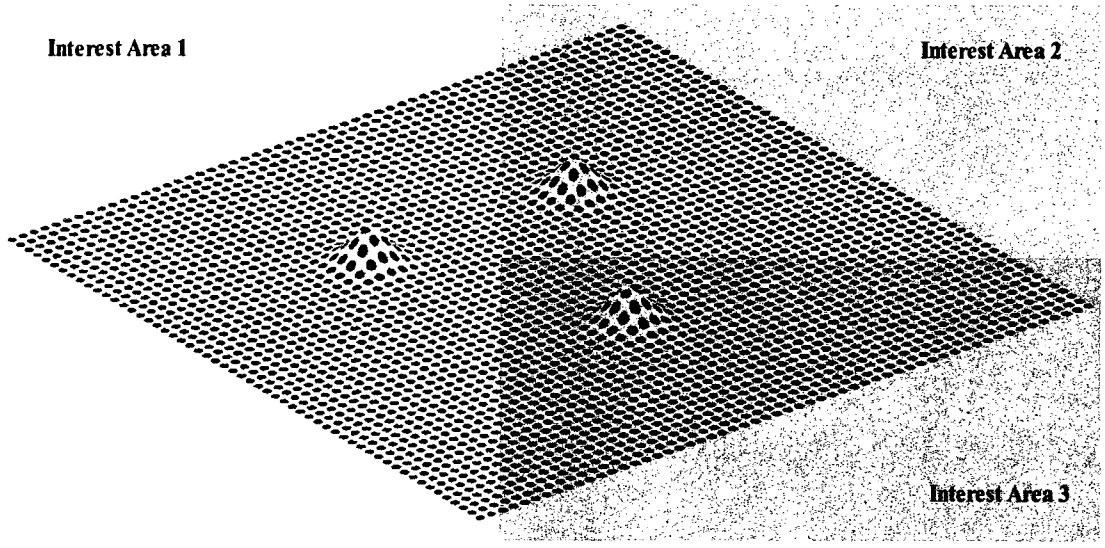


Figure 5. The locations and sizes of 3 interest areas (IAs) in Experiment 1 and 2. On a 1024 x 768 display screen, the location of IA1 (yellow) was defined in pixels as left (100, 0), top (0, 180), right (480, 0), and bottom (0, 600). The location of IA2 (green) was defined in pixels as left (481, 0), top (0, 180), right (945, 0), and bottom (0, 384). The location of IA3 (blue) was defined in pixels as left (481, 0), top (0, 384), right (945, 0), and bottom (0, 600).

Table 1

Four Categories of the Number of Shapes in Each Interest Area (IA) and the Number of Images in Each Category

Category	1 (No shape)	2 (1 shape)			3 (2 shapes)			4 (3 shapes)
IA code		IA 1	IA 2	IA 3	IA 1 IA 2	IA 1 IA 3	IA 2 IA 3	
Image number	1	2	2	2	4	4	4	8

Note:

1. Category 1: No shape: e.g., plain/plain/plain;
2. Category 2: 1 shape in IA 1, e.g., hill/plain/plain;
3. Category 3: 2 shapes in IA 1 and IA 2, e.g., hill/hill/plain;
4. Category 4: 3 shapes, e.g., hill/hill/hill.

X, Y Fixation Shifts. The X and Y fixation shifts were computed according to the average of the following two equations in each IA:

X(fixation shift) = $ABS(X$(fixation coordinate) – X(shape central coordinate))

Y(fixation shift) = $ABS(Y$(fixation coordinate) – Y(shape central coordinate)),

where *ABS* refers to the absolute value of the difference between the fixation location and the shape location. In this way, we could compute the amount of position shift for each fixation in terms of the X and Y directions as a function of scotoma size and type, and replication. The direction of the fixation shift is given by the viewing angle variable, which will be handled below. Therefore, the zero point of the coordinates for fixations in each IA was the X and Y coordinates of the appropriate shape (see Figure 6).

For each IA in Category 4, the mean X and Y fixation shifts were computed for each participant and for each stimulus display as a function of within-subjects factors: scotoma size (0, 2, 4, 8 deg) and replication (3), and a between-groups factor: scotoma type (Relative, Absolute, Distorted, and Warped) and entered into a mixed-model factorial ANOVA.

For IA1 in Category 4, there was a main effect of replication on fixation shift along the X-axis, $F(2, 40) = 7.48, p < .01, \eta^2_p = 0.27$. The difference lay between the first and the third replication, which had a mean difference of *-5* pixels (see Figure 7). This indicated that observers learned to place their fixation away from the shape center along the X-axis. There was no significant difference on fixation shift along the Y-axis for scotoma size, type, and replication.

For IA2 in Category 4, there was a significant main effect of scotoma size on the fixation shift along the X-axis, $F(3, 54) = 3.16, p < .05, \eta^2_p = 0.15$. There was no

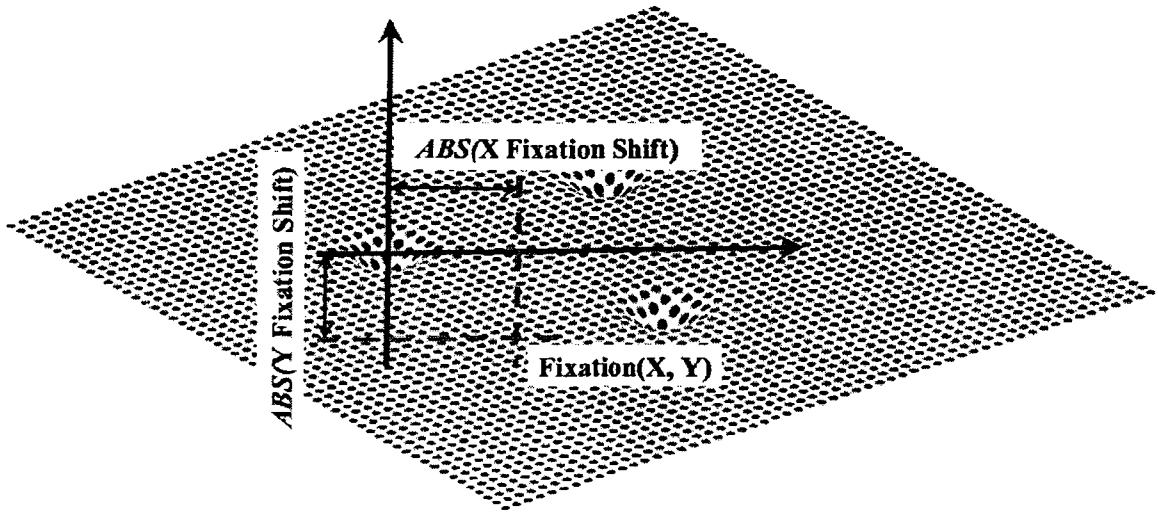


Figure 6. A demonstration of the computation of X, Y fixation shifts in Experiment 1 and 2. Fixation (X, Y) represents the X and Y coordinates of a fixation point. *ABS*(X Fixation Shift) represents the absolute value of the difference between the X fixation location and the X shape location. *ABS*(Y Fixation Shift) represents the absolute value of the difference between the Y fixation location and the Y shape location.

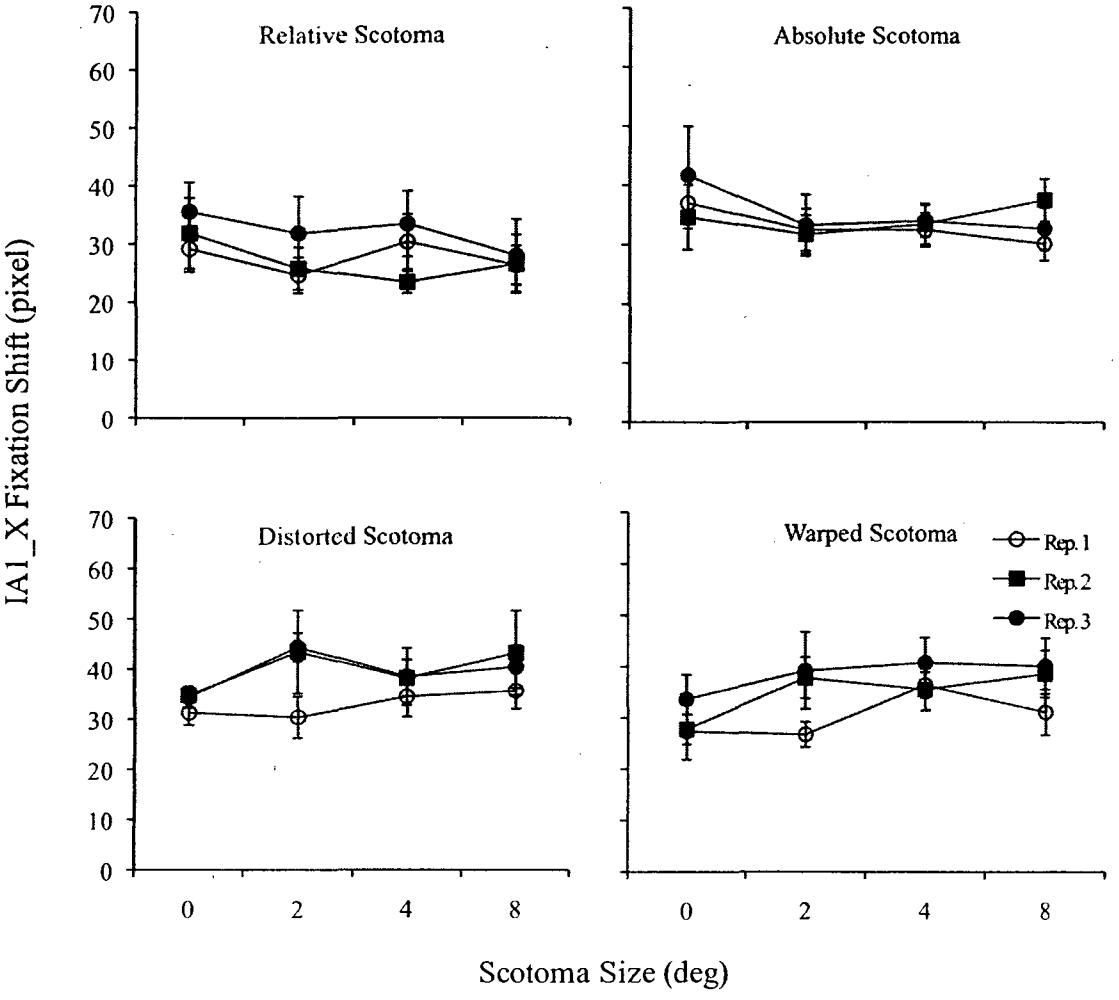


Figure 7. For IA1 in Category 4, fixation shifts along the X-axis increased as a function of replication, in Experiment 1. Error bar refers to the standard error of the mean.

significant Y- fixation shift. The mean X fixation shift for each scotoma size was *18, 17, 22, 23* pixels for the 0, 2, 4, 8 deg scotoma sizes, respectively (see Figure 8). This suggests that in order to identify the shape, observers had to shift their fixations more away from the shape along the X-axis when scotoma size increased.

For IA3 in Category 4, there was a main effect of scotoma size along the X-axis, $F(3, 42) = 5.46, p < .01, \eta^2_p = 0.28$. The difference lay between the no-scotoma and the 8 deg scotoma conditions, with a mean difference of -7 ± 2 pixels (see Figure 9). There was no significant Y-fixation shift across all conditions. When scotoma size increased, observers preferentially shifted their fixation more away from the shape center along the X-axis.

Overall, there was a general tendency for observers to shift their fixations along the X-axis to identify targets, which occurred in all 3 IAs. The scotoma type did not influence observers' viewing pattern. This indicates that we might be preferentially moving our eyes in a horizontal direction instead of a vertical direction. Performance across the visual field is not homogeneous at equal eccentricities. Previous research has shown better performance on the horizontal than the vertical meridian (i.e., horizontal-vertical anisotropy; Rovamo & Virsu, 1979), and also a better performance in the lower than the upper visual field (i.e., vertical asymmetry; Edgar & Smith, 1990). In addition, research suggests that the performance field preference may reflect ecological constraints, namely that there is more relevant visual information across the horizontal than the vertical direction. In the current study, observers might have habitually shifted their eyes away from the shape in the horizontal direction to achieve a better performance.

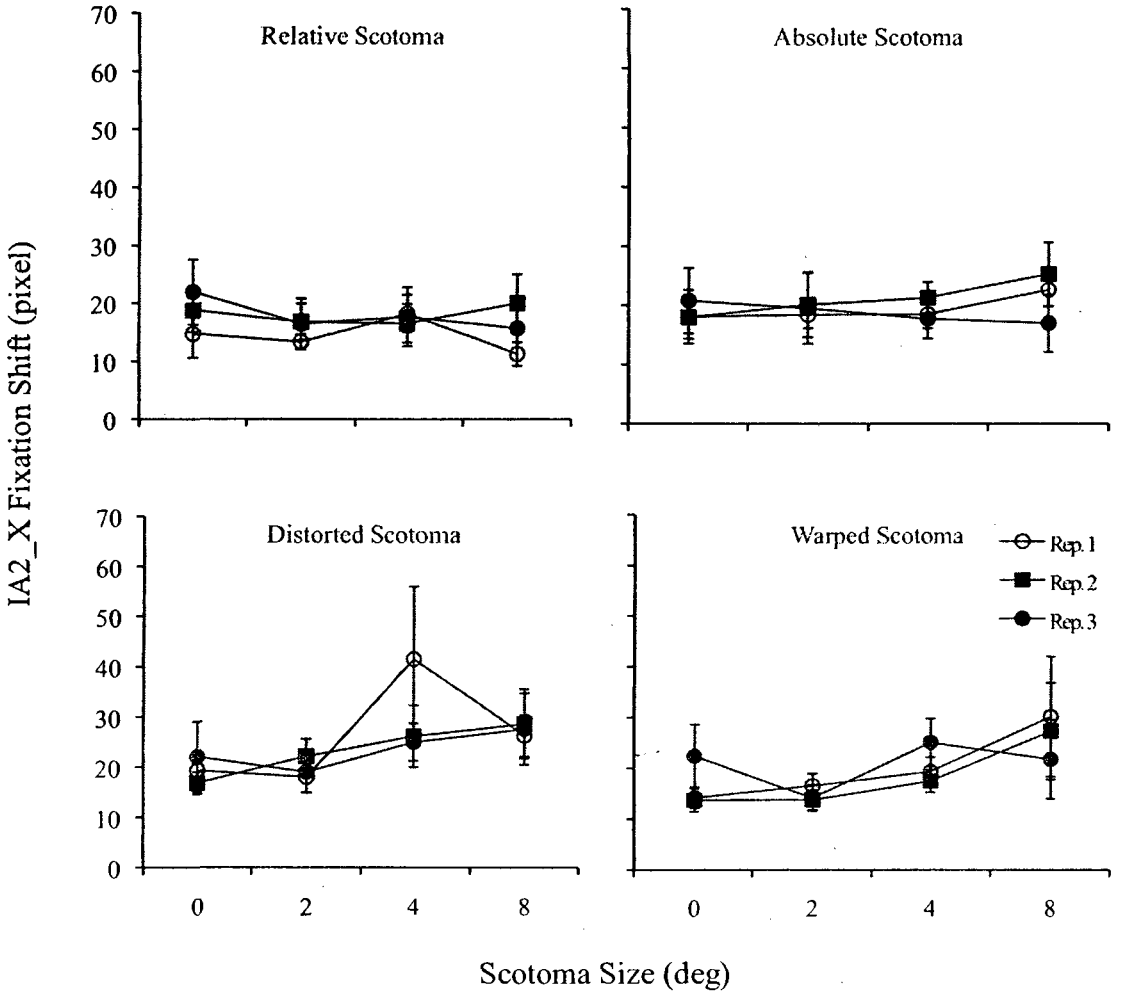


Figure 8. For IA2 in Category 4, fixation shifts along the X-axis increased as a function of scotoma size, in Experiment 1. Error bar refers to the standard error of the mean.

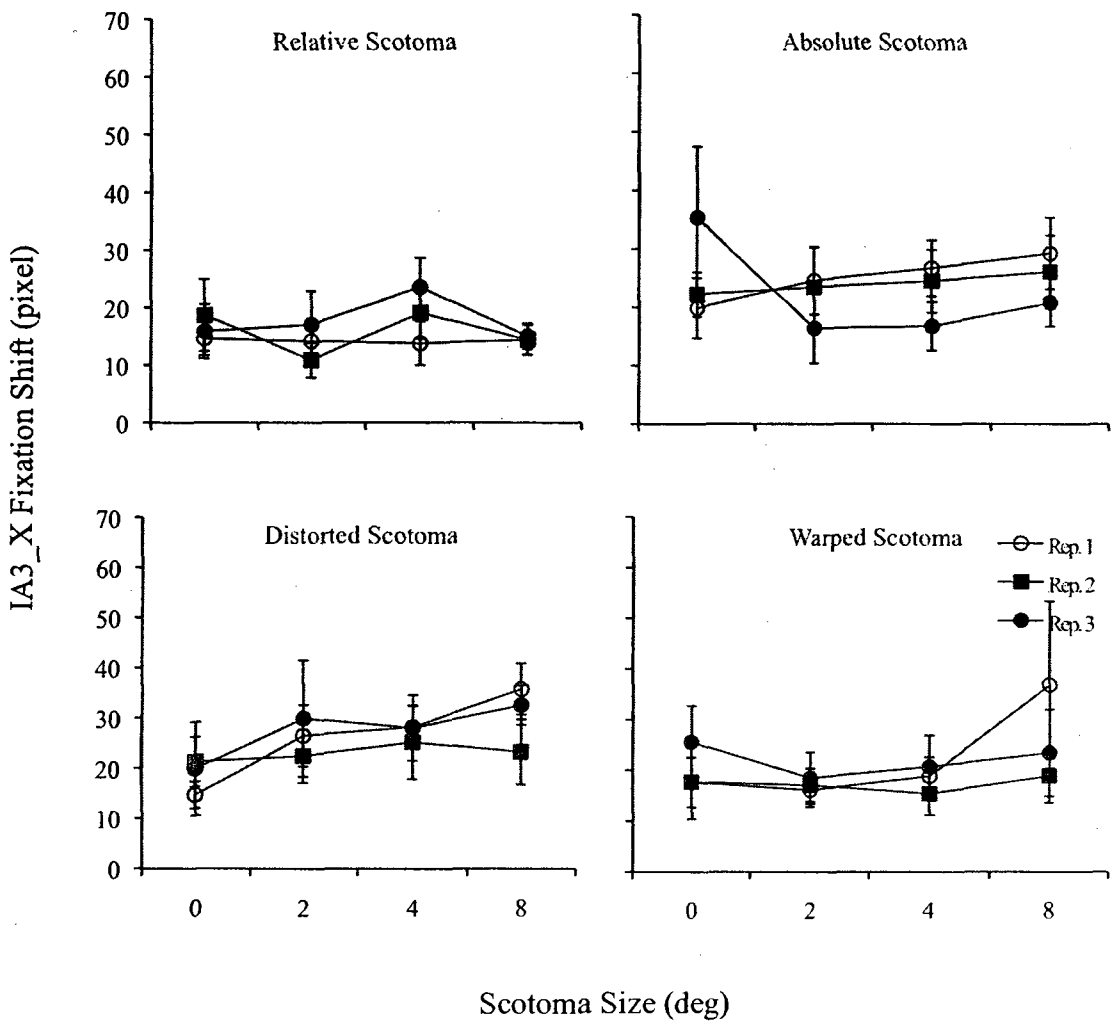


Figure 9. For IA3 in Category 4, fixation shifts along the X-axis increased as a function of scotoma size, in Experiment 1. Error bar refers to the standard error of the mean.

Preferred Eccentric Viewing Angle. The viewing angle (θ) was computed according to the following equation in each IA as the average of all fixation shifts in the IA:

$$\theta = \arctan((-Y(\text{fixation shift})/X(\text{fixation shift})).$$

The zero coordinate of the Y-axis is defined as the upper left corner of the display screen, and thus would be in the opposite direction of the angle calculation. Here, we calculated the angle θ in each IA, but using the direction of the Y-axis in the positive 90-degree direction. This is consistent with the traditional angle direction. The zero coordinates of the X and Y fixation shifts were in relation to the centers of the appropriate shape (see Figure 10).

For each IA, the mean viewing angle was computed for each participant and for each stimulus display in Category 4 as a function of within-subjects factors: scotoma size (0, 2, 4, 8 deg) and replication (3), and a between-groups factor: scotoma type (Relative, Absolute, Distorted, and Warped) and entered into a mixed-model factorial ANOVA.

There was no significant overall eccentric viewing angle difference within any IA. There were many variations in viewing directions across participants. However, when we studied the viewing angles across three IAs, we saw consistent patterns within each IA (see Figure 11). For IA1, the average viewing angle ranged from *-13.58* deg to *16.76* deg, which meant that the fixations were oriented toward the right visual field. For IA2, the average viewing angle ranged from *-64.83* deg to *-17* deg, which indicated that the fixations in this area on average also tended to shift toward the right-lower visual field. For IA3, the average viewing angle ranged from *-16.37* deg to *33.46* deg, again indicating that the average fixations were directed toward the right and shifted between the upper

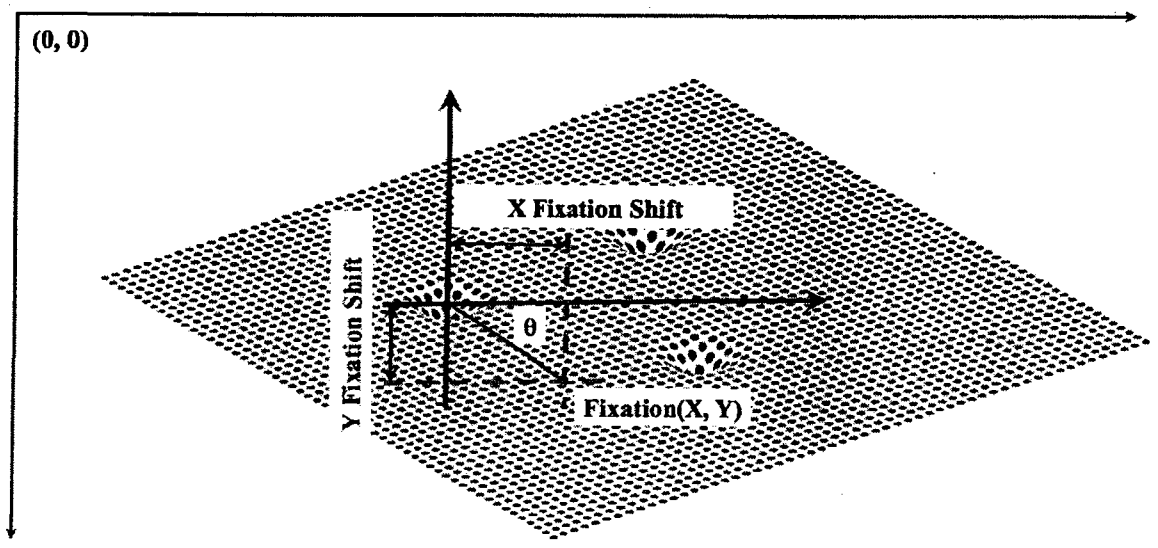


Figure 10. A demonstration of the computation of preferred eccentric viewing angle (θ) in Experiment 1 and 2. The coordinate (0, 0) represents the computer system defined zero coordinates in which the Y-axis is opposite to the direction of the angle calculation.

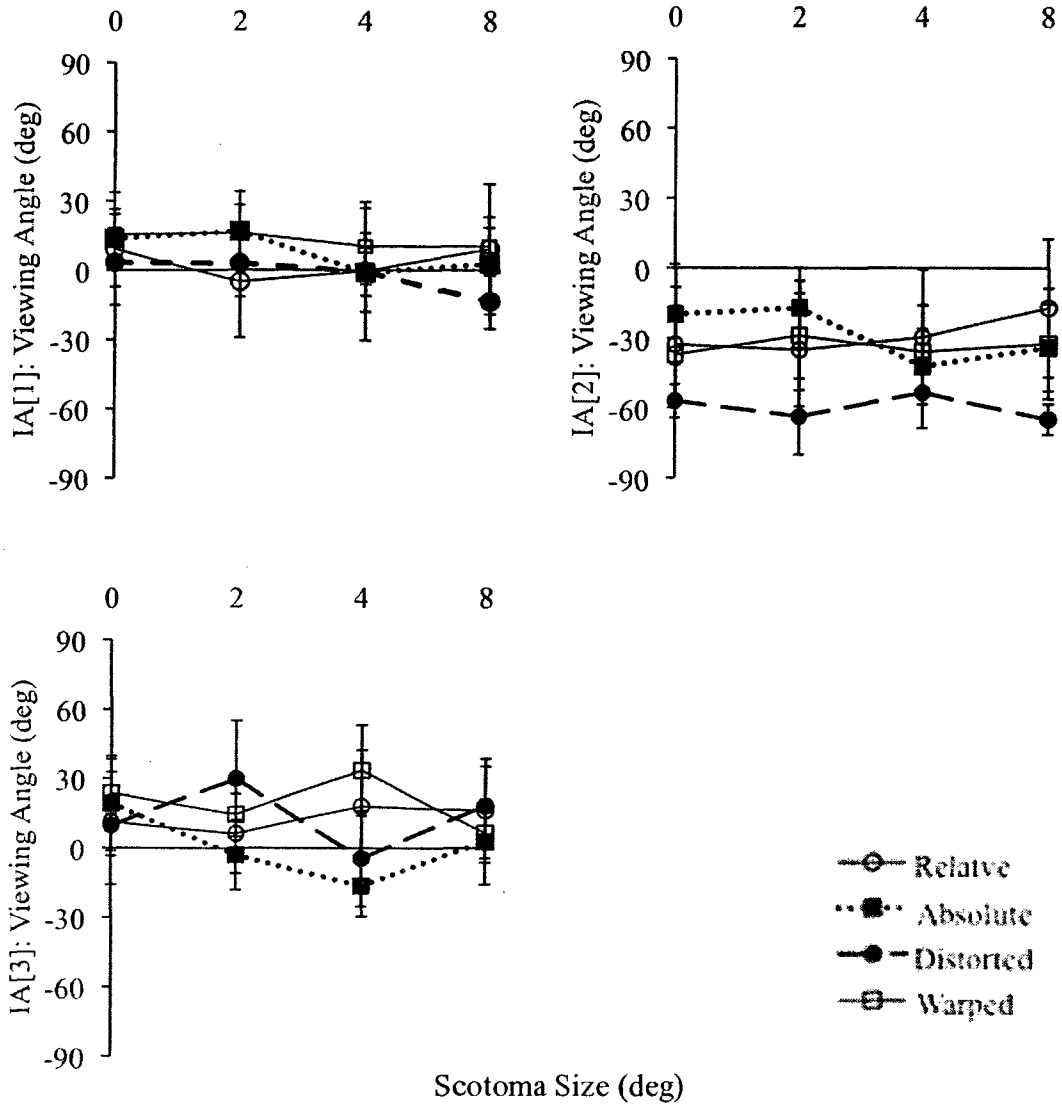


Figure 11. A demonstration of preferred eccentric viewing angle in 3 IAs in Category 4, Experiment 1. The scotoma size and type, as well as replication did not significantly change observers' viewing pattern. There was a consistent tendency that observers shifted eyes towards the right visual field. Error bar refers to the standard error of the mean.

and lower visual fields. If combined with the X- and Y- fixation shifts from the previous analysis, there was a tendency that observers shifted their eyes along the X-axis and towards the right.

Regression Path Fixation Duration in Interest Areas. Regressive eye movements occur when the eyes are re-fixated in previously fixated areas. This measure included the first path fixations on the given IA, the time spent in previous IAs following regressive eye movements, and the time due to re-fixations before the eyes moved past the given IA.

For IA2 and IA3 in Category 4, the average regression path fixation durations were calculated for each participant as a function of within-subjects factors: scotoma size (0, 2, 4, 8 deg) and replication (3), and a between-groups factor: scotoma type (Relative, Absolute, Distorted, and Warped) and entered into a mixed-model factorial ANOVA.

For the regression path fixation duration of IA2 (see Figure 12), we found a significant main effect of scotoma size, $F(3, 54) = 18.12, p < .01, \eta^2_p = 0.50$. When scotoma size increased, participants had to generate more regressive fixations in order to select a proper retinal area to identify the shape. There was also a main effect of replication, $F(2, 36) = 11.87, p < .01, \eta^2_p = 0.40$. The time participants spent for regressive fixations significantly decreased as the replication increased. This indicates that practice facilitated the efficiency of locating and using an extrafoveal retinal location for object identification. There was a main effect of scotoma type as well, $F(3, 18) = 4.55, p < .05, \eta^2_p = 0.43$, showing that scotoma type made a significant difference on regression fixation path duration. Among the four types of scotoma, observers spent the least amount of time on regression fixations when they had a Relative scotoma. The

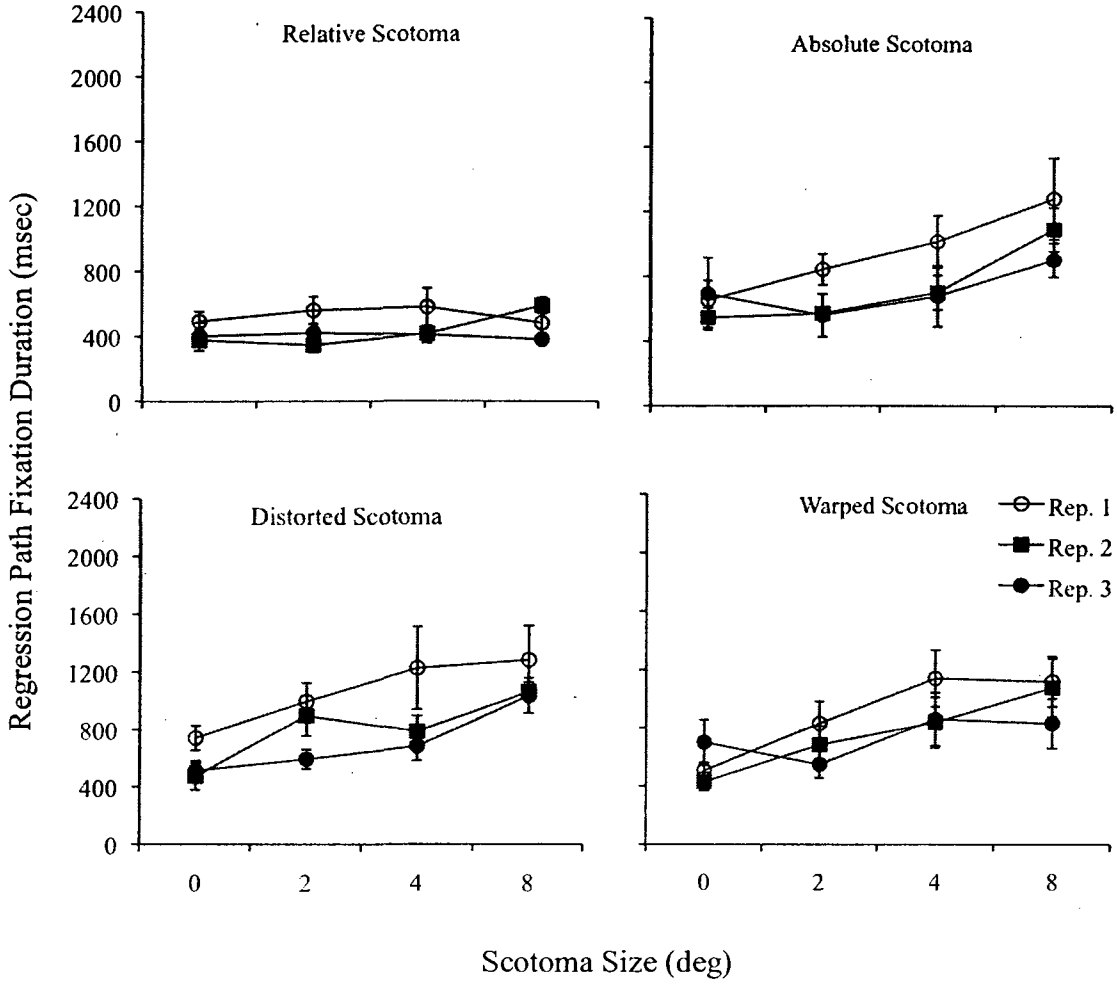


Figure 12. Regression path fixation duration of IA2 in Category 4 in Experiment 1. Regressive fixation duration increased as a function of scotoma size, and decreased as a function of replication. The Relative scotoma had the least regressive fixation duration among all 4 types of scotoma. The Distorted scotoma was the most effortful condition. Error bar refers to the standard error of the mean.

Distorted scotoma type resulted in the longest re-fixation durations, and therefore seemed to require the most effortful strategy for the participants to be able to solve the given task.

For the regression path fixation duration of IA3 (see Figure 13), we also found a significant main effect of scotoma size, $F(3, 42) = 20.74, p < .01, \eta^2_p = 0.60$, showing that observers' re-fixation duration increased as a function of scotoma size. There was a main effect of replication as well, $F(2, 28) = 14.64, p < .01, \eta^2_p = 0.51$. As expected, observers' regression fixations decreased as a function of replication. The scotoma type also had a significant influence on regressive fixation behavior, $F(3, 14) = 4.43, p < .02$, $\eta^2_p = 0.49$. Again, the Relative scotoma was the least difficult condition, and observers spent the least amount of time to generate regressive eye movements. The Absolute scotoma was the worst case.

The analysis of the regression path fixation duration variable was very useful to demonstrate observers' eye movement behavior while they have to deal with a central scotoma. When the central visual field was no longer functioning, dysfunctioning, or decreased in available contrast, observers were forced to move their eyes back and forth more in order to find a good peripheral retinal location to identify the shape. It was clear that this search process was very effortful, especially when the scotoma size increased. The novel results of this variable also indicated that the Absolute and Distorted central scotomata were the worst conditions. The Distorted central scotoma with a static distortion was to a certain degree similar to a complete loss of central visual functioning (Absolute scotoma), except it had an uneven distribution of distortions. Therefore, this result suggests that a complete loss of the central visual field was the most detrimental condition in terms of the efficiency of using the extrafoveal retinal location.

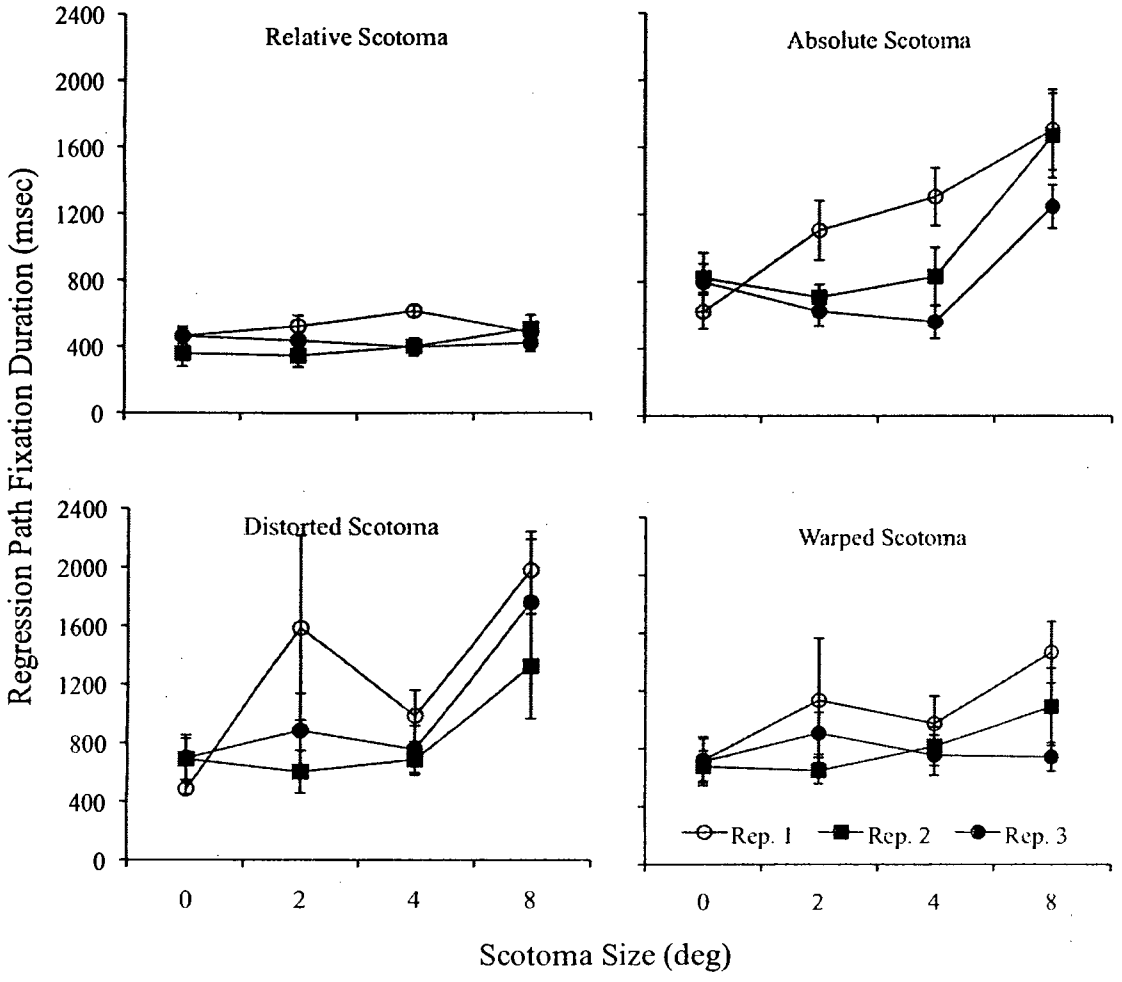


Figure 13. Regression path fixation duration of IA3 in Category 4 in Experiment 1. Regressive fixation duration increased as a function of scotoma size, and decreased as a function of replication. The relative scotoma had the least regressive fixation duration among all 4 types of scotoma. The Absolute scotoma was the most effortful condition. Error bar refers to the standard error of the mean.

Trial Duration. This variable was defined as the time interval between the stimulus onset and the last response that an observer made. This variable gave us an overall picture of the effect of different types and sizes of central scotomata on observers' eye movement capacity. The average trial duration was computed for each participant as a function of within-subjects factors: scotoma size (0, 2, 4, 8 deg) and replication (3), and a between-groups factor: scotoma type (Relative, Absolute, Distorted, and Warped) and entered into a mixed-model factorial ANOVA.

As expected, there was a significant main effect of scotoma size, $F(3, 60) = 61.78$, $p < .01$, $\eta^2_p = 0.76$, showing that when scotoma size increased, the task became more difficult, and observers spent a significantly longer time in a trial. There was also a significant main effect of replication, $F(2, 40) = 60.46, p < .01$, $\eta^2_p = 0.75$. Moreover, there was also a main effect of scotoma type, $F(3, 20) = 3.10, p = .05$, $\eta^2_p = 0.32$ (see Figure 14). Therefore, the types of scotoma influenced the overall time that observers spent in a particular trial. Observers spent significantly less time in a trial with a Relative central scotoma. The Absolute, Distorted, and Warped scotomata did not differ significantly in the overall trial duration. In clinical settings, these three conditions are also the most disrupting conditions. Our findings here are therefore consistent with the known clinical manifestations.

Total Fixation Count. The average overall number of fixations was computed for each participant as a function of within-subjects factors: scotoma size (0, 2, 4, 8 deg) and replication (3), and a between-groups factor: scotoma type (Relative, Absolute, Distorted, and Warped) and entered into a mixed-model factorial ANOVA.

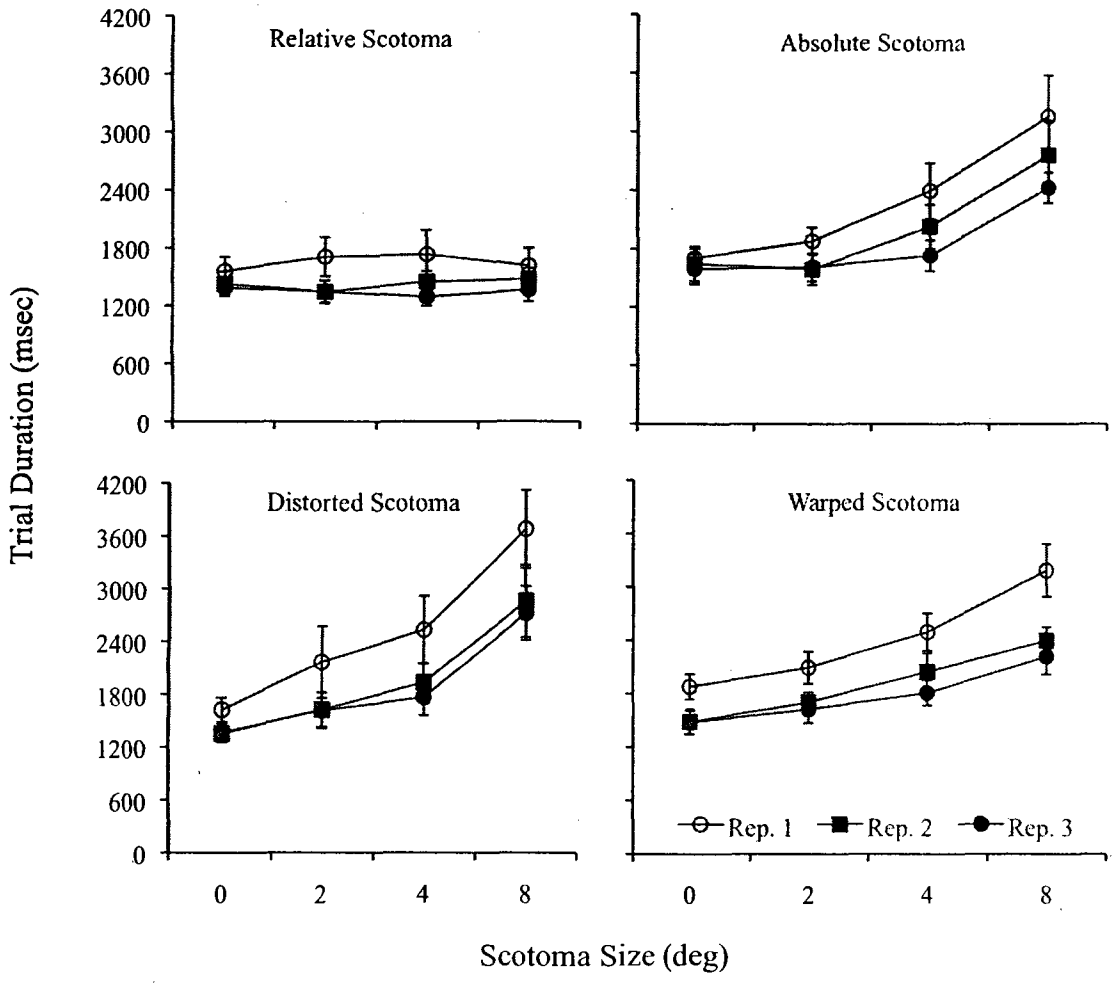


Figure 14. The average overall trial duration across participants (n =24) increased as a function of scotoma size, and decreased as a function of replication in Experiment 1. Among all 4 types of scotoma, the Relative scotoma was the least effortful condition. Error bar refers to the standard error of the mean.

There was a main effect of scotoma size, $F(3, 60) = 28.01, p < .01$, $\eta^2_p = 0.58$ and a main effect of replication, $F(2, 40) = 14.67, p < .01$, $\eta^2_p = 0.42$. There was also a significant scotoma size and type interaction, $F(9, 60) = 7.91, p < .01$, $\eta^2_p = 0.54$, showing that overall fixation numbers increased as a function of scotoma size, depending on the scotoma type (see Figure 15). For the Relative scotoma, when we increased scotoma size (0, 2, 4, 8deg), the average number of overall fixations was *5.72, 4.94, 4.94, 4.28*, respectively, showing that there was a difference of only about one fixation when scotoma size changed. For the Absolute scotoma, the average number of overall fixations was *4.39, 4.61, 5.67, 9.39*, for the 0, 2, 4, 8 deg scotoma sizes. For the Distorted scotoma, the average number of overall fixations was *4.50, 4.61, 5.67, 8.83*, for the 0, 2, 4, 8 deg scotoma sizes, respectively. For the Warped scotoma, the average number of overall fixations was *4.56, 4.44, 5.27, 6.61*, for the 0, 2, 4, 8 deg scotoma sizes, respectively. Clearly, for Absolute, Distorted, and Warped scotomata, the average number of fixations increased as a function of scotoma size. This suggests that observers with a reduced contrast central scotoma did not need to generate many eye movements to identify the target. In contrast, with no or distorted central stimulation, observers engaged in excessive eye movements, since they needed to locate a proper retinal locus for fixations. When we looked at the average fixation numbers of the Relative scotoma condition, however, we saw a slight decrease in fixation numbers when the scotoma size increased. This suggests that when there is only a reduction of central contrast, fixation stability actually increased. Why is there this difference to the other three types of scotoma? We suggest that this is another indication that the Absolute, Distorted, and Warped scotomata led to a specific altered viewing pattern, since the central visual field was too much

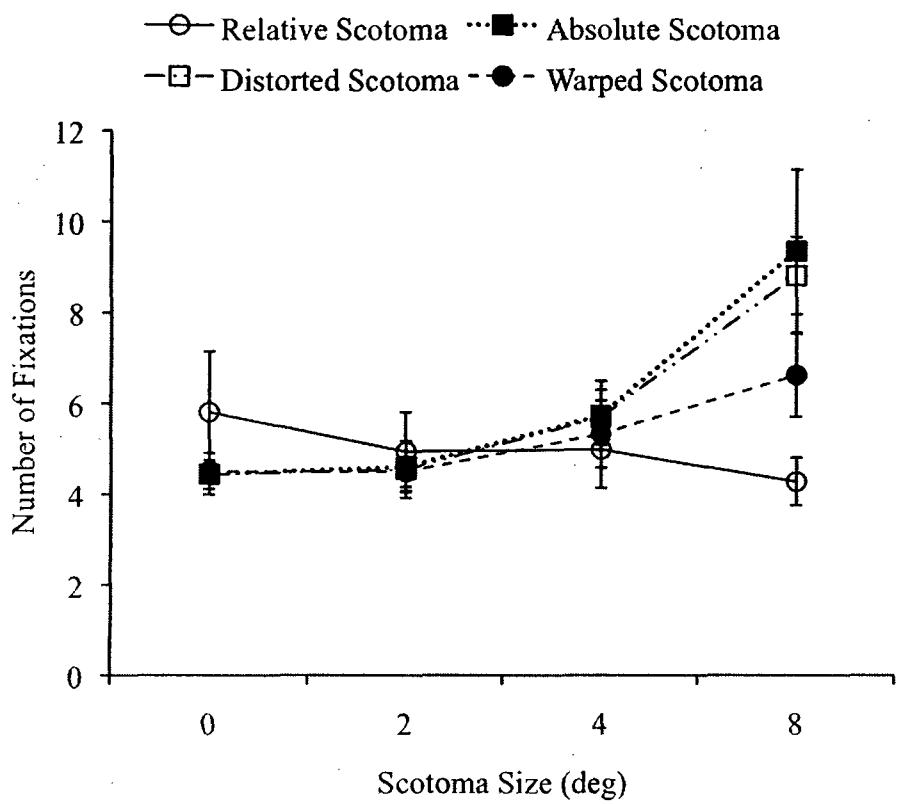


Figure 15. For each type of scotoma, the total number of fixations averaged over three replications in Experiment 1. The total number of fixations increased as a function of scotoma size for Absolute, Distorted, and Warped scotomata, but not for the Relative scotoma type. Error bar refers to the standard error of the mean.

affected so that it was no longer able to function to any useful degree. The situation is different in the case of the Relative scotoma, where observers were still able to use the residual function of the central visual field to identify objects.

Experiment 2

Rationale

Thus far, we focused on the degree to which a simulated central scotoma could interfere with visual performance and eye movement behavior among young adults. In Experiment 2, we tried to address the age factor. Aging creates cognitive changes in individuals, but it was often assumed that those changes were detrimental. For example, many people believe that elderly people perform more slowly and worse than young people. Previous studies have shown that normally sighted old adults read more slowly than young adults (Bowers, 2000; Akutsu, Legge, Ross, & Schuebel, 1991). Others, by using a multiple-regression model of reading speed with different vision- and motor-related measures as predictors, showed that age did not add additional predictive power (Legge, Ross, Isenberg, & LaMay, 1992), which suggested that age *per se* is unlikely to explain the slower reading speed.

Some neurophysiological studies on the brains of monkeys showed that some parameters do not change with age, such as the numbers of neurons in the neocortex and hippocampal formation. Changes in other parameters, such as a decrease in the thickness of layer I in primary visual cortex, can be positively correlated with chronological age. Those changes can correlate either with cognitive decline alone, or with both cognitive decline and chronological age (Peter et al., 1996).

A study by Betts, Taylor, Sekuler, and Bennett (2005) reported that on a visual motion processing test, elderly people had difficulties to focus on one thing and ignore everything else, but they were able to grasp the "big picture" quicker than young people.

They suggested that this was due to the fact that elderly people did not inhibit superfluous information in the same way that young people did.

Inspired by these previous results, in Experiment 2, we focused on comparing the spatial and temporal eye movement characteristics and response efficiency between young and old adults on the same 3D shape-from-texture identification task with a Distorted form of central scotoma, which varied in size (0, 2, 4, 8 deg). We were able to study the degree to which old adults with central visual field deficits used their residual visual field to perform visual tasks. This may provide new information for low vision research and open new possibilities for training elderly people with AMD.

To minimize the potential confounds such as abnormal vision, motor dysfunction, and cognitive deficiency associated with the aging population, in the current study we carefully used normally sighted adults with previous experience on instruments or well-educated old adults as our participants.

As in Experiment 1, the same variables of interest were measured. The index of response efficiency was defined by response latency and response accuracy. The temporal and spatial characteristics of eye movements were measured through several variables: 1) X and Y fixation shifts; 2) preferred eccentric viewing angle; 3) regression path fixation duration; 3) overall trial duration; 4) total fixation number.

We hypothesized that:

Hypothesis 1. There would be an experience-dependent plasticity in both groups. That is, through replications, both groups would have an improvement on response efficiency. Hence, the response latency would decrease as a function of replication, and the response accuracy would increase as a function of replication. However, due to the

cognitive decline associated with age, old adults would not function at the same level as young adults in terms of the response efficiency. In addition, there would be a decrease in response efficiency in both groups when the scotoma size increases (from Experiment 1).

Hypothesis 2. In terms of the spatial and temporal characteristics of eye movements, both groups would learn to use an extrafoveal retinal location for fixation, and the efficient use of this location would improve as a function of replications. Old adults would have greater difficulties to locate the extrafoveal retinal location for fixation than young adults. That means old adults would have greater X- and Y- fixation shifts, greater changes in viewing angle, and longer regressive fixation durations. Increasing the central scotoma size would impair the efficiency of locating an extrafoveal fixation area across all observers.

Method

Participants. Six old participants were recruited and were paid for their participation. They were all between 63 and 75 years of age ($M = 70.17$, $SD = 5.38$). All were naïve to the experimental hypotheses. Six young participants were the same as in Experiment 1, aged between 21 and 25 years of age ($M = 22.33$, $SD = 1.51$). All were treated according to *Tri-Council Policy Statement*: Ethical Conduct for Research Involving Humans (Medical Research Council of Canada, 2003). Informed consent was obtained from each participant. We did not retest the young group to obtain a new set of data; instead, we used the existing data obtained in Experiment 1. Participants were all tested for visual acuity with the ETDRS chart at a distance of 2 m with a letter-by-letter scoring method. The average visual acuity was 0.398 logMAR (20/50 or better). We also roughly assessed their visual field with a Damato 60-point campimeter chart to detect

visual field loss caused by eye disorders. None were found. Old participants were given the Montréal Cognitive Assessment (MoCA, see Appendix C) to screen for mild cognitive dysfunction. All had a score above 26, which was considered normal. We also required old adults to report if they had ocular diseases. None were reported. The old adults were all well educated and socially active, and some had played instruments for a long time. This minimized the impact of severe age-related decline on cognitive capacity.

Stimuli, Apparatus, and Procedure. The same experimental setting was used in Experiment 2. The stimuli, apparatus, and procedure were the same as those in Experiment 1, except we used only a Distorted central scotoma type, which was again varied in size (0, 2, 4, 8 deg) in Experiment 2.

Results & discussion

Response Latency. As in Experiment 1, response latency was computed for each participant as a function of within-subjects factors: scotoma size (0, 2, 4, 8 deg) and replication (3), and a between-groups factor: age (young, old) and entered into a mixed-model factorial ANOVA.

The response latency analysis revealed main effects of scotoma size, $F(3, 30) = 10.71, p < .01$, $\eta^2_p = 0.52$, and replication, $F(2, 20) = 13.39, p < .01$, $\eta^2_p = 0.57$, as well as an interaction between replication and age, $F(2, 20) = 4.01, p < .05$, $\eta^2_p = 0.29$, showing that old observers had greater difficulties to respond quickly at the first replication ($M = 3.04$, $SE = \pm 0.43$) when compared with young observers ($M = 1.75$, $SE = \pm 0.43$; see Figure 16). While the observers were performing the identification task with an 8 deg central scotoma, we noticed that old adults moved their eyes back and forth for a prolonged time before they made the first response. This behavior was very noticeable

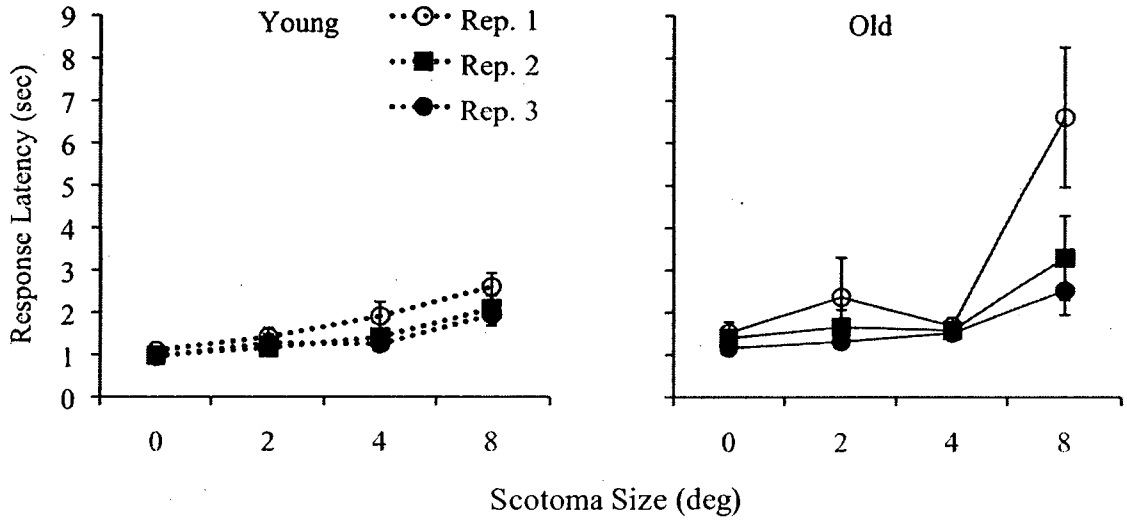


Figure 16. Mean response latency (in sec) across participants (n = 12) increased as a function of scotoma size, decreased as a function of replication, and there was an interaction of replication and age, in Experiment 2. Old adults took more time to initiate the first response especially in the first replication. Error bar refers to the standard error of the mean.

in the first replication.

Response Accuracy. A mixed-model factorial ANOVA of the number of correct responses revealed main effects of scotoma size, $F(3, 30) = 13.01, p < .01, \eta^2_p = 0.57$, and age, $F(1, 10) = 23.37, p < .01, \eta^2_p = 0.70$, as well as an interaction between age and scotoma size, $F(3, 30) = 5.21, p < .01, \eta^2_p = 0.34$, indicating that when scotoma size increased, the number of correct responses decreased significantly more for old observers (see Figure 17). Overall, old observers performed poorly on making accurate responses when compared with young adults (Mean difference was *-4.72 ± 0.98*), especially when the scotoma size increased to 4 and 8 deg. With an 8 deg scotoma, the average correct responses for old adults was *15.06 ± 1.55*, out of a maximum of 27. Old adults' performance got slightly better in the third replication, but did not reach the significance level. It seemed that old adults needed more practice to adapt to a central scotoma, especially for a large size scotoma.

X, Y Fixation Shifts. As in Experiment 1, the X- and Y- fixation shifts were computed according to the average of the following two equations in each IA:

X(fixation shift) = $ABS(X$(fixation coordinate) – X(shape central coordinate))

Y(fixation shift) = $ABS(Y$(fixation coordinate) – Y(shape central coordinate)).

The zero points of the coordinates of fixations in each IA were the X and Y coordinates of each shape.

Again, we focused for Category 4 of stimulus conditions, in which the 3 shapes were all presented, a situation that is likely to generate more eye movements. As in Experiment 1, the same interest areas were set. For each IA, the mean X and Y fixation

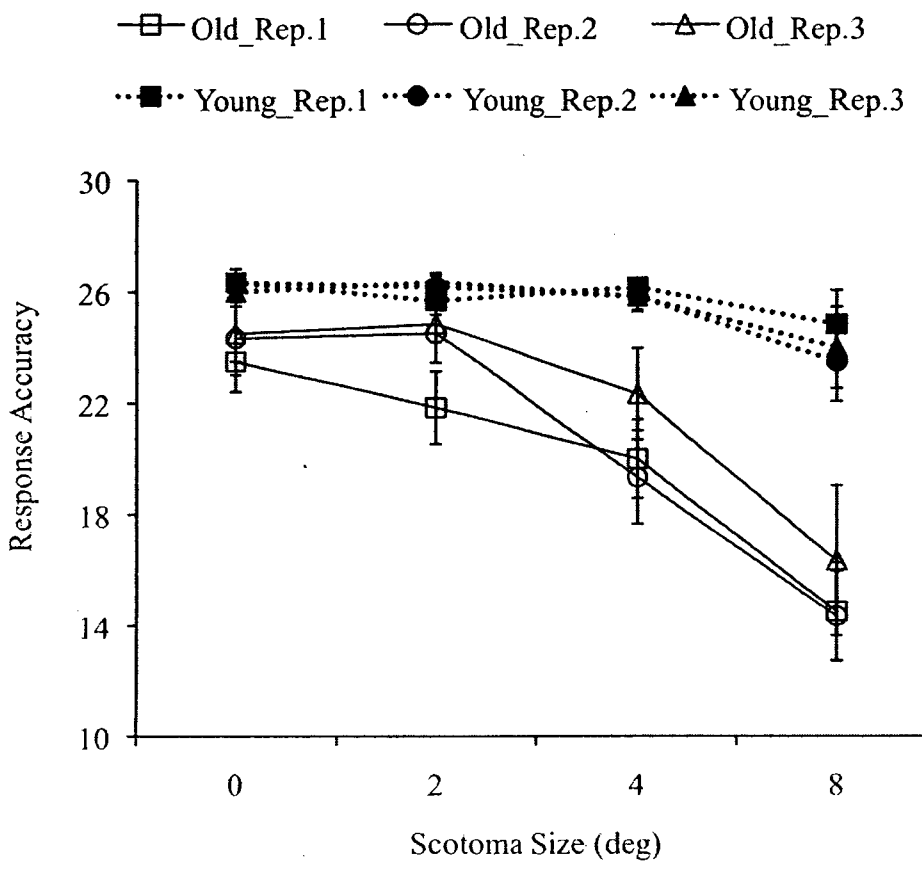


Figure 17. Mean response accuracy across participants (n = 12) decreased as a function of scotoma size. For old adults, the mean response accuracy decreased significantly when the scotoma size increased in Experiment 2. When there was an 8 deg scotoma, the difference in response accuracy between old and young adults was highly significant. Error bar refers to the standard error of the mean.

shifts were computed for each participant and for each stimulus display in Category 4 as a function of scotoma size (0, 2, 4, 8 deg), replication (3), and age (young, old) and entered into a mixed-model factorial ANOVA.

For fixation shifts along the X-axis in IA1, there was a significant main effect of replication, $F(2, 20) = 7.59, p < .01, \eta^2_p = 0.43$, showing that observers placed their fixations further away from the shape along the X-axis after a few replications. The mean difference between replication 1 and 2 was *-6 ± 2* pixels, and the mean difference between replication 1 and 3 was *-8 ± 2* pixels. This was true for both young and old observers, which suggested a strategical displacement of fixations after learning (see Figure 18). For fixation shifts along the Y-axis in IA1 (see Figure 19), there was a significant main effect of scotoma size, $F(3, 30) = 4.84, p < .01, \eta^2_p = 0.33$. As the scotoma size increased, observers' fixations shifted further away from the shape along the Y-axis, especially for the 4 and 8 deg scotomata. There was also a main effect of age, $F(1, 10) = 6.10, p < .05, \eta^2_p = 0.38$; indicating that old participants displaced fixations further away from the shape along the Y-axis as compared with young participants (with a mean difference of *24 ± 10* pixels).

For the fixation shifts along the X-axis in IA2, there was only a significant scotoma size effect, $F(3, 30) = 3.62, p < .05, \eta^2_p = 0.27$, showing that both young and old observers displaced the fixations further away from the shape along the X-axis when they had 2 and 4 deg scotomata. Along the Y-axis in IA2, there was a main effect of scotoma size, $F(3, 30) = 7.37, p < .01, \eta^2_p = 0.42$, indicating that observers displaced their fixations further away from the shape along the Y-axis when scotoma size increased, especially with an 8 deg scotoma (see Figure 20). Although there was no age difference

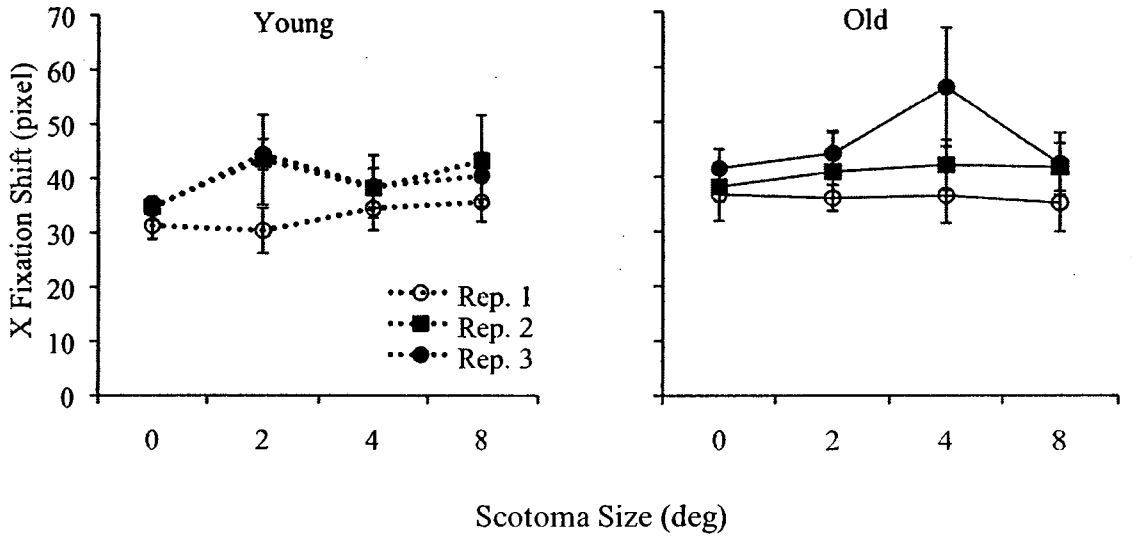


Figure 18. For IA1 in Category 4, both young and old adults' (n = 12) fixation shifts along the X-axis increased as a function of replication in Experiment 2. Error bar refers to the standard error of the mean.

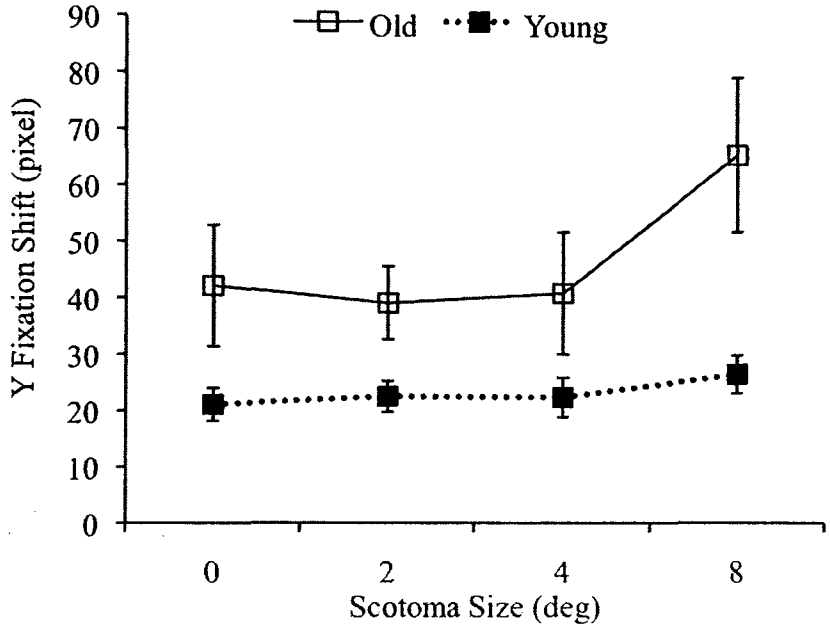


Figure 19. For IA1 in Category 4, fixation shifts along the Y-axis increased as a function of scotoma size and age in Experiment 2. Old adults displaced fixations much further away from the shape when compared with young adults. Error bar refers to the standard error of the mean.

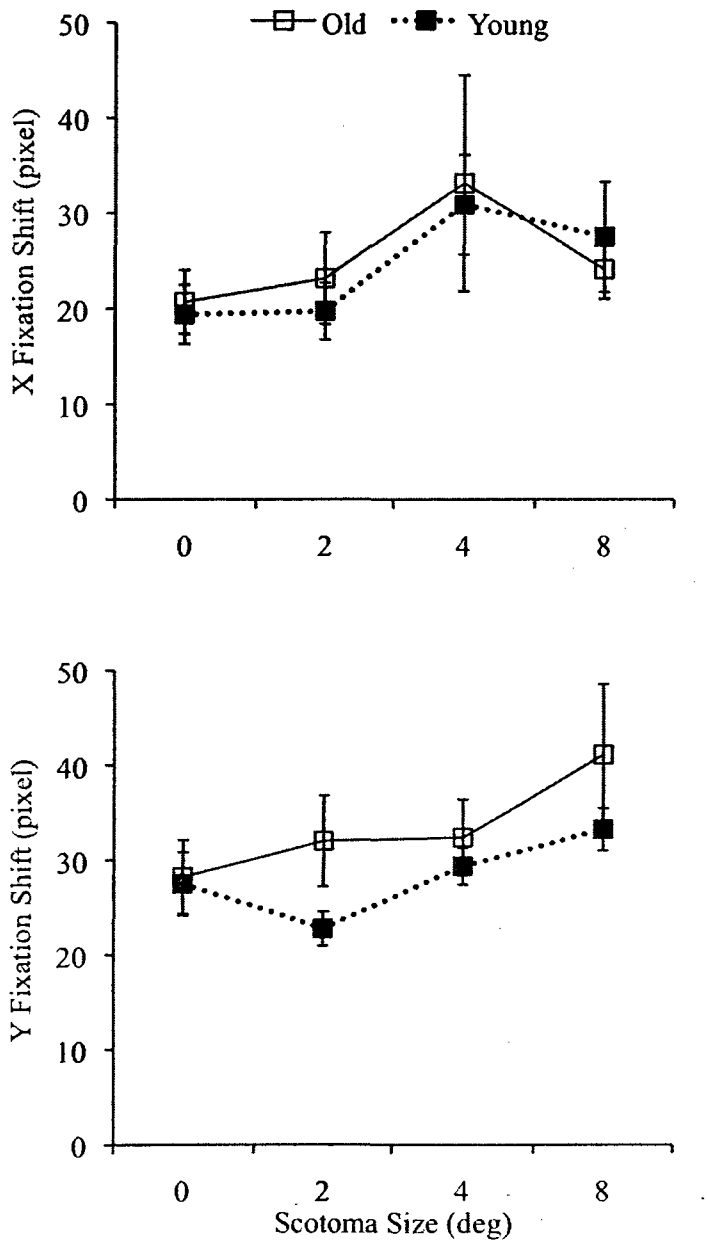


Figure 20. For IA2 in Category 4, fixation shifts along the X-axis increased as a function of scotoma size across participants (n = 12) in Experiment 2, especially for 2 and 4 deg scotomata. Along the Y-axis, fixation shifts increased as a function of scotoma size, especially for the 8 deg scotoma. Error bar refers to the standard error of the mean.

for fixation shifts along the X- and Y- axes overall, it still showed that old observers had a slightly larger fixation shift along the Y-axis (with a mean difference of *5 ± 5* pixels).

For the fixation shifts along the X-axis in IA3, there was a main effect of scotoma size, $F(3, 18) = 3.58, p < .05, \eta^2_p = 0.37$, and a main effect of age, $F(1, 6) = 9.42, p < .05, \eta^2_p = 0.61$ (with a mean difference of *14 ± 5* pixels; see Figure 21). There was no Y-axis effect on either variable of interest. Therefore, in IA3, both young and old adults shifted their fixations away along the X-axis especially with an 8 deg scotoma. The mean difference of X-fixation shifts between the no-scotoma and 8 deg scotoma conditions was *-11 ± 2* pixels. Overall, old adults shifted fixations further away along the X-axis than young adults.

There was a robust scotoma size effect in each IA. This suggests that the size of the residual visual area played a crucial role on visual performance. To a certain extent, the use of an extrafoveal location for fixating might not be possible for patients with AMD. Moreover, the X- and Y- fixation shifts appeared to vary for the different IAs. In certain IAs, there were significant fixation shifts in both the X and Y directions; but in another, there were only shifts in one direction. This result needs to be considered together with the variable of preferred eccentric viewing angle, which will be discussed below. In addition, old adults tended to have a larger fixation shift, and more so in the Y direction. It is not clear why old adults showed this type of eye movement behavior. It is possible that it is related to the effort, which is needed to pay attention to a location in the visual field without looking at it directly. Good effort would facilitate the recognition of targets (von Helmholz, 1896). Old adults may have put additional effort into moving their

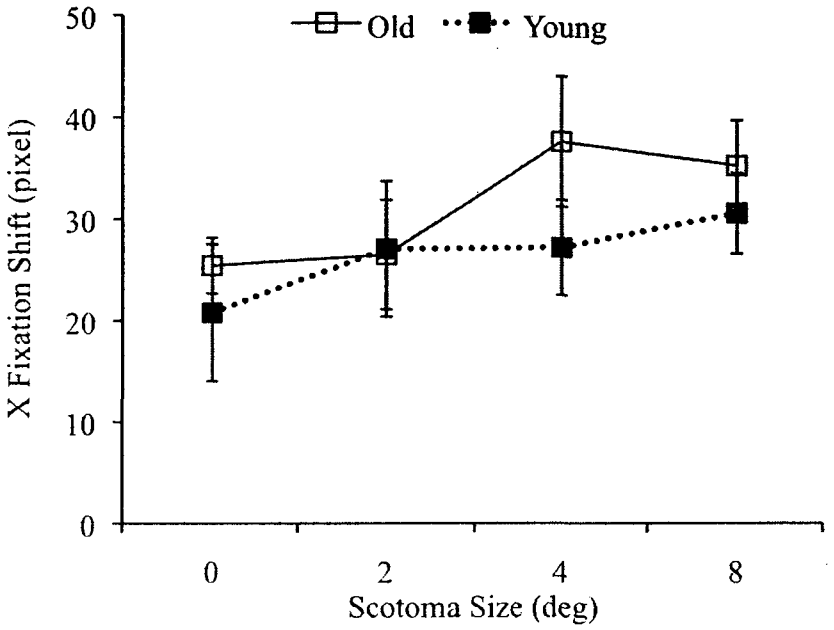


Figure 21. For IA3 in Category 4, fixation shifts along the X-axis increased as a function of scotoma size across participants (n = 12), and age, in Experiment 2. Old adults displaced fixations much further away from the shape along the X-axis when compared with young adults. Error bar refers to the standard error of the mean.

eyes further away from the shape during the task in order to achieve good performance.

Preferred Eccentric Viewing Angle. The viewing angle (θ) was computed according to the average of the following equation in each IA:

θ = arctan((-Y(fixation shift)/X(fixation shift)).

As in Experiment 1, the zero coordinate of the Y-axis is defined as the upper left corner of the display screen, and thus would be in the opposite direction of the angle calculation. Here, we used the direction of the Y-axis in the positive 90-degree direction. This is consistent with the traditional angle direction. The zero coordinates of the X and Y fixation shifts were in relation to the centers of the appropriate shape.

For each IA of Category 4, the mean viewing angle was computed for each participant and for each stimulus display as a function of within-subjects factors: scotoma size (0, 2, 4, 8 deg) and replication (3), and a between-groups factor: age (young, old) and entered into a mixed-model factorial ANOVA.

There was only one significant age effect on eccentric viewing angle, which occurred in IA2, $F(1, 10) = 11.95, p < .01, \eta^2_p = 0.54$ (see Figure 22). In IA1 and IA3, there was no significant viewing angle change across all experimental manipulations. In IA2, the average eccentric viewing angle for old adults was *-7.91* deg with a standard error of *10.60.* For young adults, the average eccentric viewing angle was *-59.70* deg with a standard error of *10.60.* Both groups were directing their eyes toward the lower-right visual field. However, the eccentric viewing angle for old adults was significantly smaller than that for young adults, even when the scotoma size was increased to 8 deg. As mentioned above, old adults had a larger fixation shift when compared with young adults. This suggests that old adults tended to move their fixations further away from the shape

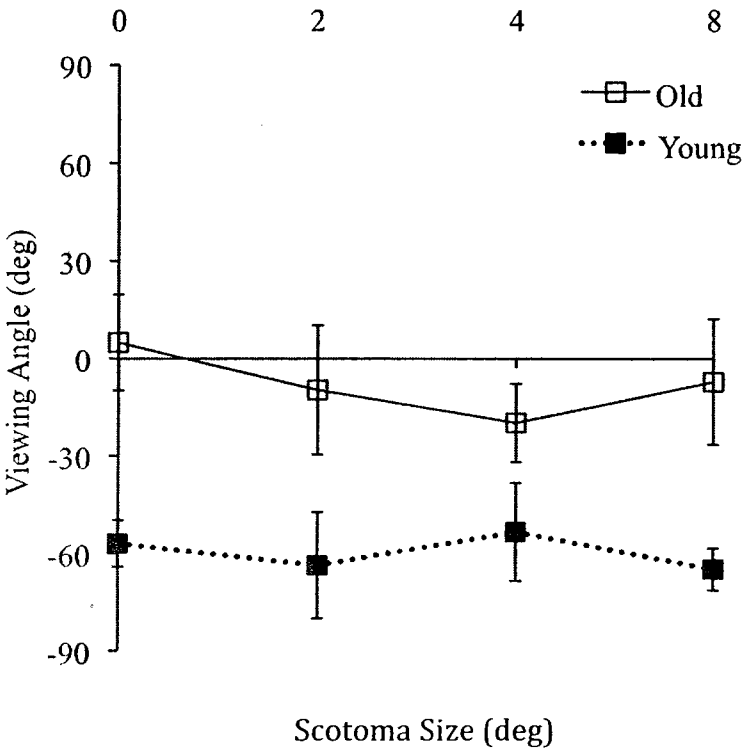
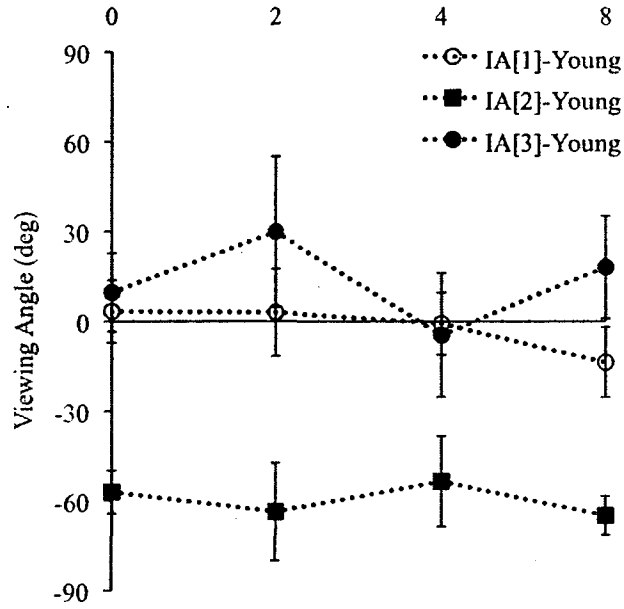


Figure 22. For IA2 in Category 4, preferred eccentric viewing angle (in deg) changed as a function of age in Experiment 2. Error bar refers to the standard error of the mean.

but with a small change in viewing angle to identify the contour of the shape. In contrast, young adults had smaller displacements in eye position, but this was accompanied by a greater angular change.

When we compared preferred eccentric viewing angle across the 3 IAs (see Figure 23), we noticed that in IA2 both young and old adults preferentially made eye movements towards the lower visual field, while in IA1 and IA3, the preferred eccentric viewing angles were often in the upper visual field. This led us consider the idea that the choice of direction for orienting the eyes might be determined by the context. In the stimulus displays, there were three shapes, which were located in different geographic areas. On a 1024 x 768 display screen, the central X and Y positions for each shape were: Shape 1 (IA1; 378, 378); shape 2 (IA2; 530, 318); shape 3 (IA3; 570, 416) in pixel units with the origin in the upper left corner. We instructed observers to identify the shapes in a clockwise order, starting with Shape 1. Hence, while observers were identifying a particular shape, they might be already moving their eyes towards the next shape, in order to achieve a fast response time. It appears that young observers, when analyzing Shape 2 strongly lowered their gaze toward Shape 3. This would explain the large negative viewing angle found in this condition.

a)



b)

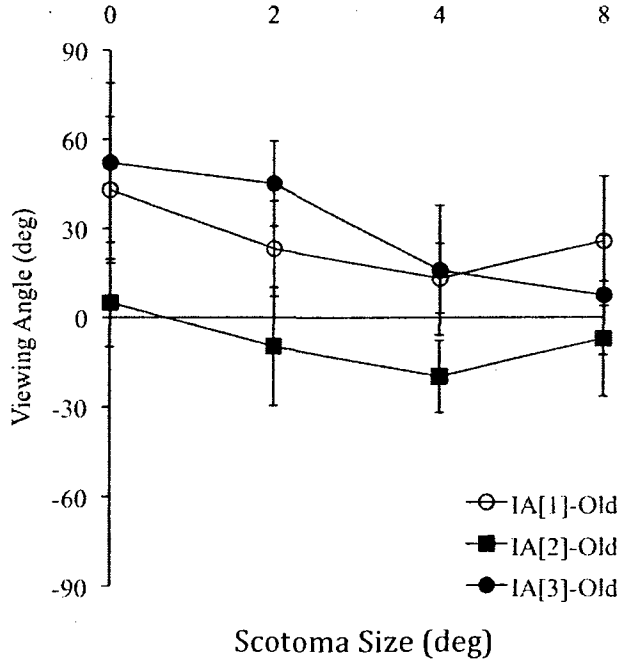


Figure 23. A demonstration of preferred eccentric viewing angle in 3 IAs in Category 4, Experiment 2: a) young adults; b) old adults. Error bar refers to the standard error of the mean.

Regression Path Fixation Duration in Interest Areas. As in Experiment 1, this included the first path fixations on the IA, time spent in previous IAs following regressive eye movements, and time due to re-fixations before the eyes moved past the given IA.

For IA2 and IA3 of Category 4, the average regression path fixation durations were calculated for each participant as a function of within-subjects factors: scotoma size (0, 2, 4, 8 deg) and replication (3), and a between-groups factor: age (young, old) and entered into a mixed-model factorial ANOVA.

For IA2, there was a main effect of scotoma size, $F(3, 30) = 10.02, p < .01$, $\eta^2_p = 0.50$, a main effect of replication, $F(2, 20) = 4.43, p < .05$, $\eta^2_p = 0.31$, and a main effect of age, $F(1, 10) = 6.14, p < .05$, $\eta^2_p = 0.38$. There was also an interaction of scotoma size and age, $F(3, 30) = 3.36, p < .05$, $\eta^2_p = 0.25$ (see Figure 24). The regression path fixation duration increased as a function of scotoma size, and decreased as a function of replication. When the scotoma size increased, old adults had a significantly longer regression path fixation duration, compared with young adults, especially for 4 deg and 8 deg scotomata. This indicates that old adults generated many regressive saccades for identifying the shapes. Therefore, using an extrafoveal location for fixation was extremely effortful for old adults. However, old adults adapted to the condition quickly after a few replications.

For IA3, there was a main effect of scotoma size, $F(3, 18) = 5.49, p < .01$, $\eta^2_p = 0.48$, showing that the regressive fixation duration increased as a function of scotoma size (see Figure 25). There was a tendency that age might make a difference on the regressive fixation duration with a significant p value at *0.055*. The old adults had a greater

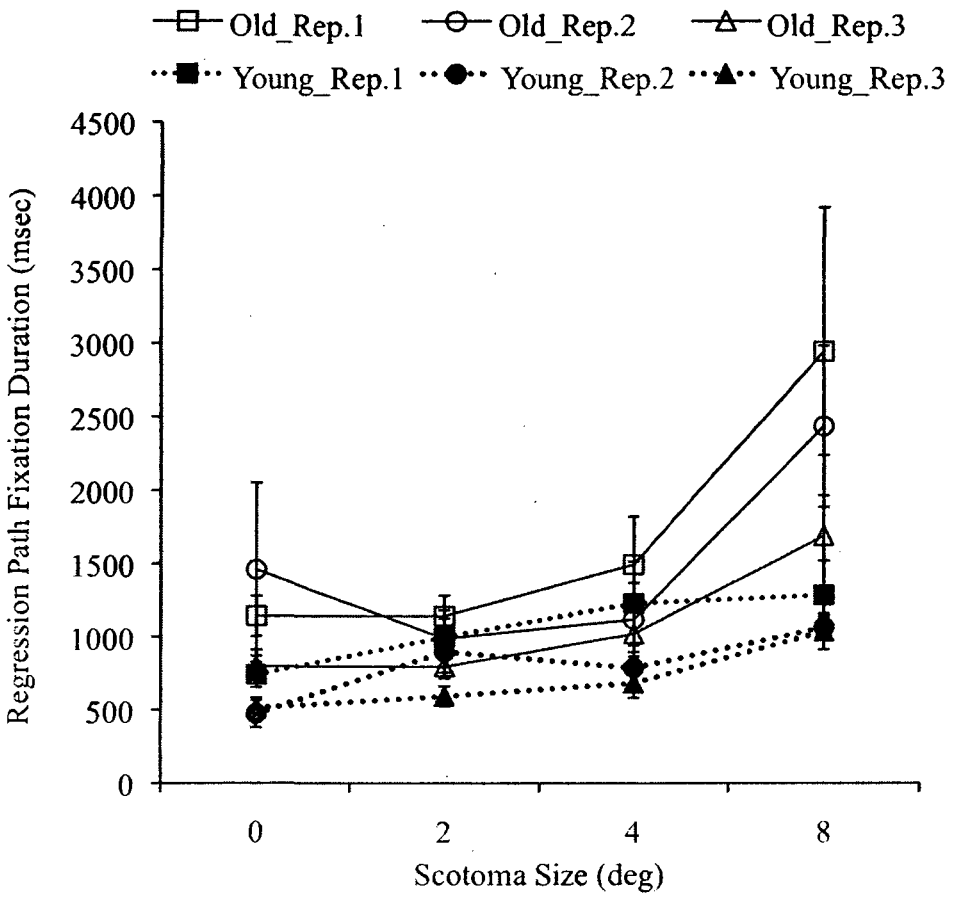


Figure 24. Regression path fixation duration of IA2 in Category 4 in Experiment 2. There was an interaction between scotoma size and age, showing that when scotoma size increased, old adults had an increased regressive fixation duration compared with young adults. Regressive fixation duration also decreased as a function of replication. Error bar refers to the standard error of the mean.

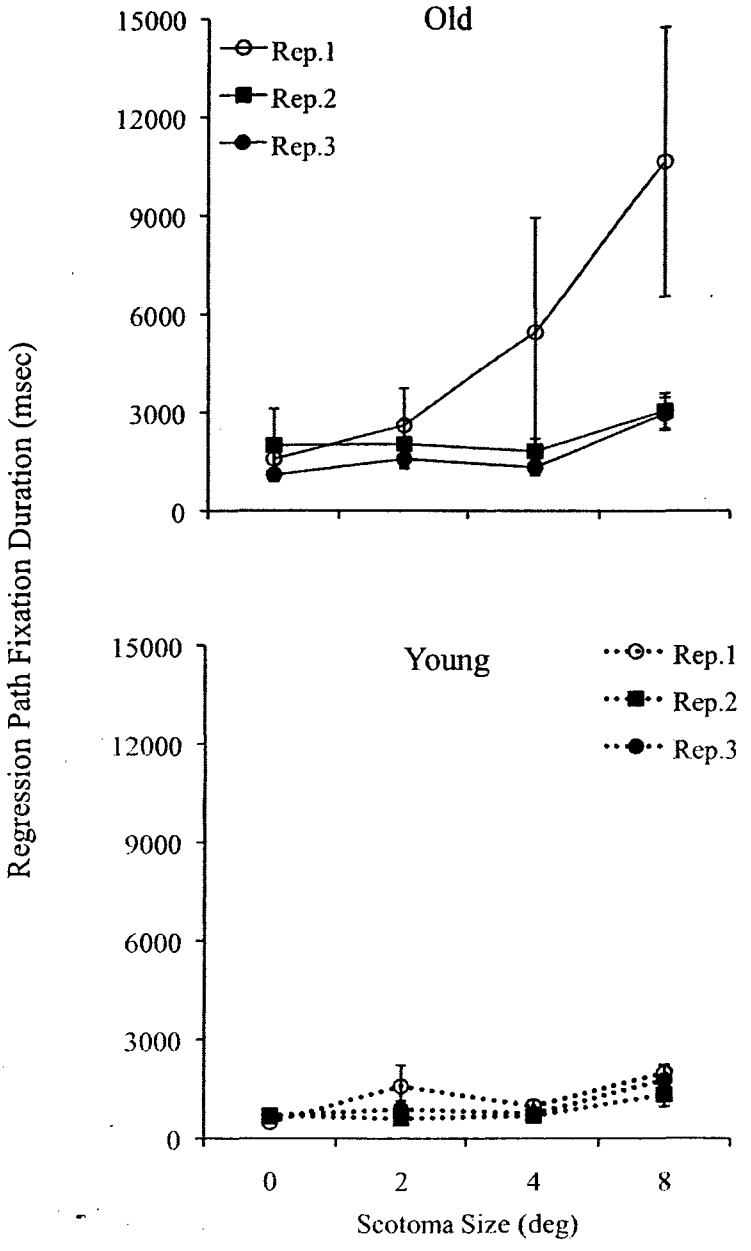


Figure 25. Regression path fixation duration of IA3 in Category 4 in Experiment 2. Regression path fixation duration increased as a function of scotoma size. Error bar refers to the standard error of the mean.

regressive fixation duration in replication 1, especially for 4 and 8 deg scotomata.

Trial Duration. The average trial duration was computed for each participant as a function of within-subjects factors: scotoma size (0, 2, 4, 8 deg) and replication (3), and a between-groups factor: age (young, old) and yet entered into a mixed-model factorial ANOVA.

There was a main effect of scotoma size, $F(3, 30) = 13.73, p < .01, \eta^2_p = 0.58$, showing that trial duration increased as a function of scotoma size. When observers had an 8 deg scotoma, their overall trial duration increased significantly as compared with other scotoma sizes ($M = 4914.47$, $SE = \pm 699.28$). As expected, there was a significant main effect of replication, $F(2, 20) = 9.19, p < .01, \eta^2_p = 0.48$. The mean difference of the average overall trial duration between the first and the third replication was *1653.61* msec. The learning curve was steep. Moreover, there was a significant main effect of age, $F(1, 10) = 8.75, p < .05, \eta^2_p = 0.47$, showing that old adults spent a significantly longer time in trials compared with young adults. The mean difference on trial duration between young and old adults was *-1935.73± 654.34* (see Figure 26), suggesting that old adults were less efficient in performing visual tasks by using extrafoveal retinal locations.

Total Fixation Count. The number of fixations was computed for each participant as a function of within-subjects factors: scotoma size (0, 2, 4, 8 deg) and replication (3), and a between-groups factor: age (young, old) and entered into a mixed-model factorial ANOVA.

As expected, there was a main effect of scotoma size, $F(3, 30) = 16.64, p < .01$, $\eta^2_p = 0.63$, a main effect of replication, $F(2, 20) = 8.18, p < .01, \eta^2_p = 0.45$, and a main effect of age, $F(1, 10) = 6.43, p < .01, \eta^2_p = 0.39$. The total number of fixations increased

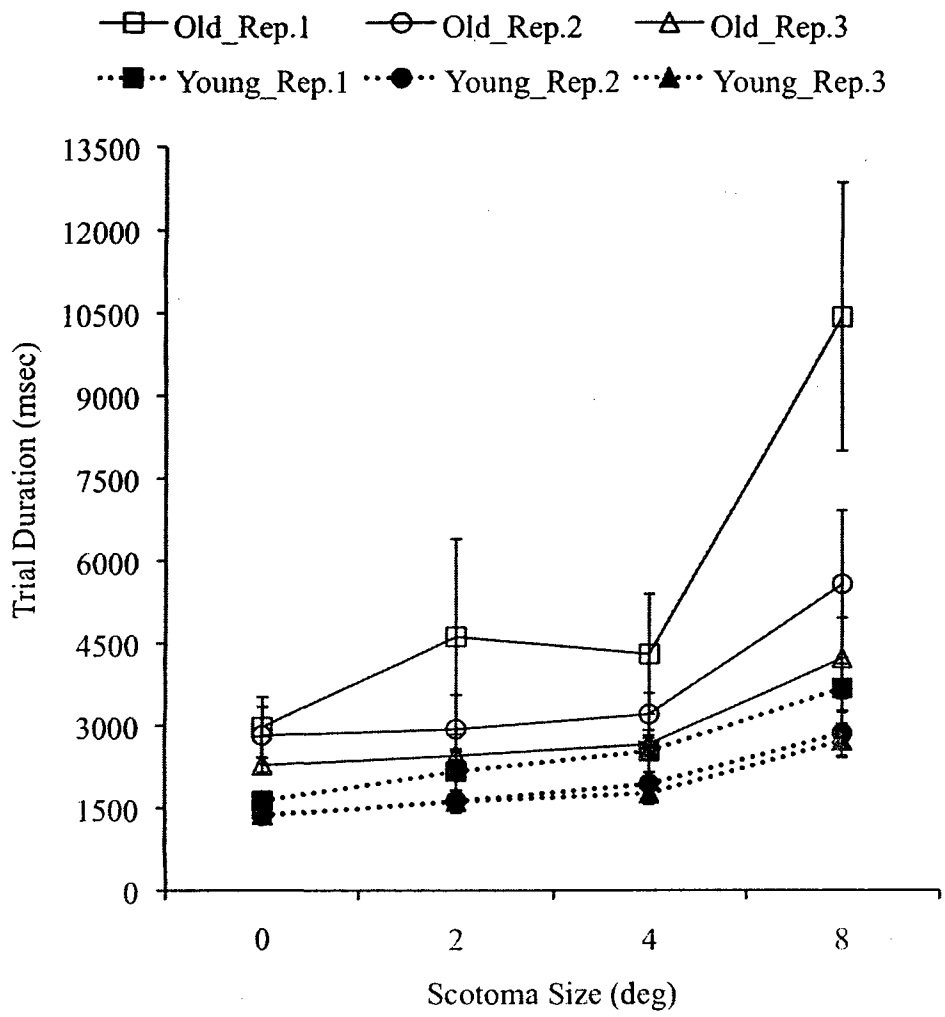


Figure 26. The average overall trial duration across participants (n = 12) increased as a function of scotoma size, and old adults had a significantly longer trial duration than young adults in Experiment 2. Error bar refers to the standard error of the mean.

as a function of scotoma size. The average total fixation numbers were 5.67, 6.14, 6.86, and 12.78, for the 0, 2, 4, and 8 deg scotomata, respectively. There were about twice as many fixations for the 8 deg scotoma. Therefore, the scotoma size had a detrimental impact on eye movement performance. There was also a decrease in the number of fixations as a function of replication. The mean difference of fixation numbers between the first and the third replications was *3.69± 1.26*. Again, learning occurred only within a few replications. Old adults still had more fixations when compared with young adults. The mean difference in fixation numbers between young and old adults was *-3.92± 1.55* (see Figure 27).

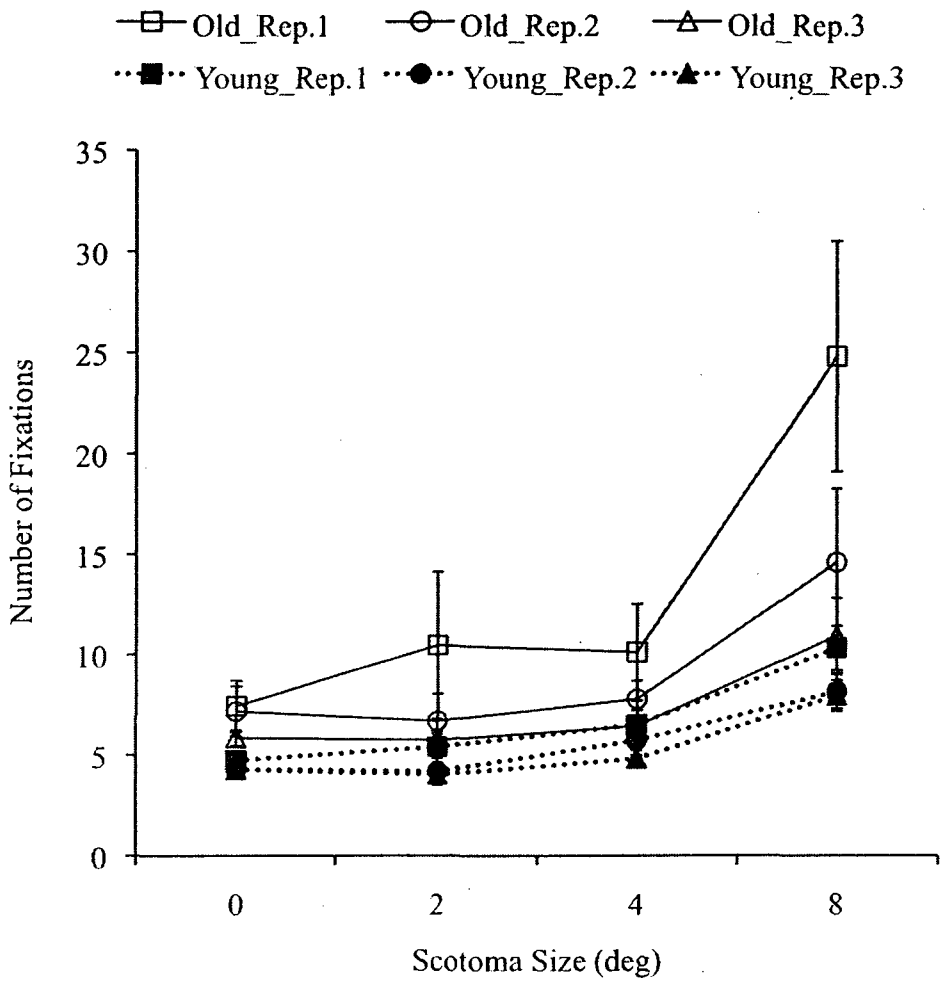


Figure 27. The total number of fixations increased as a function of scotoma size, and old adults had significantly more fixations than young adults in Experiment 2. Error bar refers to the standard error of the mean.

General Discussion

To my knowledge, this is the first study that compared the effects of a variety of simulated central scotomata, resembling various pathological conditions of AMD, on behavioral and eye movement measures.

Response efficiency during eccentric viewing

The experiments presented here clearly demonstrate that the presence of a central scotoma can significantly affect people's response efficiency (defined as response latency and accuracy) during target identification, especially as response latency is concerned. The size of the scotoma determined the residual area of the peripheral retinal region. When scotoma size increased to cover a large part of the macula, the effort to use eccentric fixations became demanding. Therefore, the compensation of the loss of central visual field through increased extrafoveal exploration was less likely to succeed. As demonstrated in Experiment 1, response accuracy in general remained unaffected across different types of scotoma and replications. However, there was a linear decline in response accuracy when scotoma size increased. Moreover, for old adults (Experiment 2), the effect of a central scotoma on the response efficiency was very pronounced. The choice of a proper retinal locus to identify the target was more challenging for old adults, especially when they first encountered the larger sizes of the scotoma (i.e., 4 and 8 deg). When there was a large scotoma, they had a much longer response latency, and response accuracy dropped to chance level. In terms of the influence of different scotoma types, Experiment 1 showed, that with a Relative scotoma observers responded as quickly as in the control condition. But for the other types this was not the case, indicating that a

complete loss of the central visual field or a distorted sensory input added an extra load for observers so they could no longer function normally and efficiently.

Eye movement patterns with a central scotoma

The present experiments also studied observers' eye movement patterns in detail for a subset of the stimuli. Each stimulus in this set contained 'hills' or 'valleys' in the three locations. Within three pre-defined IAs (containing the locations of the shapes), the spatial characteristics of eye movements were examined through the variables of X- and Y-fixation shifts and preferred eccentric viewing angle.

Consistent with the original assumption, Experiment 1 showed an increasing fixation shift along the X-axis when scotoma size increased. Overall, observers were preferentially turning their eccentric viewing angle towards the right visual field. In this respect, there was no particular scotoma type influence. We therefore suggested a general eccentric viewing preference along the horizontal meridian towards the right visual field. A similar result of X- and Y-fixation shifts was found for both young and old adults in Experiment 2, except that old adults showed larger shifts along the Y-axis for all IAs, when compared to the shifts produced by young adults. In terms of the preferred eccentric viewing angle in Experiment 2, there was also a significant age difference in IA2. That is, old adults had a smaller angular change when compared with young adults, *-7.91 versus -59.70* deg, which did not occur in the other two IAs.

Function-Driven Choice of the Extrafoveal Location. Having found the fixation shifts and viewing angle changes, several questions are brought up: Why did observers displace their fixations in one direction and not the other? Why did this directional preference exist in one interest area, but not in the others? Why was there an age-related

difference in the selection of a retinal area for fixations? Previous research tried to explain the possible reasons for the choice of the extrafoveal retinal location during eccentric viewing in different ways. Many studies were in favor of a function-driven explanation. They proposed that an eccentric fixation location above or below the retinal lesion, which corresponds to fixation in the lower or upper visual field, respectively, should be more advantageous for English reading. Fine and Rubin (1999), in a simulated scotoma study on reading performance, showed that reading performance was best when the observers were forced to read with the lower visual field. However, Sunness et al. (1996) reported that 63% of 27 eyes with GA (geographic atrophy) had a PRL to the left of a central scotoma, which seemed to be counterproductive for English reading. This fixation would occlude part of the upcoming text on the fixated line during left-to-right reading, which was therefore against the function-driven theory.

Performance-Driven Choice of the Extrafoveal Location. Therefore, other studies proposed a performance-driven theory. That is, the selection of a particular extrafoveal location by people with a central scotoma was determined by the extent to which it could maximize visual performance. As mentioned earlier, there exists a horizontal-vertical anisotropy of visual performance and acuity, in which the horizontal meridian has a higher visual acuity than the vertical meridian, given the same eccentricity. In normal subjects, visual acuity falls off more rapidly along the vertical than the horizontal meridian (Millidot & Lamont, 1974). In addition, as suggested by anatomical and physiological evidence in monkey, this may provide a possible neural correlate: A lower density of ganglion cells and a faster decline of cone density with increasing distance from the fovea along the vertical than horizontal meridian was found (Curcio, Sloan,

Packer, Hendrickson, & Kalina, 1987). Such evidence of a horizontal-vertical anisotropy exists in the LGN and V1 as well (van Essen, Newsome, & Maunsell, 1984). Along the vertical meridian, performance was also better in the lower than the upper visual field (Edgar et al., 1990).

The present results in Experiment 1 showed that observers preferred to shift their fixations along the X-axis while scotoma size increased, regardless of the type of scotoma. Such a result could be supported by the performance-driven theory in which the observers naturally adopted a horizontal direction that had a performance advantage. In Experiment 2, old adults had a smaller angular fixation change compared with young adults in IA2. A strategic change in old adults who tried to achieve a better performance was therefore suggested. The shape in IA2 geographically belonged to the upper visual field of the whole stimulus display. To compensate for the upper visual field disadvantage, instead of generating large angular changes and turning the preferred eccentric viewing angle towards the lower visual field, as young adults did, old adults adopted a different strategy: They tended to shift fixations further away along the horizontal meridian, which might have given them a greater advantage than using shifts along the vertical meridian (Rovamo et al., 1979; Edgar et al., 1990).

However, this performance-driven theory does not seem to be adequate to explain all changes in preferred eccentric viewing angle in our experiments. If there was a performance priority of the horizontal over the vertical meridian, and of lower over upper visual field, why did observers not have a consistent angular change of fixations within each of the three IAs? In fact, as in Experiment 1, there was an angular change towards the upper visual field in IA1 and IA3. In contrast, in IA2, observers' fixation angles were

pointing toward the lower visual field. This was the case in Experiment 2 as well. We therefore considered that the performance-driven theory alone might not be able to account for all these variations. In particular, most of the previous evidence was based on a reading paradigm, which might have biased the conclusions in favor of the particular nature of the reading task and arbitrarily ruled out other possible explanations.

Context Effect. The current research went beyond the traditional reading paradigm by using a 3D shape-from-texture stimulus, which made it possible to observe more 2-dimensional eye movement patterns. As mentioned earlier, in these stimulus displays, there were three shapes, which were located in different geographic areas (see Figure 1). On a 1024 x 768 display screen, the central X and Y positions for each shape were: Shape 1 (IA1; 378, 378); shape 2 (IA2; 530, 318); shape 3 (IA3; 570, 416) in pixel units with the origin in the upper left corner. We instructed observers to identify the shapes in a clockwise order, starting with Shape 1. When identifying Shape 1 in the leftmost-middle of the display, observers tended to already start to move their eyes toward Shape 2 that was located in the upper-right of the display. This could explain why in IA1 there was a tendency for observers to often shift the preferred eccentric viewing angle towards the upper-right visual field. Following the same reasoning for IA2, observers were prematurely moving their eyes downward to Shape 3 that was located in the lower-right area. Thus, the preferred eccentric viewing angle was often pointing towards the lower-right visual field. Such a result might suggest that the visual behavior with a central scotoma was both performance-driven and context-driven. That is, observers adopted a strategy that could maximize their visual performance whereas the particular strategy selection depended on the visual context. The difference between old adults and young

adults in eccentric viewing direction change suggests that young adults weighted more heavily on the context-driven than the performance-driven part. Old adults, in contrast, weighted more on the performance-driven than the context-driven part. However, all were combining the performance-driven and context-driven strategies to maximize their performance.

Fixation Stability. The purpose of normal viewing is to generate saccadic eye movements to bring targets onto the fovea so that detailed information can be obtained. Therefore, foveating saccades are embedded in our natural viewing process, which are automatic and reflexive. The presence of a central scotoma requires an alteration of the normal eye movement behavior, because people are forced to use peripheral retinal locations to perceive the world. Peripheral fixation is 3-4 times less stable than foveal fixation in normal observers (Sansbury et al., 1973). Moreover, people have to consciously inhibit natural foveating saccades and fixations while they are trying to fixate with a peripheral retinal location. This was clearly demonstrated through the present measurement of regression path fixation duration, which defined a quantitative combination of spatial and temporal characteristics of eye movements. The forward and backward eye movement behavior was summarized through the summation of the forward and backward fixation durations.

When there was a central scotoma, the regressive fixation duration increased significantly, more so for larger scotoma sizes. This was the case in both experiments. Moreover, it seemed especially difficult for old adults to maintain a relatively stable fixation in an extrafoveal location in the presence of a large scotoma. The results in Experiment 2 showed that old adults had significantly longer regressive fixation

durations with a large scotoma. In this case, old adults generated twice the number of fixations as compared to when there was no scotoma. Such a result indicates that observers engaged in longer periods of extrafoveal exploration to pinpoint a suitable location to use for identification. During the experiment, when the largest scotoma condition was presented to old observers, their eyes moved in such a way as if they wanted to bypass the scotoma, but could not.

Moreover, the analysis of regression path fixation duration, overall trial duration, and number of fixations in Experiment 1 showed that different types of scotoma affected eye movement behavior differently. Among all 4 types of scotoma, the Relative scotoma with reduced contrast was more effortful than no scotoma, but it was the least disruptive condition as compared to the other three types of scotoma. A complete absence of the central visual field (i.e., Absolute, Distorted) or a dynamically distorted sensory input (i.e., Warped) had a detrimental effect on the efficient locating of a proper retinal locus for identifying targets. This was reflected in a significant increase in regression path fixation duration, overall trial duration, and number of fixations.

Interestingly, a slight decrease in fixation numbers with a Relative scotoma when the scotoma size increased was noticed. This actually suggested a slight increase in fixation stability in the Relative scotoma condition. White and Bedell (1990) reported that patients might fixate with a retinal area at the edge of the lesion but within the Relative scotoma. Therefore, observers might still have preferred to use their fovea for fixation, rather than the peripheral region in the present experiments. When the central region was still partially available, observers might have been able to continue to use their fovea for target identification. Although it was more effortful than in the no-scotoma

condition, it might still have been relatively more comfortable than suppressing foveal fixation altogether and instead using peripheral fixation. Due to the decreased contrast in the center, observers had to stare at the target longer than usual. This could help to explain the slight decrease in the number of fixations with simultaneously unchanging trial duration in the Relative scotoma condition.

Learning effect

The brain circuitry is not hard-wired but is significantly modifiable by experience. There is an increasing amount of evidence that the large capacity for adaptation of the brain that has been amply documented for young organisms, can be extended into adulthood. In adulthood, the brain retains a substantial capacity for adaptive modification in response to continuing interaction with the environment. The enlarged cortical representation of central vision has been linked to better performance in psychophysical tasks in central vision compared with peripheral vision. The loss of central vision or dysfunction of central vision did have a significant impact on observers' response efficiency, and altered their eye movement behavior. However, in both experiments, learning occurred naturally. Response efficiency was improved with practice. The regression path fixation duration, overall trial duration, and the number of fixations were all significantly decreased as a function of replication. Such results suggest that during the learning processes, a more or less conscious correction of eye movement patterns occurred, and eventually led to more automatic and accurate initial saccades. This was true for old adults as well.

Moreover, one might expect that this adaptation would be even more pronounced in patients with AMD. Within the patient population, this learning and adaptation might

be strengthened due to the damage of the retinal cells so that anatomical and functional cortical re-arrangement might occur (Gilbert & Wiesel, 1992; Darian-Smith & Gilbert, 1994). This cortical plasticity might in turn enhance the patients' eccentric viewing capacity as compared with the normal observers with a simulated central scotoma. The length of the pathological scotoma condition might also be correlated with the amount of adaptation. As mentioned in the Introduction, Cummings et al. (1985) reported that patients were relatively accurate in a reading task even with a large central scotoma. During adaptation to a central scotoma, patients frequently depended on a non-foveating saccade, which could eventually lead to a re-definition of the retinal null point. Cortical adaptation and re-organization might occur quite readily. All these could facilitate the eccentric viewing proficiency found in many AMD patients.

Implications for future research and application

One of the main implications for future research that needs to be drawn from the present study, is that research with artificial scotomata in healthy adults needs to take into consideration the kind of pathological AMD condition that is to be simulated. As pointed out in the Introduction, AMD comes in many varieties. Central scotomata not only have different sizes, they also can be classified into different types, based on etiology and length of disease presentation. The present results show that different types of simulated scotoma lead to different effects in terms of eye movement patterns and performance efficiency. It might never be possible to exactly reproduce the pathological defect in a particular individual through a simulation. But, in order to obtain the most accurate picture of how a particular scotoma will affect behaviour, one needs to use artificial

scotomata in healthy individuals that approach the nature of the pathological scotoma as closely as possible.

This also implies that training schemes developed according to outcomes obtained by the use of simulated scotomata, will be most successful if there is a good match between the type of the pathological and the simulated scotoma. In the present case, the rate of improvement with practice depended on the type of scotoma.

A second main implication to be drawn relates to the age factor. It is certainly easiest to use young adults in research with simulated scotomata, since they are readily available and usually present fewer additional complications. But since most cases of AMD occur in older adults, our finding of differential effects in the two populations, means that a more meaningful simulation would be obtained from healthy adults that are age-matched to the group of interest with the pathological scotoma.

Conclusions

Taken together, the present experiments demonstrated clear behavioral and eye movement effects of central scotomata. First, the presence of a central scotoma deteriorated observers' response efficiency. Second, the spatial and temporal characteristics of eye movements were altered by the presence of a central scotoma. Third, the kind of scotoma mattered: when there was a complete or a distorted central vision loss, the negative impact was much larger than for simple contrast reduction. Fourth, young and old adults had different eccentric viewing strategies to obtain a better performance level. Fifth, although eccentric fixation is an adaptive and effective mechanism for regaining residual visual functions, this might be possible only to a lesser

degree when the scotoma size becomes too large. Very large scotomata may become unmanageable, even with a large amount of practice.

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Appendix A

Informed Consent Form

INFORMED CONSENT

FOR PARTICIPATION IN PSYCHOPHYSICAL RESEARCH

I hereby state my agreement to participate in a **Master's Thesis** study being conducted by **Rong Zhou** under the supervision of **Dr. Michael von Grünau** in the **Visual Perception Laboratory, Department of Psychology at Concordia University.**

PURPOSE

I have been informed the purpose of the research is to understand observers' eye movement patterns while being presented with a simulated central scotoma during a 3D shape-from-texture identification task. The research is being conducted to partially fulfill the requirements for a Master's Thesis.

PROCEDURES

I have been informed that I will wear a head-mounted Eyetracker during the experiment, which will be a 1 hr testing session. A computer generated 3D shape-from-texture stimulus will be presented on a display screen. There will be 27 stimuli in one trial and 12 blocks presented in random order. My task will be to identify the shapes as quickly as possible, and as accurately as possible. I have been informed to maintain my head position stable on a chinrest during the experimental process.

I understand that my name, data, and information that I provided in the experiment will be confidential. I understand that if the results are published, my data will be reported but my identity will not be revealed.

CONDITIONS OF PARTICIPATION

- I understand that I am free to withdraw or discontinue my participation at any time without negative consequences.
- I understand that my data may be published, but my identity will remain confidential.
- I understand the nature of the study is for the advancement of the knowledge of the basic visual process, as well as medical knowledge.

I HAVE CAREFULLY READ AND UNDERSTOOD ALL OF THE ABOVE AND I FREELY CONSENT TO PARTICIPATE IN THIS RESEARCH.

NAME (print): _____

SIGNATURE: _____

EXPERIMERIMENTER'S SIGNATURE: _____

DATE: _____

Appendix B

Screening Tool: Early Treatment Diabetic Retinopathy Study (ETDRS) Chart

2000 Series Revised ETDRS Chart "1" (2 Meter; Precision Vision)

Appendix C

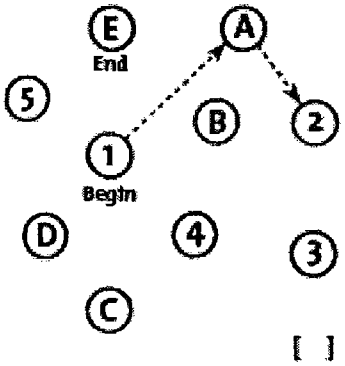
Screening Questionnaire: Montréal Cognitive Assessment

(For Experiment 2 old participants only)

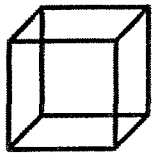
MONTREAL COGNITIVE ASSESSMENT (MOCA)

NAME :
Education : Date of birth :
Sex : DATE :

VISUOSPATIAL / EXECUTIVE



Copy cube



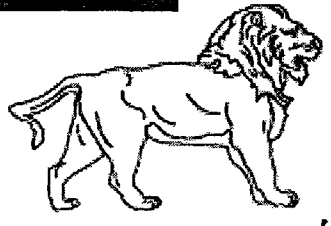
[ ] [ ]

Draw CLOCK (Ten past eleven) (3 points)

[ ] Contour [ ] Numbers [ ] Hands

POINTS __/5

NAMING



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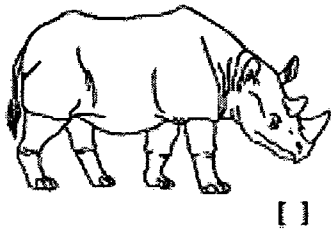
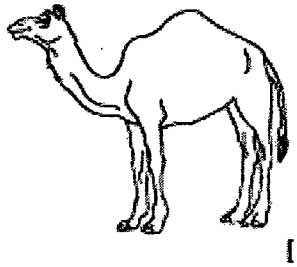


[ ]



[ ] __/3

MEMORY Read list of words, subject must repeat them. Do 2 trials. Do a recall after 5 minutes.

	FACE	VELVET	CHURCH	DAISY	RED
1st trial					
2nd trial					

No points

ATTENTION Read list of digits (1 digit/sec.) Subject has to repeat them in the forward order [ ] 2 1 8 5 4

Subject has to repeat them in the backward order [ ] 7 4 2 __/2

Read list of letters. The subject must tap with his hand at each letter A. No points if ≥ 2 errors

[ ] F B A C M N A A J K L B A F A K D E A A A J A M O F A A B __/1

Serial 7 subtraction starting at 100 [ ] 93 [ ] 86 [ ] 79 [ ] 72 [ ] 65

4 or 5 correct subtractions: 3 pts, 2 or 3 correct: 2 pts, 1 correct: 1 pt, 0 correct: 0 pt __/3

LANGUAGE Repeat : I only know that John is the one to help today. [ ]

The cat always hid under the couch when dogs were in the room. [ ] __/2

Fluency / Name maximum number of words in one minute that begin with the letter F [ ]____ (N ≥ 11 words) __/1

ABSTRACTION Similarity between e.g. banana - orange = fruit [ ] train – bicycle [ ] watch - ruler __/2

DELAYED RECALL

	Has to recall words WITH NO CUE	FACE	VELVET	CHURCH	DAISY	RED	Points for UNCUED recall only
		[ ]	[ ]	[ ]	[ ]	[ ]	
Optional	Category cue						
	Multiple choice cue						

__/5

ORIENTATION [ ] Date [ ] Month [ ] Year [ ] Day [ ] Place [ ] City __/6

www.mocatest.org

Normal ≥ 26/30

TOTAL __/30

Add 1 point if ≤ 12 yr edu

Administered by: _____

Appendix D

Source Tables for Experiment 1 & 2

Table D1

ANOVA Summary Table for Response Latency (in Sec) in Experiment 1

Source	*SS*	*df*	*MS*	*F*	η^2_p
Between:					
Type (T)	13.65	3	4.55	4.25*	0.39
Error (T)	21.43	20	1.07		
Within:					
Replication (R)	5.19	2	2.59	51.27*	0.72
Error (R)	2.02	40	0.05		
Size (S)	19.96	3	6.65	38.61*	0.66
S x T	7.53	9	0.84	4.86*	0.42
Error (S)	10.34	60	0.17		
R x S	1.47	6	0.25	5.99	0.23
Error (R x S)	4.90	120	0.04		

Bonferroni Pairwise Comparison on Response Latency (in Sec) across Participants (n = 24) as a Function of Replication in Experiment 1

Comparison		Mean difference (I -J)	*SE*	*p*
Replication (I)	Replication (J)			
1	2	0.24*	0.03	0.00*
1	3	0.32*	0.04	0.00*
2	3	0.08*	0.02	0.01*

Note: * $p < .05$.

Table D2

Bonferroni Pairwise Comparison on Response Latency (in Sec) across Participants (n = 24) as a Function of Scotoma Size (in Deg) in Experiment 1

Comparison		Mean difference (I -J)	*SE*	*p*
Scotom size (I)	Scotoma size (J)			
0	2	-0.10*	0.03	0.03*
0	4	-0.27*	0.05	0.00*
0	8	-0.69*	0.09	0.00*
2	4	-0.18*	0.05	0.03*
2	8	-0.59*	0.09	0.00*
4	8	-0.42*	0.08	0.00*

Bonferroni Pairwise Comparison on Response Latency (in Sec) across Participants (n = 24) as a Function of Scotoma Type in Experiment 1

Comparison		Mean difference (I -J)	*SE*	*p*
Scotoma type (I)	Scotoma type (J)			
Relative	Absolute	-0.49	0.17	0.06
Relative	Distorted	-0.57*	0.17	0.02*
Relative	Warped	-0.33	0.17	0.41
Absolute	Distorted	-0.07	0.17	1.00
Absolute	Warped	0.16	0.17	1.00
Distorted	Warped	0.23	0.17	1.00

Note. * $p < .05$.

Table D3

ANOVA Summary Table for Response Accuracy in Experiment 1

Source	*SS*	*df*	*MS*	*F*	η^2_p
Between:					
Type (T)	5.65	3	1.88	0.12	0.02
Error (T)	311.51	20	15.58		
Within:					
Replication (R)	16.67	2	8.34	1.41	0.07
Error (R)	236.61	40	5.92		
Size (S)	87.98	3	29.33	6.10*	0.23
Error (S)	288.65	60	4.81		
R x S	12.88	6	2.15	0.73	0.04
Error (R x S)	351.39	120	2.93		

Note: * $p < .05$.

Table D4

Bonferroni Pairwise Comparison on Response Accuracy across Participants (n = 24) as a Function of Scotoma Size (in Deg) in Experiment 1

Comparison		Mean difference (I -J)	*SE*	*p*
Scotom size (I)	Scotoma size (J)			
0	2	0.56	0.36	0.83
0	4	0.64	0.23	0.07
0	8	1.54*	0.43	0.01*
2	4	0.08	0.24	1.00
2	8	0.99	0.48	0.31
4	8	0.90	0.39	0.18

Note. * $p < .05$.

Table D5

ANOVA Summary Table for X Fixation Shift (in Pixel) in IA1 in Experiment 1

Source	*SS*	*df*	*MS*	*F*	η^2_p
Between:					
Type (T)	2727.76	3	909.25	1.35	0.17
Error (T)	13434.80	20	671.74		
Within:					
Replication (R)	1396.42	2	698.21	7.48*	0.27
Error (R)	3732.55	40	93.31		
Size (S)	52.65	3	17.55	0.13	0.01
Error (S)	8399.31	60	139.99		
R x S	553.50	6	92.25	2.06	0.09
Error (R x S)	5376.33	120	44.80		

Bonferroni Pairwise Comparison on X Fixation Shift (in Pixel) in IA1 across Participants (n = 24) as a Function of Replication in Experiment 1

Comparison		Mean difference (I -J)	*SE*	*p*
Replication (I)	Replication (J)			
1	2	-3.02	1.16	0.05
1	3	-5.38*	1.25	0.00*
2	3	-2.36	1.71	0.55

Note. * $p < .05$.

Table D6

ANOVA Summary Table for X Fixation Shift (in Pixel) in IA2 in Experiment1

Source	*SS*	*df*	*MS*	*F*	η^2_p
Between:					
Type (T)	2008.32	3	669.44	0.86	0.13
Error (T)	13953.64	18	775.20		
Within:					
Replication (R)	37.78	2	18.89	0.15	0.01
Error (R)	4664.74	36	129.58		
Size (S)	1699.70	3	566.57	3.16*	0.15
Error (S)	9672.74	54	179.13		
R x S	842.36	6	140.39	1.88	0.10
Error (R x S)	8064.82	108	74.67		

Note. * $p < .05$.

Table D7

Bonferroni Pairwise Comparison on X Fixation Shift (in Pixel) in IA2 across Participants (n = 22) as a Function of Scotoma Size (in Deg) in Experiment 1

Comparison		Mean difference (I -J)	*SE*	*p*
Scotom size (I)	Scotoma size (J)			
0	2	1.68	1.31	1.00
0	4	-3.64	1.54	0.18
0	8	-4.52	3.03	0.92
2	4	-5.32*	1.51	0.02*
2	8	-6.20	2.94	0.30
4	8	-0.88	2.95	1.00

Note. * $p < .05$.

Table D8

ANOVA Summary Table for X Fixation Shift (in Pixel) in IA3 in Experiment1

Source	*SS*	*df*	*MS*	*F*	η^2_p
Between:					
Type (T)	2064.40	3	688.13	0.49	0.09
Error (T)	19789.15	14	1413.51		
Within:					
Replication (R)	211.38	2	105.69	1.42	0.09
Error (R)	2092.09	28	74.72		
Size (S)	1470.78	3	490.26	5.46*	0.28
Error (S)	3772.90	42	89.83		
R x S	280.32	6	46.72	0.57	0.04
Error (R x S)	6876.49	84	81.86		

Note. * $p < .05$.

Table D9

Bonferroni Pairwise Comparison on X Fixation Shift (in Pixel) in IA3 across Participants (n = 18) as a Function of Scotoma Size (in Deg) in Experiment 1

Comparison		Mean difference (I -J)	*SE*	*p*
Scotom size (I)	Scotoma size (J)			
0	2	-0.69	1.38	1.00
0	4	-3.35	1.14	0.06
0	8	-6.68*	1.89	0.02*
2	4	-2.67	1.03	0.13
2	8	-5.99	2.47	0.18
4	8	-3.32	2.52	1.00

Note. * $p < .05$.

Table D10

ANOVA Summary Table for Regression Path Fixation Duration (in Msec) in IA2 in Experiment1

Source	*SS*	*df*	*MS*	*F*	η^2_p
Between:					
Type (T)	5247693.62	3	1749231.21	4.55*	0.43
Error (T)	6923723.01	18	384651.28		
Within:					
Replication (R)	2288608.24	2	1144304.12	11.87*	0.40
Error (R)	3470669.37	36	96407.48		
Size (S)	5868715.66	3	1956238.55	18.12*	0.50
Error (S)	5830708.11	54	107976.08		
R x S	813504.93	6	135584.16	2.18	0.11
Error (R x S)	6709305.82	108	62123.20		

Note. * $p < .05$.

Table D11

Bonferroni Pairwise Comparison on the Regression Path Fixation Duration (in Msec) in IA2 across Participants (n = 22) as a Function of Scotoma Size (in Deg) in Experiment 1

Comparison		Mean difference (I -J)	*SE*	*p*
Scotom size (I)	Scotoma size (J)			
0	2	-88.38	35.87	0.14
0	4	-226.00*	54.34	0.00*
0	8	-396.27*	74.00	0.00*
2	4	-137.62*	43.40	0.03*
2	8	-307.89*	60.50	0.00*
4	8	-170.27	67.36	0.13

Bonferroni Pairwise Comparison on Regression Path Fixation Duration (in Msec) in IA2 across Participants (n = 22) as a Function of Replication in Experiment 1

Comparison		Mean difference (I -J)	*SE*	*p*
Replication (I)	Replication (J)			
1	2	175.83*	40.26	0.00*
1	3	214.99*	48.99	0.00*
2	3	39.16	51.07	1.00

Note. * $p < .05$.

Table D12

Bonferroni Pairwise Comparison on Regression Path Fixation Duration (in Msec) in IA2 across Participants (n = 22) as a Function of Scotoma Type in Experiment 1

Comparison		Mean difference (I -J)	*SE*	*p*
Scotoma Type (I)	Scotoma Type (J)			
Relative	Absolute	-310.04	108.41	0.06
Relative	Distorted	-372.87*	108.41	0.02*
Relative	Warped	-301.15	113.23	0.10
Absolute	Distorted	-62.83	103.37	1.00
Absolute	Warped	8.90	108.41	1.00
Distorted	Warped	71.73	108.41	1.00

Note. * $p < .05$.

Table D13

ANOVA Summary Table for Regression Path Fixation Duration (in Msec) in IA3 in Experiment1

Source	*SS*	*df*	*MS*	*F*	η^2_p
Between:					
Type (T)	11490479.60	3	3830159.88	4.43*	0.49
Error (T)	12115443.70	14	865388.83		
Within:					
Replication (R)	3204992.37	2	1602496.18	14.64*	0.51
Error (R)	3065686.76	28	109488.81		
Size (S)	12375330.90	3	4125110.29	20.74*	0.60
Error (S)	8352449.65	42	198867.85		
R x S	1002200.55	6	167033.43	1.92	0.12
Error (R x S)	7316193.38	84	87097.54		

Note. * $p < .05$.

Table D14

Bonferroni Pairwise Comparison on the Regression Path Fixation Duration (in Msec) in IA3 across Participants (n = 18) as a Function of Scotoma Size (in Deg) in Experiment 1

Comparison		Mean difference (I -J)	*SE*	*p*
Scotom size (I)	Scotoma size (J)			
0	2	-137.52	60.15	0.23
0	4	-208.88*	50.29	0.01*
0	8	-643.98*	127.19	0.00*
2	4	-71.36	51.77	1.00
2	8	-506.46*	102.72	0.00*
4	8	-435.10*	95.86	0.00*

Bonferroni Pairwise Comparison on Regression Path Fixation Duration (in Msec) in IA3 across Participants (n = 18) as a Function of Replication in Experiment 1

Comparison		Mean difference (I -J)	*SE*	*p*
Replication (I)	Replication (J)			
1	2	255.46*	61.62	0.00*
1	3	264.34*	59.81	0.00*
2	3	8.88	43.17	1.00

Note. * $p < .05$.

Table D15

Bonferroni Pairwise Comparison on Regression Path Fixation Duration (in Msec) in IA3 across Participants (n = 18) as a Function of Scotoma Type in Experiment 1

Comparison		Mean difference (I -J)	*SE*	*p*
Scotoma Type (I)	Scotoma Type (J)			
Relative	Absolute	-576.52*	180.15	0.04
Relative	Distorted	-521.37	180.15	0.07
Relative	Warped	-419.77	169.84	0.16
Absolute	Distorted	55.15	189.89	1.00
Absolute	Warped	156.75	180.15	1.00
Distorted	Warped	101.59	180.15	1.00

Note. * $p < .05$.

Table D16

ANOVA Summary Table for Overall Trial Duration (in Msec) in Experiment1

Source	*SS*	*df*	*MS*	*F*	η^2_p
Between:					
Type (T)	18649414.10	3	6216471.37	3.10*	0.32
Error (T)	40055164.80	20	2002758.24		
Within:					
Replication (R)	13446869.60	2	6723434.81	60.46*	0.75
Error (R)	4448560.28	40	111214.01		
Size (S)	37186657.50	3	4125110.29	61.78*	0.76
Error (S)	12039020.80	60	200650.35		
R x S	1882916.97	6	313819.50	3.56	0.15
Error (R x S)	10593767.70	120	88281.40		

Note. * $p < .05$.

Table D17

Pairwise Comparison on Overall Trial Duration (in Msec) across Participants (n = 24) as a Function of Scotoma Size (in Deg) in Experiment 1

Comparison		Mean difference (I -J)	*SE*	*p*
Scotom size (I)	Scotoma size (J)			
0	2	-150.10*	55.97	0.01*
0	4	-391.94*	60.24	0.00
0	8	-945.11*	96.11	0.00*
2	4	-241.84*	66.03	0.00*
2	8	-795.02*	83.45	0.00*
4	8	-553.17*	78.23	0.00*

Pairwise Comparison on Overall Trial Duration (in Msec) across Participants (n = 24) as a Function of Replication in Experiment 1

Comparison		Mean difference (I -J)	Standard error	*p*
Replication (I)	Replication (J)			
1	2	392.90*	48.82	0.00*
1	3	503.58*	60.30	0.00*
2	3	110.68*	30.53	0.00*

Note. * $p < .05$.

Table D18

Pairwise Comparison on Overall Trial Duration (in Msec) across Participants (n = 24) as a Function of Scotoma Type in Experiment 1

Comparison		Mean difference (I -J)	*SE*	*p*
Scotoma Type (I)	Scotoma Type (J)			
Relative	Absolute	-566.61*	235.87	0.03*
Relative	Distorted	-627.34*	235.87	0.02*
Relative	Warped	-559.60*	235.87	0.03*
Absolute	Distorted	-60.73	235.87	0.80
Absolute	Warped	7.01	235.87	0.98
Distorted	Warped	67.74	235.87	0.78

Note. * $p < .05$.

Table D19

ANOVA Summary Table for the Number of Fixations in Experiment1

Source	*SS*	*df*	*MS*	*F*	η^2_p
Between:					
Type (T)	56.08	3	18.69	0.48	0.07
Error (T)	776.36	20	38.82		
Within:					
Replication (R)	50.36	2	25.18	14.67*	0.42
Error (R)	68.64	40	1.72		
Size (S)	316.03	3	105.34	28.01*	0.58
S x T	267.67	9	29.74	7.91*	0.54
Error (S)	225.64	60	3.76		
R x S	13.81	6	2.30	2.65*	0.12
Error (R x S)	104.03	120	0.87		

Note. * $p < .05$.

Table D20

Bonferroni Pairwise Comparison on the Number of Fixations across Participants (n = 24) as a Function of Scotoma Size (in Deg) in Experiment 1

Comparison		Mean difference (I -J)	*SE*	*p*
Scotom size (I)	Scotoma size (J)			
0	2	0.14	0.21	1.00
0	4	-0.60	0.25	0.17
0	8	-2.49*	0.50	0.00*
2	4	-0.74*	0.15	0.00*
2	8	-2.63*	0.38	0.00*
4	8	-1.89*	0.32	0.00*

Bonferroni Pairwise Comparison on the Number of Fixations across Participants (n = 24) as a Function of Replication in Experiment 1

Comparison		Mean difference (I -J)	*SE*	*p*
Replication (I)	Replication (J)			
1	2	0.58	0.23	0.06
1	3	1.02*	0.17	0.00*
2	3	0.44*	0.15	0.03*

Note. * $p < .05$.

Table D21

ANOVA Summary Table for Response Latency (in Sec) in Experiment 2

Source	*SS*	*df*	*MS*	*F*	η^2_p
Between:					
Age (A)	18.21	1	18.21	3.67	0.27
Error (A)	49.66	10	4.97		
Within:					
Replication (R)	21.78	2	10.89	13.39*	0.57
R x A	6.51	2	3.26	4.01*	0.29
Error (R)	16.26	20	0.81		
Size (S)	85.72	3	28.57	10.71*	0.52
Error (S)	80.01	30	2.67		
R x S	20.11	6	3.35	7.13*	0.42
Error (R x S)	28.19	60	0.47		

Note. * $p < .05$.

Table D22

Bonferroni Pairwise Comparison on Response Latency (in Sec) across Participants (n = 12) as a Function of Scotoma Size (in Deg) in Experiment 2

Comparison		Mean difference (I -J)	*SE*	*p*
Scotom size (I)	Scotoma size (J)			
0	2	-0.35	0.17	0.40
0	4	-0.37*	0.09	0.02*
0	8	-1.99*	0.51	0.02*
2	4	-0.03	0.20	1.00
2	8	-1.64	0.54	0.08
4	8	-1.62	0.51	0.06

Bonferroni Pairwise Comparison on Response Latency (in Sec) across Participants (n = 12) as a Function of Replication in Experiment 2

Comparison		Mean difference (I -J)	*SE*	*p*
Replication (I)	Replication (J)			
1	2	0.70*	0.17	0.01*
1	3	0.91*	0.25	0.01*
2	3	0.21	0.10	0.22

Note. * $p < .05$.

Table D23

Descriptive Data on Response Latency (in Sec) across Participants (n = 12) as a Function of Replication between Old and Young Observers in Experiment 2

Age	Replication	*M*	*SE*
Old	1	3.04	0.43
Old	2	1.98	0.25
Old	3	1.63	0.17
Young	1	1.75	0.43
Young	2	1.41	0.25
Young	3	1.35	0.17

Table D24

ANOVA Summary Table for Response Accuracy in Experiment 2

Source	*SS*	*df*	*MS*	*F*	η^2_p
Between:					
Age (A)	802.78	1	802.78	23.37*	0.70
Error (A)	343.44	10	34.34		
Within:					
Replication (R)	22.51	2	11.26	1.15	0.10
Error (R)	195.56	20	9.78		
Size (S)	712.83	3	237.61	13.01*	0.57
S x A	285.72	3	95.24	5.21*	0.34
Error (S)	548.11	30	18.27		
R x S	25.88	6	4.31	0.85	0.08
Error (R x S)	304.22	60	5.07		

Bonferroni Pairwise Comparison on Response Accuracy across Participants (n = 12) between Old and Young Observers in Experiment 2

Comparison		Mean difference (I -J)	*SE*	*p*
Age (I)	Age (J)			
Old	Young	-4.72*	0.98	0.00*

Note. * $p < .05$.

Table D25

Bonferroni Pairwise Comparison on Response Accuracy across Participants (n = 12) as a Function of Scotoma Size (in Deg) in Experiment 2

Comparison		Mean difference (I -J)	*SE*	*p*
Scotom size (I)	Scotoma size (J)			
0	2	0.28	0.51	1.00
0	4	1.92	1.02	0.53
0	8	5.58*	1.21	0.01*
2	4	1.64	0.93	0.66
2	8	5.31*	1.33	0.02*
4	8	3.67*	0.84	0.01*

Descriptive Data on Response Accuracy across Participants (n = 12) as a Function of Scotoma Size (in Deg) between Old and Young Observers in Experiment 2

Age	Scotoma Size	*M*	*SE*
Old	0	24.11	0.80
Old	2	23.72	0.94
Old	4	20.56	1.02
Old	8	15.06	1.55
Young	0	26.22	0.80
Young	2	26.06	0.94
Young	4	25.94	1.02
Young	8	24.11	1.55

Note. * $p < .05$.

Table D26

ANOVA Summary Table for X Fixation Shift (in Pixel) in IA1 in Experiment 2

Source	*SS*	*df*	*MS*	*F*	η^2_p
Between:					
Age (A)	448.10	1	448.10	1.01	0.09
Error (A)	4458.35	10	445.84		
Within:					
Replication (R)	1711.52	2	855.76	7.59*	0.43
Error (R)	2244.44	20	112.77		
Size (S)	484.60	3	161.53	0.62	0.06
Error (S)	7760.80	30	258.69		
R x S	420.67	6	70.11	0.96	0.09
Error (R x S)	4390.75	60	73.18		

Note. * $p < .05$.

Table D27

ANOVA Summary Table for Y Fixation Shift (in Pixel) in IA1 in Experiment 2

Source	*SS*	*df*	*MS*	*F*	η^2_p
Between:					
Age (A)	20155.01	1	20155.01	6.10*	0.38
Error (A)	33032.02	10	3303.20		
Within:					
Replication (R)	25.17	2	12.58	0.02	0.00
Error (R)	13766.50	20	688.33		
Size (S)	5650.10	3	1883.37	4.84*	0.33
Error (S)	11675.97	30	389.20		
R x S	1509.57	6	251.59	0.90	0.08
Error (R x S)	16810.79	60	280.18		

Note. * $p < .05$.

Table D28

Bonferroni Pairwise Comparison on X Fixation Shift (in Pixel) in IA1 across Participants (n = 12) as a Function of Replication in Experiment 2

Comparison		Mean difference (I -J)	*SE*	*p*
Replication (I)	Replication (J)			
1	2	-5.77*	1.62	0.02*
1	3	-8.23*	1.97	0.01*
2	3	-2.45	2.76	1.00

Pairwise Comparison on Y Fixation Shift (in Pixel) in IA1 across Participants (n = 12) as a Function of Scotoma Size (in Deg) in Experiment 2

Comparison		Mean difference (I -J)	*SE*	*p*
Scotom size (I)	Scotoma size (J)			
0	2	0.84	2.69	0.76
0	4	0.04	4.16	0.99
0	8	-14.16*	5.66	0.03*
2	4	-0.78	3.93	0.84
2	8	-14.99*	4.75	0.01*
4	8	-14.19*	4.75	0.01*

Note. * $p < .05$.

Table D29

ANOVA Summary Table for X Fixation Shift (in Pixel) in IA2 in Experiment2

Source	*SS*	*df*	*MS*	*F*	η^2_p
Between:					
Age (A)	28.90	1	28.90	0.02	0.00
Error (A)	13973.39	10	1397.34		
Within:					
Replication (R)	122.31	2	61.16	0.23	0.02
Error (R)	5390.26	20	269.51		
Size (S)	3122.17	3	1040.72	3.62*	0.27
Error (S)	8616.31	30	287.21		
R x S	527.93	6	87.99	0.65	0.06
Error (R x S)	8155.85	60	135.93		

Note. * $p < .05$.

Table D30

ANOVA Summary Table for Y Fixation Shift (in Pixel) in IA2 in Experiment2

Source	*SS*	*df*	*MS*	*F*	η^2_p
Between:					
Age (A)	983.45	1	983.45	1.10	0.10
Error (A)	8947.11	10	894.71		
Within:					
Replication (R)	411.96	2	205.98	1.22	0.11
Error (R)	3383.28	20	169.16		
Size (S)	2208.92	3	736.31	7.37*	0.42
Error (S)	2998.68	30	99.96		
R x S	1240.80	6	206.80	2.06	0.17
Error (R x S)	6016.38	60	100.27		

Note. * $p < .05$.

Table D31

Bonferroni Pairwise Comparison on X Fixation Shift (in Pixel) in IA2 across Participants (n = 12) as a Function of Scotoma Size (in Deg) in Experiment 2

Comparison		Mean difference (I -J)	*SE*	*p*
Scotom size (I)	Scotoma size (J)			
0	2	-1.41	2.48	0.58
0	4	-11.96*	5.02	0.04*
0	8	-5.76	3.15	0.10
2	4	-10.55*	4.16	0.03*
2	8	-4.35	2.44	0.11
4	8	6.20	5.60	0.29

Bonferroni Pairwise Comparison on Y Fixation Shift (in Pixel) in IA2 across Participants (n = 12) as a Function of Scotoma Size (in Deg) in Experiment 2

Comparison		Mean difference (I -J)	*SE*	*p*
Scotom size (I)	Scotoma size (J)			
0	2	0.47	2.12	1.00
0	4	-3.01	2.80	1.00
0	8	-9.35*	2.76	0.04*
2	4	-3.49	1.52	0.27
2	8	-9.82*	2.17	0.01*
4	8	-6.34	2.52	0.19

Note. * $p < .05$.

Table D32

ANOVA Summary Table for X Fixation Shift (in Pixel) in IA3 in Experiment2

Source	*SS*	*df*	*MS*	*F*	η^2_p
Between:					
Age (A)	4783.57	1	4783.57	9.42*	0.61
Error (A)	3045.71	6	507.62		
Within:					
Replication (R)	254.09	2	127.05	0.77	0.11
Error (R)	1992.45	12	166.04		
Size (S)	2296.70	3	765.57	3.58*	0.37
Error (S)	3854.51	18	214.14		
R x S	1009.01	6	168.17	1.52	0.20
Error (R x S)	3987.99	36	110.78		

Note. * $p < .05$.

Table D33

Bonferroni Pairwise Comparison on X Fixation Shift (in Pixel) in IA3 of across Participants (n = 8) as a Function of Scotoma Size (in Deg) in Experiment 2

Comparison		Mean difference (I -J)	*SE*	*p*
Scotom size (I)	Scotoma size (J)			
0	2	-3.97	2.91	1.00
0	4	-11.25	5.17	0.44
0	8	-11.46*	1.62	0.00*
2	4	-7.28	3.49	0.49
2	8	-7.49	4.05	0.69
4	8	-0.21	6.38	1.00

Bonferroni Pairwise Comparison on X Fixation Shift (in Pixel) in IA3 across Participants (n = 8) as a Function of Age in Experiment 2

Comparison		Mean difference (I -J)	*SE*	*p*
Age (I)	Age (J)			
Old	Young	14.12*	4.60	0.02*

Note. * $p < .05$.

Table D34

ANOVA Summary Table for Preferred Eccentric Viewing Angle (in Deg) in IA2 in Experiment 2

Source	*SS*	*df*	*MS*	*F*	η^2_p
Between:					
Age (A)	96570.22	1	96570.22	11.95*	0.54
Error (A)	80840.00	10	8084.00		
Within:					
Replication (R)	12726.69	2	6363.35	4.24	0.30
Error (R)	30013.09	20	1500.65		
Size (S)	2924.24	3	974.75	0.40	0.04
Error (S)	74103.71	30	2470.12		
R x S	3810.35	6	635.06	0.47	0.05
Error (R x S)	80764.77	60	1346.08		

Bonferroni Pairwise Comparison on Preferred Eccentric Viewing Angle (in Deg) in IA2 across Participants (n = 12) as a Function of Age in Experiment 2

Comparison		Mean difference (I -J)	*SE*	*p*
Age (I)	Age (J)			
Old	Young	51.79*	14.99	0.01*

Note. * $p < .05$.

Table D35

ANOVA Summary Table for Regression Path Fixation Duration (in Msec) in IA2 in Experiment 2

Source	*SS*	*df*	*MS*	*F*	η^2_p
Between:					
Age (A)	11326781.00	1	11326780.96	6.14*	0.38
Error (A)	18451326.30	10	1845132.64		
Within:					
Replication (R)	5551018.73	2	2775509.37	4.44*	0.31
Error (R)	12511279.00	20	625563.95		
Size (S)	18340655.30	3	6113551.78	10.02*	0.50
S x A	6138813.42	3	2046271.14	3.36*	0.25
Error (S)	18297401.60	30	609913.39		
R x S	1169638.23	6	194939.71	0.48	0.05
Error (R x S)	24583372.30	60	409722.87		

Bonferroni Pairwise Comparison on Regression Path Fixation Duration (in Msec) in IA2 across Participants (n = 12) as a Function of Age in Experiment 2

Comparison		Mean difference (I -J)	*SE*	*p*
Age (I)	Age (J)			
Old	Young	560.92*	226.39	0.03*

Note. * $p < .05$.

Table D36

Bonferroni Pairwise Comparison on Regression Path Fixation Duration (in Msec) in IA2 across Participants (n = 12) as a Function of Scotoma Size (in Deg) in Experiment 2

Comparison		Mean difference (I -J)	*SE*	*p*
Scotom size (I)	Scotoma size (J)			
0	2	-46.91	143.35	1.00
0	4	-199.49	149.46	1.00
0	8	-888.53*	174.15	0.00*
2	4	-152.58	64.86	0.24
2	8	-841.62*	247.54	0.04*
4	8	-689.04	254.18	0.13

Bonferroni Pairwise Comparison on Regression Path Fixation Duration (in Msec) in IA2 across Participants (n = 12) as a Function of Replication in Experiment 2

Comparison		Mean difference (I -J)	*SE*	*p*
Replication (I)	Replication (J)			
1	2	218.86	173.08	0.70
1	3	480.30	204.65	0.12
2	3	261.44*	79.74	0.03*

Note. * $p < .05$.

Table D37

Descriptive Data on Regression Path Fixation Duration (in Msec) in IA2 across Participants (n = 12) as a Function of Age and scotoma size (in Deg) in Experiment 2

Age	Scotoma Size	*M*	*SE*
Old	0	1132.58	193.46
Old	2	973.92	99.38
Old	4	1208.97	143.23
Old	8	2357.45	369.25
Young	0	575.49	193.46
Young	2	827.98	99.38
Young	4	898.08	143.23
Young	8	1127.68	369.25

Table D38

ANOVA Summary Table for Regression Path Fixation Duration (in Msec) in IA3 in Experiment 2

Source	*SS*	*df*	*MS*	*F*	η^2_p
Between:					
Age (A)	30044322.40	1	30044322.41	5.65	0.49
Error (A)	31885740.20	6	5314290.04		
Within:					
Replication (R)	11896478.70	2	5948239.34	2.75	0.31
Error (R)	25940372.00	12	2161697.67		
Size (S)	73099566.40	3	24366522.13	5.49*	0.48
Error (S)	79828425.70	18	4434912.54		
R x S	25104753.90	6	4184125.66	1.49	0.20
Error (R x S)	100791513	36	2799764.25		

Note. * $p < .05$.

Table D39

Bonferroni Pairwise Comparison on Regression Path Fixation Duration (in Msec) in IA3 across Participants (n = 8) as a Function of Scotoma Size (in Deg) in Experiment 2

Comparison		Mean difference (I -J)	*SE*	*p*
Scotom size (I)	Scotoma size (J)			
0	2	-368.79	100.02	0.06
0	4	-371.67*	73.02	0.01*
0	8	-2231.57	877.82	0.26
2	4	-2.88	74.80	1.00
2	8	-1862.79	847.84	0.42
4	8	-1859.90	840.90	0.41

Note. * $p < .05$.

Table D40

ANOVA Summary Table for Overall Trial Duration (in Msec) in Experiment 2

Source	*SS*	*df*	*MS*	*F*	η^2_p
Between:					
Age (A)	134893629.00	1	134893629.20	8.75*	0.47
Error (A)	154136181.00	10	15413618.11		
Within:					
Replication (R)	71368594.10	2	35684297.04	9.19*	0.48
Error (R)	77650206.00	20	3882510.30		
Size (S)	171608695.00	3	57202898.28	13.73*	0.58
Error (S)	125014326.00	30	4167144.20		
R x S	37293104.40	6	6215517.392	4.40*	0.31
Error (R x S)	84826441.80	60	1413774.03		

Bonferroni Pairwise Comparison on Overall Trial Duration (in Msec) across Participants (n = 12) as a Function of Age in Experiment 2

Comparison		Mean difference (I -J)	*SE*	*p*
Age (I)	Age (J)			
Old	Young	1935.73*	654.34	0.01*

Note. * $p < .05$.

Table D41

Bonferroni Pairwise Comparison on Overall Trial Duration (in Msec) across Participants (n = 12) as a Function of Scotoma Size (in Deg) in Experiment 2

Comparison		Mean difference (I -J)	*SE*	*p*
Scotom size (I)	Scotoma size (J)			
0	2	-499.99	236.52	0.36
0	4	-664.81	246.67	0.14
0	8	-2845.15*	593.21	0.00*
2	4	-164.82	392.89	1.00
2	8	-2345.16*	606.52	0.02*
4	8	-2180.34*	630.98	0.04*

Bonferroni Pairwise Comparison on Overall Trial Duration (in Msec) across Participants (n = 12) as a Function of Replication in Experiment 2

Comparison		Mean difference (I -J)	*SE*	*p*
Replication (I)	Replication (J)			
1	2	1250.43*	384.39	0.03*
1	3	1653.61*	547.11	0.04*
2	3	403.18	195.51	0.20

Note. * $p < .05$.

Table D42

ANOVA Summary Table for the Number of Fixations in Experiment 2

Source	*SS*	*df*	*MS*	*F*	η^2_p
Between:					
Age (A)	552.25	1	552.25	6.43*	0.39
Error (A)	859.31	10	85.93		
Within:					
Replication (R)	344.85	2	172.42	8.18*	0.45
Error (R)	421.53	20	21.08		
Size (S)	1186.39	3	395.46	16.64*	0.63
Error (S)	713.03	30	23.77		
R x S	195.15	6	32.53	4.36*	0.30
Error (R x S)	448.14	60	7.47		

Bonferroni Pairwise Comparison on the Number of Fixations across Participants (n = 12) as a Function of Age in Experiment 2

Comparison		Mean difference (I -J)	*SE*	*p*
Age (I)	Age (J)			
Old	Young	3.92*	1.55	0.03*

Note. * $p < .05$.

Table D43

Bonferroni Pairwise Comparison on the Number of Fixations across Participants (n = 12) as a Function of Scotoma Size (in Deg) in Experiment 2

Comparison		Mean difference (I -J)	*SE*	*p*
Scotom size (I)	Scotoma size (J)			
0	2	-0.47	0.53	1.00
0	4	-1.19	0.50	0.22
0	8	-7.11*	1.42	0.00*
2	4	-0.72	0.81	1.00
2	8	-6.64*	1.44	0.01*
4	8	-5.92*	1.63	0.03*

Bonferroni Pairwise Comparison on the Number of Fixations across Participants (n = 12) as a Function of Replication in Experiment 2

Comparison		Mean difference (I -J)	*SE*	*p*
Replication (I)	Replication (J)			
1	2	2.60	0.92	0.06
1	3	3.69*	1.26	0.05*
2	3	1.08	0.45	0.11

Note. * $p < .05$.