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Scotoma Visibility and Reading Rate with Bilateral Central Scotomas

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Abstract

Purpose—In this experiment we tested whether perceptually delineating the scotoma location and border with a gaze contingent polygon overlay improves reading speed and reading eye movements in patients with bilateral central scotomas.

Methods—Eight patients with age related macular degeneration and bilateral central scotomas read aloud MNRead style sentences with their preferred eye. Eye movement signals from an EyeLink II eyetracker were used to create a gaze contingent display in which a polygon overlay delineating the area of the patient's scotoma was superimposed on the text during 18 of the 42 trials. Blocks of 6 trials with the superimposed polygon were alternated with blocks of 6 trials without the polygon. Reading speed and reading eye movements were assessed before and after the subjects practiced reading with the polygon overlay.

Results—All of the subjects but one showed an increase in reading speed. A paired-samples t test for the group as a whole revealed a statistically significant increase in reading speed of 0.075 ± 0.060 (SD) log wpm after reading with the superimposed polygon. Individual subjects demonstrated significant changes in reading eye movements, with the greatest number of subjects demonstrating a shift in the average vertical fixation locus. Across subjects, there was no significant difference between the initial and final reading eye movements in terms of saccades/s, average fixation duration, average amplitude of saccades, or proportion of non-horizontal saccades.

Conclusions—The improvement in reading speed (0.075 log wpm or 19%) over the short experimental session for the majority of subjects indicates that making the scotoma location more visible is potentially beneficial for improving reading speed in patients with bilateral central scotomas. Additional research to examine the efficacy of more extended training with this paradigm is warranted.

Keywords

macular degeneration; scotoma; perceptual filling-in; eccentric viewing; low vision rehabilitation; reading speed; reading eye movements; gaze contingent display

Macular degeneration can be severely disabling as patients frequently develop central scotomas, which decrease or eliminate their ability to read, drive, and recognize faces. To

compensate for their loss of central vision, patients with absolute central scotomas must learn to use their peripheral retina to perform tasks normally performed with the fovea and parafovea. Patients typically adopt one or more specific eccentric retinal loci to track and view objects and to read. These loci have been termed preferred retinal loci (PRLs) and their characteristics have been described.^{1,2} In most patients, the use of a PRL as a pseudofovea is incomplete, as their oculomotor behavior demonstrates a lack of complete re-referencing from the fovea. Some patients may continue to image objects of interest in the scotoma by making foveating saccades.³

One of the most frequently used techniques for teaching a patient to use his/her remaining functional vision is eccentric viewing training, in which a patient is taught to move his/her eyes or head so that objects are imaged on healthier peripheral retina.⁴ A 2004 survey of United States Veterans' Administration (VA) optometrists and visual skills instructors indicates that eccentric viewing training is widely implemented within the VA system with the most commonly used form being the practice of scotoma placement and eye movement control while reading with an optical low vision device or a closed-circuit television.⁵ In this type of training, a patient is guided to look in the direction thought by the examiner to be the best position for the eye to read. The examiner relies heavily on the patients' ability to recognize where they have remaining vision, as the trainer has no accurate method of monitoring eye position and cannot tell whether the patient is moving his/her eye sufficiently or too much. During training it is unclear where precisely the scotoma is in relation to the targets being viewed and whether the patient's scotoma overlaps the target of interest. Although training patients to eccentrically view has been widely implemented as a regular part of low vision services, the benefit of current techniques is debatable.⁶

Fundus imaging devices such as the Nidek MP-1 microperimeter and the scanning laser ophthalmoscope (SLO) allow the examiner to evaluate eccentric viewing with greater accuracy.⁷⁻¹⁰ With these instruments, the examiner is able to observe an image of the patient's fundus while the patient is performing a task such as fixating a target or reading a sentence. The patient is still unable to perceive the location of his/her scotoma, but the examiner can coach the patient to move his/her eye to a more "optimal" location.^{11,12} Use of these instruments has yet to become widely implemented in routine low vision evaluations, possibly because of their limited accessibility, high cost, increase in examination time, and the need for greater technical skill. Eccentric viewing training remains focused on helping the patient recognize where they have to look to perceive objects and perform visual tasks.

The effectiveness of any vision rehabilitation training is likely to be complicated by perceptual filling-in. In perceptual filling-in, characteristics of a scene, such as its color or texture, are perceived in an area corresponding to complete vision loss, or as in the case of the physiological blind spot, an area with no photoreceptors. Zur and Ullman demonstrated that gratings and regular dot patterns that span the scotomatous region of the visual field are nevertheless perceived by patients with AMD to be uniform and continuous.¹³ Investigators have also shown that the commonly used Amsler grid is perceived as complete by many patients with dense central scotomas.^{14,15}

Based on the observation that perceptual filling-in can occur at the physiological blind spot and in artificial scotomas produced in normal observers, it is likely that when patients with a central scotoma look at text, they perceive the color, texture, and brightness of the text in the region of their scotoma and the awareness of their scotoma is decreased.¹⁶ Because of perceptual filling-in, patients may be unaware of the specific location of their scotoma and consequently may experience difficulty moving and positioning their eyes appropriately to use their remaining peripheral vision.¹⁴ It is a common clinical observation that patients with bilateral central scotomas are not fully aware of their scotomas.¹⁷

Reduced awareness of the scotoma border and location may contribute to ineffective oculomotor control, the placement of text in a non-optimal location relative to the scotoma, and inappropriately directed attention. It can be difficult for patients to understand how they must move and position their eyes to use their remaining peripheral vision. As a result current methods of eccentric viewing training are likely inadequate in helping patients to correctly position their eye and make useful eye movements, especially when viewing paragraph text.

Allowing patients to perceive the specific border and location of their scotoma may be beneficial and has not been explored as a possible training mechanism.

It is thought that perceptual filling-in is a result of the unmasking of lateral connections within the visual cortex or, possibly, a top-down effect in which the visual information from the scotoma border is also perceived within the scotoma.^{18–20} Because the brain likely uses the information from the retina immediately adjacent to the scotoma border to fill-in the scotoma, we should be able to use this area on the retina in conjunction with a gaze-contingent display to allow patients to perceive their own scotoma.

For example, if a particular color were imaged onto the whole retinal border surrounding the scotoma, the scotoma should fill-in with that color. This is observed to occur at the physiological blind spot and in artificial scotomas, and would be expected to also occur in pathological scotomas.^{21,22} Using a gaze-contingent display, we can constantly image a stimulus along the perimeter of the scotoma, which would allow patients to perceive the location and border of their scotoma while performing a task such as reading. Training in which patients can perceive the border and location of their scotoma also is expected to help them to learn to better position the scotoma relative to the text or object of interest, appropriately direct their attention, and make more accurate eye movements.

In this experiment, we tested whether perceptually delineating the scotoma location and border can lead to an improvement of reading speed in patients with bilateral central scotomas. It was expected that perceptual filling in of the scotoma would occur when the scotoma location and border were delineated with a gaze-contingent polygon overlay. It was further expected that reading speed would be faster after the patients received practice in reading when their central scotomas were rendered more visible. If reading speed improves with delineation of the scotoma location and border, patients would be expected to benefit long-term from continued training and additional research to assess the efficacy of such training would be warranted.

METHODS

Subjects

Nineteen subjects with bilateral central scotomas were recruited from the UHCO Center for Sight Enhancement. Testing was performed monocularly using the better seeing and preferred eye of each subject. The preferred eye in those subjects with similar acuities in the two eyes and in those subjects reporting no eye preference was determined using an eye dominance test. Subjects read aloud while wearing a trial frame with +10 diopter lenses in front of both eyes. When using a +10 diopter microscope, subjects are forced to choose one eye for reading as, with this magnification, it is not possible to sustain fusion comfortably at 10 cm. The non-tested eye was patched during testing.

Eight of the subjects provided usable data (Table 1). The other 11 subjects either demonstrated relative scotomas during perimetric testing with a high contrast target (despite identification of an absolute scotoma during micro-perimetry using the Nidek MP-1), central sparing, or we could not present a letter size large enough on our monitor to assess the critical print size for the reading portion of the experiment.

The research reported here followed the tenets of the Declaration of Helsinki and the experimental protocol was approved by the University of Houston Committee for the Protection of Human Subjects. All subjects granted written informed consent before participating in the study.

Perimetry

The Nidek MP-1 microperimeter was used initially to confirm bilateral central scotomas and to assess whether subjects had central sparing or a ring scotoma. A custom perimetry program was designed using the Nidek perimetry software to display Goldmann size III stimuli (0.43 deg diameter). Tested points were spaced at half-degree intervals over the central eight degrees. Eight points were placed also at 15 degrees from the center of the target array along the 90 – 270, 0 – 180, 45 – 225, and 135 – 315 deg meridians to probe whether subjects were responsive and attentive during testing. The “raw automatic” threshold strategy was used with a step size of 10 dB. Stimulus duration was 200 ms. The center of the perimetric array was placed by the examiner at the approximate location of the vestigial fovea while the fundus was viewed in the MP-1 instrument.

In addition to the perimetry performed with the Nidek MP-1, a custom Matlab program was used to perform gaze-contingent perimetry and map out the scotoma edge on the CRT monitor prior to presenting sentences for the reading trials.

Critical Print Size

A CRT monitor was placed 57 cm from the tested eye. Cheek rests and an adjustable strap behind the head were used to stabilize head position. The cheek rests were curved and positioned to sit under the zygomatic bones. This allowed good control of lateral and forward head movement. Vertical head movement was still possible but subjects were instructed to not move their heads and were able to keep their heads relatively stable during

trials. Cheek rests were used instead of a mouth bite or head rest and chin cup to allow subjects to read aloud and to avoid possible dental concerns.

An EyeLink II eyetracker was positioned firmly on the subject's head and the camera and forehead band heights were adjusted so the top and bottom of the CRT monitor were visible to the subject. The refraction from the subject's latest optometric exam was refined and used to calculate the power of a 70 mm lens blank mounted on the forehead band of the EyeLink. For example, for a subject with a -1.00 D refractive error, a $+0.75$ D lens blank (-1.00 D + 1.75 D for the working distance of 57 cm) was used. The bottom was cut off the set of lens blanks used in the experiment so that the lens did not interfere with the EyeLink II camera adjustment but still allowed the subject to view the whole screen.

To determine the critical print size, subjects read aloud MNRead style sentences composed of 4 rows of Courier text with 13 characters per row.^{23,24} (The sentences displayed on clinical MNRead charts are arrayed in 3 lines of Times Roman font.) The sentences were presented one at a time on the CRT monitor and viewed from a distance of 57 cm. A set of 271 sentences was randomly ordered for each subject and this order was used for all sentence presentations during the study session. No sentence was presented twice during a study session. Some subjects were not able to complete the study in a single visit. The sentence order was randomized again at the second visit and occasionally a sentence that was used in the first visit was presented also during the second visit. The elapsed time and number of words read correctly was used to calculate reading speed. Initial letter size was 1.3 logMAR and descended in 0.2 logMAR steps until a decrease in reading speed occurred that was greater than twenty percent of the maximum initial reading speed. The critical print size was further refined using ascending steps of 0.1 logMAR. The best bilinear fit of reading speed versus logMAR was used to determine the critical print size (Figure 1). A custom Matlab program and Psychtoolbox were used to present the sentences and calculate the bilinear fit.^{25,26} Subsequent parts of the experiment were not completed for individuals whose critical print size appeared to be greater than 1.3 logMAR.

When allowed to more readily perceive the location of their central scotoma, subjects may adapt a strategy in which they move their scotoma out of the way and use a slightly more peripheral locus for reading. To account for the possibility of a slightly more peripheral reading locus, a text size equal to 0.2 logMAR greater than the measured critical print size was used in the main experiment to measure reading speed when the central scotoma was and was not visible.

EyeLink II Set-up and Calibration

A Rodenstock Scanning Laser Ophthalmoscope (SLO) was fitted with a 4f relay lens system to allow for imaging of the retina after reflection from a dichroic mirror. The SLO images were used to verify that subjects used the same retinal locus to view each of the nine calibration targets used in a modified version of the Eye Link calibration program. The dichroic mirror reflected infrared light from the SLO while passing visible light from the monitor to the subjects' eye. Subjects were thus able to view the monitor through the dichroic mirror while the SLO was used to image the retina from the side (Figure 2).

To allow for SLO imaging during calibration of the EyeLink II, the locations of the 9 calibration targets were adjusted inward toward the center of the screen from EyeLink's default locations. The resulting nine-point calibration had target positions in a grid pattern. Non-central calibration points were ± 7.3 deg horizontally and ± 5.5 deg vertically from center. Screen dimensions were 36.4×27.3 cm or 35.4×26.9 deg. Each of the non-central targets could be moved on the monitor by the experimenter using the computer keyboard during the calibration process in case a subject did not use the same retinal locus to view one or more of the calibration targets, as explained below.

To register the positions in the SLO raster that corresponded to the calibration locations on the CRT monitor, five normal subjects successively fixated each of the nine fixation targets while their fundi were viewed with the SLO. For each of the nine calibration points on the CRT, the position of the foveal pit seen in the SLO image was marked with an indelible pen on a transparency affixed to the SLO monitor screen. The locations of the foveal pit for each of the calibration positions were similar for all of the subjects and the average position was used as a reference for subjects with macular degeneration. A laser pointer mounted on the rail that held the SLO relay-lens system was used to ensure that the SLO raster center was aligned with the CRT monitor center prior to calibration.

If a subject's pupils were smaller than about 4 mm under normal room illumination, they were dilated with 2.5% phenylephrine. Each subject was calibrated in the following manner: The EyeLink eyetracker was mounted on the subject's head, and the non-viewing eye was patched. The camera in front of the viewing eye was positioned to provide an optimal image of the eye, the illuminated iris, and the infrared corneal reflection. Cheek rests and a strap behind the head were adjusted to stabilize the head.

The subject was asked to keep his or her head as still as possible and to look at the center of a calibration target, a letter x, presented at the center of the screen. An image of the subject's fundus was viewed simultaneously on the SLO monitor. The retinal locus used by the subject to view the central calibration target was determined and each of the remaining eight calibration points was then presented in a random sequence. Calibration points were manually accepted using the EyeLink II software after it was confirmed from the SLO image that the fixation target was imaged at the same retinal locus as the first, central target. If the subject used a different locus to view any of the calibration targets, he or she was coached to look at the center of the 'x' and hold his/her eye still. If the subject still didn't image the 'x' using the same retinal locus, the 'x' was moved on the monitor until the initially-used retinal locus lined up with the calibration mark made for the normal subjects.

Gaze-Contingent Display

Eye position data from the EyeLink II eye tracker were used with a custom Matlab program and Psychtoolbox to create a gaze-contingent display. The eyetracker was used in the 250 Hz pupil-corneal reflex mode with headtracking engaged. Because of physical interference from the components of the relay optical system attached to the SLO, the markers used for headtracking had to be shifted horizontally to be visible to the head mounted camera on the EyeLink. Two of the markers were placed above and below the horizontal center of the display screen and two were mounted 37.9 cm to the right of center when imaging the left

eye and 37.9 cm to the left of center when imaging the right eye. The non-central markers were mounted on a board attached to the monitor. The normal horizontal separation and vertical heights of the markers were conserved.

After calibration of the eyetracker, stabilized kinetic perimetry was performed along eight meridians (0 deg to 315 deg, in 45 deg increments) that emanated from the center of the scotoma. The approximate center of the scotoma in the SLO image was determined using retinal landmarks from the MP-1. The subject was asked to fixate a letter, which was moved on the CRT display screen until the scotoma center was positioned near the center of the SLO raster. The subject was asked to hold his or her eye steady at this position for the duration of the perimetry portion of the experiment. The offset from fixation of the approximate scotoma center was recorded and the letter was removed.

A continuously presented square black probe, two times the stroke width of the letter size to be used during the final part of the experiment, was positioned at the center of the screen, inside the scotoma. The probe was moved from the screen center in 2 deg increments along one of the eight meridians until the subject reported seeing the probe. The probe was then stepped back toward the center of the scotoma in 1 deg increments until the subject reported it disappeared. The probe then was stepped outward again in 0.5 degree increments until the subject reported it returned to visibility. This position at which the probe was just visible was recorded and the probe was returned to the screen center. Testing was then conducted along the next meridian until all 8 meridians had been tested. The 8 transition points from non-seeing to seeing were connected and the resulting polygon was filled on the CRT screen to form a gaze-contingent black polygon corresponding to the location of the subject's scotoma. Because seeing points were used to create the polygon overlay, the edges of the polygon covered an area slightly larger than the actual scotoma. This caused the scotoma to fill-in and allowed the patients to perceive the location of their scotoma. The stabilization of the black polygon was not absolute as no subject reported that the polygon faded.

After mapping the location of the central scotoma, subjects were asked to look at the center of a letter 'x' positioned at the center of the CRT screen while the fundus image was viewed in the SLO. To ensure that the polygon indicating the location of the scotoma did not cover viable retina near the PRL, the border of the polygon was adjusted inward if it covered any part of the letter 'x' while the experimenter monitored the SLO image to ensure that the subject was not positioning the scotoma on the letter. When necessary, only the border of the polygon near the 'x' was adjusted inward.

The measures of horizontal and vertical eye position from the Eye Link II were used to update the location of the polygon displayed on the CRT monitor. Timing measurements indicate that the display was updated reliably on the next available frame, i.e., within 12 ms. The innate noise of the Eye Link II eye tracker (approximately 0.25 deg RMS) prevented fading of the polygon overlay.²⁷ The usable range of the Eye Link is estimated to be ± 20 degrees horizontally and ± 18 degrees vertically in the 250 Hz tracking mode. With thirteen characters per line, this limited the maximum displayable letter size to 2.3 degrees, equivalent to 1.44 logMAR. However, our display screen and experimental setup limited the maximum displayable letter size to 1.3 logMAR, with a 1.66 deg 'x' letter height. This

resulted in a horizontal line length of 28 degrees and a total vertical height of 14.6 degrees, which are within the trackable range of the EyeLink eyetracker.

Reading Speed with and without Scotoma Visibility

Subjects read aloud sentences with and without the superimposed black polygon that marked the location of their scotoma. The same random sentence order that was determined prior to assessing the critical print size was maintained so that none of the sentences were presented twice during a study session. Blocks of 6 trials with the superimposed polygon were alternated with blocks of 6 trials without the polygon. There were a total of 42 trials (7 blocks) for each subject. The first block was without the superimposed polygon and was used to determine baseline reading rate and to represent the subject's natural reading eye-movements.

A drift correction of the Eye Link was performed before each of the blocks of trials with the superimposed polygon. Occasionally the nine-point calibration had to be repeated if the EyeLink II camera accidentally bumped against the cheek rests or if the patient needed to take an extended break.

Analyses

Maximum initial and final reading speeds at the print size used during the experiment were calculated from the median values of the first six and the last six trials.

Saccades that resulted in a shift of fixation greater than 0.5 deg (the approximate spacing between adjacent characters for 0.7 logMAR text) were identified and counted. Saccades as small as 0.5 deg were detected reliably using a velocity criterion of 15 deg/s. The amplitude and meridian of each identified saccade were calculated using a custom Matlab program.

The average amplitude of saccades was calculated for each reading trial. Saccades per second were determined by dividing the number of saccades by the elapsed time for each trial. Saccades were categorized as horizontal (orientations between 330 – 30 and 150 – 210 deg), vertical (between 60 – 120 and 240 – 300 deg), or oblique (between 30 – 60, 120 – 150, 210 – 240, and 300 – 330 deg). The average vertical and horizontal eye position for each trial was determined from the median location during fixations, defined as the intervals between saccades.

To analyze the patients' reading eye movements more globally, two experienced eye movement researchers (authors 2 and 3) ranked the eye movement traces for the first and last 6 trials for each subject from 1 to 12. The trials were ordered from "best" to "worst," with a rank of 1 corresponding to the trial that most resembled normal reading eye movements and a rank of 12 given to that subject's trial that was least similar to normal reading movements. Both researchers reported using multiple criteria to define "normal reading eye movements," including the presence of stair step sequences of left-to-right eye movements along each line of text, a consistent downward progression of vertical eye position from line to line, and minimum numbers of regressive and apparently extraneous saccades. The researchers were masked to trial order and the trials were randomized for each researcher. Figure 3 depicts the vertical and horizontal eye movement traces for one of the first 6 trials for patient 13, with

an average rank of 9, and the vertical and horizontal eye movement traces for one of the last 6 trials for the same patient, with an average rank of 3.

RESULTS

The mean reading speed of the initial 6 trials without the superimposed polygon and the mean reading speed of the last 6 trials, also without the superimposed polygon were compared for each individual subject. All of the subjects but one showed an increase in reading speed (Table 2). The individual that showed no improvement (Subject 78) had the smallest scotoma and was also the fastest reader with an initial mean reading speed of 114 words per minute. The improvement in reading speed was statistically significant for only two of the subjects when paired t tests were performed on each of the individual data sets (Table 2). However, a paired-samples t test for the group as a whole revealed a statistically significant increase in reading speed of 0.075 ± 0.060 (SD) log wpm, corresponding to an improvement of 19%, after the subjects practiced reading with the superimposed polygon ($t(7) = 3.53, p = 0.01$).

The mean log reading speed for all trials without and with the superimposed polygon for each subject were also analyzed. A paired-samples t test revealed that the mean log reading speed was significantly faster without (1.89 ± 0.13 log wpm) than with (1.82 ± 0.16 log wpm) the superimposed polygon, $t(7) = -3.360, p = 0.012$ (Figure 4).

The initial reading speed and eye movement data for subject 39 were lost due to a program crash. Therefore, the reading speeds for the reading trials that determined the critical print size were used to calculate the initial reading speed for this subject. Trials for letter sizes at or above the critical print size were used. Because eye movements were not recorded during the assessment of the critical print size, analyses comparing initial to final eye movement data could not be performed for this subject.

The following eye movement parameters were analyzed with statistical tests of significance between the initial and final blocks of 6 reading trials: the mean vertical and horizontal position of the fixation locus, the number of saccades/s, the median fixation duration, the mean amplitude of saccades, and the number of non-horizontal saccades. For each of these parameters, a t -test was used to compare the first 6 and last 6 reading trials *without* the superimposed polygon for each individual subject. Individual subjects demonstrated significant changes in reading eye movements, with the greatest number of subjects (5 of 7) demonstrating a shift in the average vertical fixation locus (Table 3). The shift of the PRL location was upward in 3 of these subjects and downward in the other 2.

The difference between the average of the initial 6 and last 6 trials for each subject comprised the group data used to analyze the sample as a whole. One-sample t tests were performed for changes in saccades/s, average fixation duration, average amplitude of saccades, and proportion of non-horizontal saccades. There were nonsignificant trends for an *increase* in the average amplitude of saccades (6/7 subjects) and for a decrease in the number of saccades per second (5/7 subjects). However, there was no significant difference between

the initial and final reading eye movements across subjects for any of the above parameters (Table 4).

To compare the ranks given by each researcher to the patients' reading eye movements, correlations were performed between the two sets of rankings for each individual patient. For four of the patients (13, 51, 64, 78) the rankings correlated very well ($R^2 = 0.814, 0.891, 0.865, 0.945$, Figure 5); for one patient (55) the rankings correlated well ($R^2 = 0.681$); and for the other two patients (31 and 96) the correlation was not as good ($R^2 = 0.247, 0.290$, Figure 5). A review of the eye-movement traces of subjects 31 and 96 indicates that these two subjects made the greatest proportions of non-horizontal saccades. Disagreement between researchers SBS and HEB in ranking these two subjects' eye-movement traces appears to have resulted from placing different weights on the patterns of vertical and horizontal movements during reading. Specifically, SBS rated the traces with disordered vertical eye movements but a relatively normal horizontal reading pattern as poor whereas HEB rated the same traces as good.

Overall the rankings of the two researchers agreed quite well and an additional analysis to compare the improvement in reading speed and reading eye movements was performed. The average rank given by the two researchers for the last 6 trials was subtracted from the average rank for the first 6 trials. A positive difference indicates that eye movements were judged more similar to normal reading eye movements during the last 6 trials. The percent differences in average reading speed also were calculated, with a more positive number corresponding to a greater improvement in reading speed.

Regression analysis of the average change in the rankings demonstrated a highly significant relationship between improvements in reading speed and eye movements that were judged to be more similar to normal reading eye movements ($F[1,5] = 17.89, p = 0.0082$, Figure 6).

The position of the scotoma relative to the text was also analyzed across trials.

After practice reading with the overlaid polygon, five of the seven patients showed a shift that positioned the scotoma further from the text (Figure 7 and Figure 8). Two of the subjects who had large scotomas that were initially positioned above the center of text re-positioned the scotoma closer to the center of the text in the final reading trials. Four of the subjects who moved the scotoma further from the text while reading, shifted the scotoma upward. One subject positioned the scotoma further down and right to move it out of the way while reading.

Five of the seven subjects used a PRL that projected in visual space inferior and to the left of the scotoma. This is consistent with past findings that many patients place their scotoma up and to the right when they eccentrically view.^{28–31} This preference is interesting in that it doesn't appear to depend on which eye is used, as is the case also for the small sample of patients reported here.

All patients reported that the polygon overlay looked completely filled in, was uniform in color (black) and had sharp borders. After the experiment, the subjects were asked what they perceived in the area of the scotoma without the polygon overlay. The subjects were

instructed to hold their eye still while viewing the center of a MNRead sentence. The eye not tested during the experiment remained patched. All patients reported a blank white area with the same color and luminance as the background. None of the patients reported perceiving letters or other information content within the scotoma.

DISCUSSION

The improvement in reading speed (average 0.075 log wpm or 19%) over the 42-trial experimental session for all subjects but one indicates that making the scotoma location more visible is potentially beneficial to improving reading speed. It is possible but unlikely that the observed improvement in reading speed was a result of learning the specific reading task instead of the influence of the polygon overlay.

Three reasons that the observed results are unlikely to reflect learning of the experimental task are: 1. Reading is an overlearned task and most of the subjects reported being avid readers even after the onset of their central vision loss, 2. The subjects were allowed to practice the experimental paradigm during the trials used to calculate the critical print size and generally showed a similar reading speed for the critical print size and the initial reading speed before introduction of the polygon to mark the scotoma location, 3. The fixation location changed over the study session and resulted in a shift of the scotoma away from the center of text for five of the seven subjects, indicating that the patients were either adopting an alternate eye movement strategy or shifting their PRL. Further, the eye movements of the subjects who showed the most improvement in reading speed were judged to be more consistent with normal reading eye movements after practice with the overlaid polygon, which made the borders and location of their scotoma more visible.

This study did not explore patient characteristics, such as scotoma size or shape, and there were no apparent characteristics of subjects 64 and 55 to explain why these subjects had a greater improvement in reading speed compared to the other subjects.

The fact that all of the subjects read more slowly when the polygon overlay was visible argues against the polygon overlay resulting in the observed improvement in reading speed. Subjects may have read more slowly with the polygon overlay because the polygon was slightly larger than the actual scotoma and may have covered part of the area used normally by the patient to read. The EyeLink II does not provide perfect image stabilization as indicated, for example, by the absence of image fading, and may have produced small shifts in the retinal area covered by the polygon, disrupting the patient's "normal" reading pattern.³² The polygon overlay also may have caused attention to be allocated to the region of the visible "scotoma" resulting in less sustained attention on the text.

After reading with the superimposed polygon it was thought that subjects might shift their position of gaze to move their scotoma and better position the area near the PRL to read text. For example the initial fixation locus or single-letter PRL is shown as the gray polygon in Figure 7 for subject 55, demonstrating a PRL that is down and to the left of the scotoma in visual space. During reading, this subject's scotoma would be expected to cover part of a

word to the right of the PRL. However the whole word should become more visible if the subject moved his eye to shift the scotoma further up (the green polygon in Figure 7).

An alternative possibility is that the scotoma became more centered on the text as the patient learns to “read around” the scotoma. Some patients may understand that they need to view words eccentrically, but may not be able to judge how far to the side to position their eye and may use a retinal locus farther than necessary from the scotoma. By using the polygon overlay to make the scotoma location more visible, patients might position their eyes more effectively. After practice this would result in the patient positioning the scotoma closer to the text of interest.

After patients had experience with the polygon overlay, during subsequent reading without the polygon the PRL typically (5 out of 7) shifted further from the scotoma. This shift presumably allows more of the fixated word to be imaged on seeing retina. The PRL is frequently located at or very near the border of the scotoma, which may be problematic for efficient reading.^{2,33} In normal reading, visibility of the letters to the right and, to a lesser extent, the letters to the left of fixation are important for achieving optimal reading speed.³⁴ For this reason, it is likely that the fraction of a word that a patient with central vision loss can see during a single fixation will exert an influence on reading speed.

Patients with central scotomas may have multiple reading PRLs and it is plausible that under binocular conditions some subjects would use viable retina in both eyes to read. Rivalry may also influence which PRL is used. However, if we were able to accurately map the binocular scotoma and present it as a polygon overlay on a gaze-contingent display that compensated for both changes in vergence and conjugate eye movements, we believe we would get a similar shift in the binocular PRL to position the scotoma out of the way.

CONCLUSIONS

Reading speed increased by an average of 19% in a sample of patients with bilateral central scotomas after a relatively brief period of practice in reading text with a gaze-contingent polygon overlay that allowed the patients to perceive the location of their scotoma. Based on these results, we suggest that the long-term benefit of a more extended period of this type of training, compared to conventional methods of eccentric-viewing training should be investigated.

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Figure 1.

Bilinear fit of MNRead data (log reading speed vs. print size in logMAR) for subject 78 demonstrating a critical print size of 1.0 logMAR. Reading trials with and without a visible polygon that marked this subject's scotoma were performed using a print size equivalent to 1.2 logMAR.

Figure 2.

Schematic representation of the SLO setup with imaging of subjects' fundus, as seen from the side. In the top image, the SLO is on the right and the subject's disembodied eyes are represented at the left. The positions of the SLO and the subject's eyes are reversed in the bottom image. The configuration shown was used to test a subject with a preferred left eye. The orientation of the dichroic mirror that allowed the SLO to view the subject's fundus could be flipped to permit testing of a subject with a preferred right eye.

Figure 3. Horizontal (blue) and vertical (green) eye trace for a trial at the beginning (**A**) and the end (**B**) of the study session for patient 13. The average rank for these trials was 9 and 3 respectively.

Figure 4. Mean reading speed compared for trials with a superimposed polygon and trials with no superimposed polygon.

Figure 5.
Correlation of ranking of reading eye movements between researchers for patients 13 (A)
and 96 (B).

Figure 6.

Percent change in reading speed compared to the change in the average ranking of eye movements (average rank of beginning trials - average rank of end trials) between the first 6 and the last 6 reading trials without a superimposed polygon.

Figure 7.

Horizontal and vertical shift in fixation locus for subject 55. The average position of the scotoma location for the initial 6 trials is drawn in gray and the average position for the final 6 trials is drawn in green. The polygon used to represent the scotoma location in this image is the actual polygon overlay used during alternate sets of reading trials for this subject. However the polygon overlay was not visible during the trials compared in this analysis. The polygon overlay is used here solely to approximate the position and size of the patient's scotoma. The patient's actual scotoma was slightly smaller than displayed here, as the polygon is based on the locations where the patient was just able to see the test probe. The length of the black arrow is scaled to represent the shift in fixation locus from the first to the last 6 trials and represents a 4.5 degree change. Letter size is 1.2 logMAR, such that a lower case x subtends 1.3 degrees. The dimensions of the monitor, as represented by the rectangular outline, were 35 deg by 27 deg. An asterisk marks the location of the single-letter PRL in relation to the position of the initial (gray) scotoma.

Figure 8. Horizontal and vertical shift in fixation locus between the first and last 6 reading trials without the polygon overlay for subjects 64 (A), 78 (B), 31 (C), 51 (D), 13 (E), and 96 (F). The length of the black arrow is scaled to represent the shift in fixation locus from the first to the last 6 trials. Other conventions are as in Figure 7.

Table 1

Patient characteristics.

Subject Number	Age (yrs)	Gender	Diagnosis	Study Eye	Critical Print Size logMAR
64	76	F	Exudative AMD	OS	0.7
55	74	M	Exudative AMD	OS	1.0
78	84	M	Non-exudative AMD	OD	1.0
31	88	M	Non-exudative AMD	OD	0.9
51	82	M	Non-exudative AMD	OD	1.0
13	81	F	Non-exudative AMD	OS	0.7
96	78	F	Exudative AMD	OS	1.0
39	81	M	Myopic Choriorretinal Degeneration + Non-exudative AMD	OS	0.7

Table 2

Average reading speed (wpm) for the initial 6 and last 6 trials for each patient.

Patient	Initial 6 Trials	Last 6 Trials	Difference	<i>t</i> (5)	<i>p</i>
64	51	75	24	3.960	0.011
55	84	110	26	3.652	0.015
78	114	112	-2	-0.167	0.874
31	86	90	4	0.828	0.446
51	36	45	9	1.584	0.174
13	67	82	15	1.916	0.114
96	92	97	5	0.930	0.395
39	52	60	8	1.088	0.326

Average vertical and horizontal fixation locus before and after reading with a polygon overlay at the position of the central scotoma (degrees from center of the screen, up and left are positive).

Table 3

Subject Number	Vertical			<i>p</i>	Horizontal			<i>p</i>
	Before	After	Difference		Before	After	Difference	
64	1.76	1.15	-0.61	0.058	-0.07	0.20	0.27	0.533
55	-1.19	3.31	4.5	0.001	6.70	7.26	0.56	0.234
78	-1.70	-0.42	1.28	0.075	1.58	-0.09	-1.67	0.003
31	0.83	3.13	2.3	0.004	0.89	0.23	-0.66	0.278
51	1.16	-1.02	-2.18	0.001	3.34	0.83	-2.51	0.012
13	-0.17	0.92	1.09	0.003	1.75	1.77	0.02	0.980
96	7.86	6.33	-1.53	0.024	6.24	6.72	0.48	0.670

Table 4
Change in reading eye movements compared between first and last 6 trials averaged across all subjects.

	Initial			Final		
	Mean	Median	SIQR	Mean	Median	SIQR
sac/s	3.08	3.16	0.48	2.82	2.79	0.28
amplitude of saccades (deg)	4.41	4.02	0.85	4.65	4.26	0.81
fixation duration (s)	0.23	0.24	0.04	0.23	0.24	0.02
proportion of non-horizontal saccades	0.15	0.06	0.06	0.13	0.09	0.09