Contour integration in peripheral vision reduces gradually with eccentricity

Alex K. Nugent, Rajesh N. Keswani, Russell L. Woods *, Eli Peli

The Schepens Eye Research Institute, Harvard Medical School, 20 Staniford Street, Boston, MA 02114-2500, USA

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Abstract

Hess and Dakin [Nature 390 (1997) 602; Vision Res. 39 (1999) 947] reported that normally-sighted subjects using peripheral vision (beyond 10°) were unable to detect paths of alternating-phase Gabors embedded within randomly positioned Gabors, but could detect same-phase paths. This result led them to propose a "fundamental difference" between central and peripheral visual processing. While we were able to replicate many of their results, our normally-sighted observers could detect alternating-phase paths beyond 10°. We found that path detection decreased monotonically as a function of eccentricity (0°–30°) for both alternating-phase and same-phase stimuli. As with most visual functions the more difficult path detection condition (alternating-phase) declined slightly faster. The results for the normally-sighted observers could not be explained by poor fixation. Three people with substantial central vision loss (i.e. they can only use peripheral vision) could see both same- and alternating-phase stimuli with eccentric viewing of 13°–17°. Therefore central and peripheral vision appear to use similar visual mechanisms to perform the task, there being no fundamental difference.
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1. Introduction

Hess and Dakin (1997, 1999) studied the difference in contour integration between foveal and peripheral vision in normally-sighted observers. They concluded that there is a "fundamental difference" in the way foveal vision performs path detection compared to how peripheral vision (beyond 10° eccentricity) carries out the task. Hess and Dakin's experiment involved the detection of paths composed of Gabor patches with correlated carrier orientations (same phase) embedded within a field of Gabor patches of random position and orientation. They also evaluated the ability to detect similar paths in which the elements alternated in phase by 180° and were embedded in a field of similar, randomly orientated elements of either phase. Hess and Dakin's results showed that performance in the alternating-phase path detection was slightly reduced in the fovea (as compared to the same-phase condition), and reduced

similarly to the same-phase performance up to 10° eccentricity. However, for larger eccentricities (20°) alternating-phase performance was reduced to the level of chance. Thus, Hess and Dakin concluded that the fundamental difference in performance of the alternating-phase path detection task in the periphery meant that performing that task required additional processing that was not available in the periphery. Same-phase path detection did not decline significantly beyond 10° because a simple filtering mechanism, that did not require the intercellular linking operations necessary to detect the alternating-phase paths, was sufficient. They demonstrated with simulations that such simple filtering could account for the declining performance of the task as a function of increasing path angle of same-phase paths, but the simple filter could not detect the alternating-phase stimuli, leading to chance performance prediction.

We are studying vision in people with bilateral central scotomata (areas of partial or complete blindness) due to retinal diseases, and developing methods for image enhancement for these people. As these people are forced to use their peripheral vision for tasks commonly

* Corresponding author. Tel.: +1-617-912-2589; fax: +1-617-912-0169.
E-mail address: rwoods@vision.eri.harvard.edu (R.L. Woods).

performed with foveal vision, we are interested in the way the near periphery functions in tasks that may be relevant for image perception. Contour integration appears to be such a task. In addition, their peripheral visual function may improve or change with adaptation to the use of peripheral vision (Heinen & Skavenski, 1991, 1992). Improvements in the ability to perform complex visual tasks such as reading are noted in clinical practice with the passage of time after bilateral visual impairment and are presumed to improve with practice and training (Backman & Inde, 1979; Goodrich & Quillman, 1977; Holcomb & Goodrich, 1976; Nilsson, 1990; Nilsson, Frennesson, & Nilsson, 1998).

The clinically noted improvements might be a general result of training in a difficult task, or could be explained by the person's ability to direct and concentrate their attention at the newly developed preferred retinal locus (PRL) (Timberlake et al., 1986). Also, the improvements may represent plasticity in the visual system, where visual cortical areas devoid of input from the scotomatous retina may be reassigned to processing of the peripheral retinal signals (Heinen & Skavenski, 1991). We hoped that the contour integration path detection could be useful in probing such performance changes in peripheral vision if the alternating-phase performance could be shown to improve in people with bilateral scotoma as compared with normally-sighted subjects or people with a unilateral scotoma.

To assess these functions, first we attempted to replicate Hess and Dakin's results. We replicated many of their results for a range of conditions. However, we failed to replicate the critical finding of a large difference in performance between same-phase and alternating phase path stimuli when viewed at 20° eccentricity. Our three normally-sighted subjects achieved above chance performance beyond 20° eccentricity. Performance reduced gradually with increasing eccentricity for both conditions, declining slightly faster for the more difficult (alternating-phase) paths. This difference was not caused by improper fixation (peeking foveally at the stimulus). Also, task performance of three visually-impaired subjects who had to view with eccentricities greater than 10° was consistent with the performance of our normally-sighted subjects on both same-phase and alternating-phase conditions at the corresponding eccentricities.

2. Methods

2.1. Subjects

Five normally-sighted subjects aged 20–33 and three visually-impaired subjects with substantial central field loss (CFL) aged 47–58 participated in the study. One of the normally-sighted observers (author AN) had previous experience as a psychophysical subject and was aware of the purposes of the experiments, while the other two normally-sighted observers and the three CFL subjects had minimal prior experience and were naïve to the purpose of the study. All subjects who participated in the study provided consent in accordance with the Institutional Review Board approved protocol.

2.2. Apparatus

The monochrome stimuli were pre-generated using Matlab 5.0 and were stored. The stimuli were presented on a Hewlett-Packard A4033A color monitor using a custom made program written in C. The program ran on a Hewlett-Packard Apollo 725/100 computer. The video resolution was 1280×1024 occupying an area of 36.6 cm (horizontal) by 28.9 cm (vertical); or $20.7° \times 16.4°$ at a viewing distance of 100 cm. Mean display luminance was 17 cd/m^2 in an otherwise dark environment.

2.3. Stimuli

The stimuli (Fig. 1) that were used replicated, as closely as possible, the conditions used in earlier experiments (Hess & Dakin, 1997, 1999). Oriented, sine-wave Gabor elements were distributed over a 624×624 pixel square ($10.0° \times 9.9°$ at 100 cm) that was divided equally into a 13×13 grid (i.e. 169 cells). Each Gabor was defined by the equation:
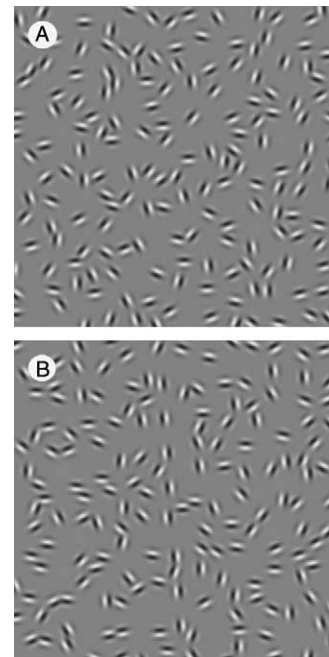

Fig. 1. (A) An example of a 0°-path-angle, same-phase path that runs from bottom-left to top-right, through the centre of this stimulus and (B) a similar path in alternating-phase that runs from the top to the bottom in the centre of this stimulus.

$$g(x, y, \theta) = 1 + c \cdot \sin(2\pi f(x \sin\theta + y \cos\theta) + \psi)$$
$$\cdot e^{-(x^2 + y^2)/(2\sigma^2)}$$

where (x, y) was the distance from the element centre, θ was the orientation of the element, c was the Michelson contrast, f was the spatial frequency, ψ was the spatial phase relative to the element centre, and the standard deviation, σ, was $1/(2.5f)$. The contrast, c, was 90%, ψ was either 0 or π. The period $(1/f)$ was set at 20 pixels and σ was equal to 8 pixels. At 100 cm f was 3.1 cycles/degree. Note that individual Gabor elements were sine phase (Hess & Dakin, 1999) not cosine phase as incorrectly reported by Hess and Dakin (1997).

The path and no-path stimuli were constructed in the manner described by Field, Hayes, and Hess (1993) with the following minor variations to match the stimuli of Hess and Dakin (1997, 1999). The centre of each element was at least 3σ from the centre of the other Gabor elements that surrounded it, thereby avoiding clumping or overlapping of elements. In both sets of stimuli, there were no empty cells. Elements along a path were placed along the angle of the path line (β in Field et al.) plus an additional random jitter angle ($\Delta\beta$) uniformly distributed between $\pm 4°$. One element was within a 30-pixel radius of the centre of the stimulus. Each path had eight elements.

Two sets of 150 no-path stimuli were constructed. One set of no-path stimuli had all the Gabor elements in the 'same phase' ($\psi = \pi$); the other set of stimuli had the elements constructed in 'randomly alternating phase' (i.e. $\psi = 0$ or π, randomly determined for each element). Eight sets of path stimuli were constructed: four path angles ($\beta = 0°$, $10°$, $20°$, or $30°$) and two phases (same or alternating). Each set contained 50 different stimuli. The average distance between the centre of the elements in the 'no-path stimuli' and the 'path stimuli' was equal (67 pixels).

2.4. Procedure

A two-alternative temporal forced-choice procedure was used. Normally-sighted subjects sat at a distance of 100 cm, viewed the stimuli using their right eye and stimuli were presented in their nasal visual field. Subjects with CFL sat at variable viewing distances. The non-tested eye was covered with an eye-patch.

Each session in the experiment consisted of 50 or 100 trials. Each trial consisted of two presentations; one containing a path and background elements (path stimulus), and the other containing random background elements with no path (no-path stimulus). The order of presentation was randomized. For normally-sighted subjects, the first stimulus presentation (either the path or no-path stimulus) was displayed on the screen for 2 s, followed by a blank screen set to the mean luminance

for 1 s, and then followed by the second stimulus presentation for 2 s. For two of the three low vision subjects, the first presentation (either the path or no-path stimulus) was displayed on the screen for 4 s, followed by a blank screen for 1 s, and then followed by the second stimulus presentation for 4 s. For the third low vision subject, the path stimuli and no-path stimuli were each presented for 10 s. Hess and Dakin (1999) reported that the length of time stimuli were displayed was not critical for foveal and peripheral comparisons. Prior to experimental data collection, all subjects were shown images containing the path stimuli until the subject was comfortable with the task of identifying the path foveally and without time constraint.

The subjects indicated, via pressing the left or right button on a mouse, whether the first or the second stimulus contained the path. Immediately after the subject indicated their choice, the next pair of stimuli were shown. Subjects were not given feedback as to whether their responses were correct or incorrect. If in a given set of images a subject was distracted or felt that proper fixation was not maintained, that trial was discarded and the images were presented again in a later trial. For some of the experiments, an eye tracking system was used to monitor eccentric fixation (see description below). Trials in which subjects failed to fixate properly were marked and later discarded by the experimenter.

3. Experiment 1: replication of Hess and Dakin

We attempted to replicate the results reported by Hess and Dakin (1997, 1999), using three normally-sighted subjects aged 20–33 years. One subject (AN) was familiar with the purpose of the experiment. All experimental conditions replicated as closely as possible the conditions used by Hess and Dakin. The subjects were tested using three independent variables: phase (same-phase or alternating-phase), path angle (0°, 10°, 20°, or 30°), and eccentricity (0°, 10°, and 20°). Eccentricity was defined as degrees of visual angle from the point of fixation to the centre of the stimulus. All three subjects were presented 100–200 trials for each condition in random order.

Fig. 2 shows the path detection rates for the foveal and two eccentricities, as a function of path angle, for our three subjects and averaged data from Hess and Dakin (lowest panel). Our results are very similar to those of Hess and Dakin for the foveal and 10° eccentricity conditions (left and centre columns). Contrary to Hess and Dakin, our subjects could detect the alternating-phase paths at 20° eccentricity (right column). The subjects verbally reported seeing the alternating-phase paths frequently and all detected the alternating-phase paths at levels significantly higher than chance for
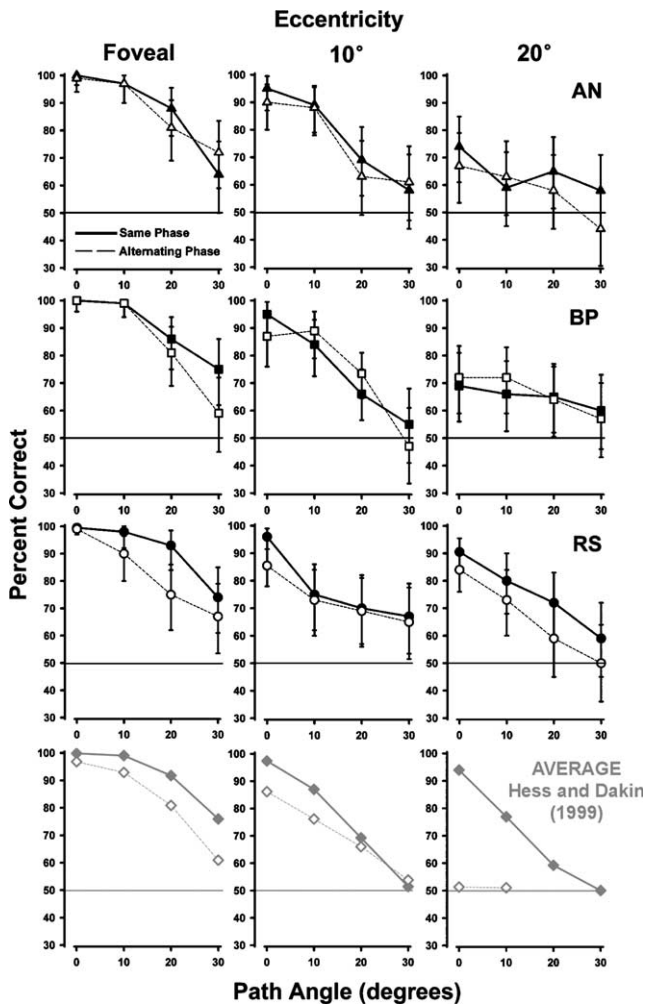
Fig. 2. Replication of Hess and Dakin (1997, 1999), showing percent correct for path detection as a function of path angle for three normally-sighted subjects tested at three different eccentricities (Fovea, 10°, and 20°). For comparison, Hess and Dakin's results are shown in the lowest panel. For the foveal and 10° eccentricity conditions, our results were similar to Hess and Dakin. Contrary to Hess and Dakin, our three subjects were able to perform the alternating-phase (open symbols) task at 20° eccentricity (for both 0° and 10° path angles). Error bars represent 95% confidence intervals.

the 0° path angle condition ($z \geqslant 2.44$, $p \leqslant 0.007$) (Score test: Hays, 1981) and the 10° path angle condition ($z \geqslant 1.85$, $p \leqslant 0.03$). At 20° eccentricity, 20°-path angle alternating-phase condition, subject BP was able to detect the paths at a level above chance (64%, $z = 2.00$, $p = 0.02$), but the other two subjects were performing at levels not significantly different from chance (58% and 59%) (Hess and Dakin did not measure at this condition). Our subjects' performance for most conditions tested was not different for the same-phase and alternating-phase conditions, whereas Hess and Dakin found a large difference between same-phase and alternating-phase at 20° eccentricity, especially for the 0°-path angle (lowest right panel).

It is not clear why we could not replicate all aspects of Hess and Dakin's results. After testing foveal (0°) and 10°, 20°, 25°, and 30° eccentricities, Hess and Dakin (1999) reported that alternating-phase paths could not be detected beyond 10° eccentricity for all path angles tested. Our results give strong evidence that detecting the contour paths beyond 10° eccentricity is possible, but one cannot determine from these results at what eccentricity the ability to detect the contours was lost, i.e. our subjects were able to detect the contours at 20° eccentricity. Hess and Dakin's proposition that foveal and peripheral vision is fundamentally different presumes that there is a sudden reduction in the ability to perform the alternating-phase task at greater than 10° eccentricity (or at least before 20°) while same-phase ability is maintained. In Experiment 2, we measured path detection using smaller increments, presented in random order of eccentricity, to determine the eccentricity at which this ability was lost for either task.

4. Experiment 2: detection of paths as a function of eccentricity

To more closely examine the relationship between eccentricity and path detection performance for both same-phase and alternating-phase conditions, the same three normally-sighted subjects viewed the paths at eccentricities 0° and 6°–30° in 2° increments. At each eccentricity at least 100 sets of both same-phase and alternating-phase stimuli were presented to each subject. Only 0°-path angle stimuli were presented, as this condition showed the greatest difference at 20° eccentricity in the results of Hess and Dakin (lowest right panel of Fig. 2). The order of the conditions from 0° to 30° eccentricity was randomized. Each subject viewed 2400–3000 pairs of stimuli, all with a 0°-path angle.

As shown in Fig. 3, for all three subjects, the ability to detect the contour paths decreased with increasing eccentricity. The reduction in performance accuracy was slightly faster for the more difficult path condition (alternating-phase). However, all three subjects were able to detect the paths at the 20°-eccentricity, alternating-phase condition ($z \geqslant 4.5$, $p \leqslant 0.001$). Detection rates for alternating-phase paths were not significantly different from chance at 22°, 28° and 30° for AN, BP and RS respectively.

Hess and Dakin (1999) reported that the ability to detect the alternating-phase paths was reduced to chance beyond 10° eccentricity, regardless of path angle, while same-phase path detection rate was maintained (lowest panel of Fig. 2). We found that (1) there was no abrupt drop in the ability to detect the alternating-phase paths beyond 10° and (2) these paths were seen beyond 20° for both the same-phase and alternating-phase conditions. Thus, contour path detection, as with most
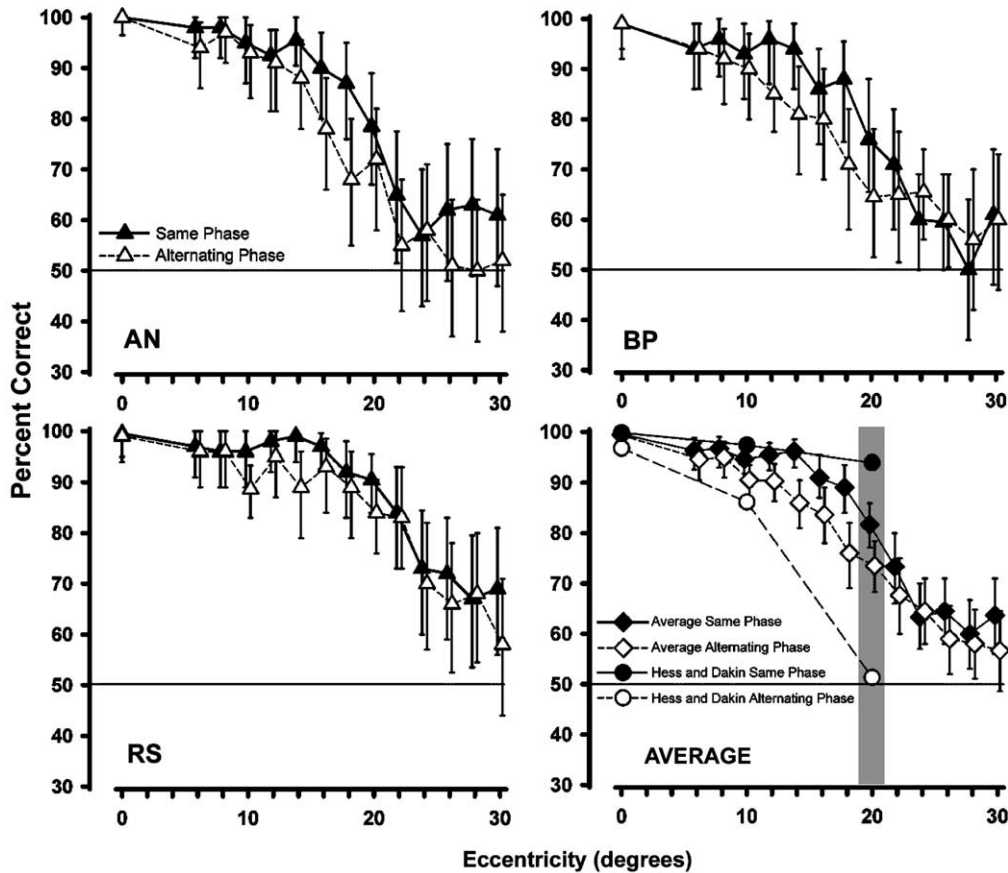
Fig. 3. Percent correct for path detection as a function of eccentricity (0°-path angle), measured in small (2°) increments for same-phase (filled) and alternating-phase (open) paths. Error bars represent 95% confidence intervals. Note that the data points have been slightly offset from one another so that the error bars are more easily visible. As the results show, all three normally-sighted subjects were able to detect alternating-phase paths at levels above chance beyond 10° and up to 20°. In the final panel, our averaged results for the three subjects (diamonds) are compared to the averaged results of Hess and Dakin (1997, 1999) (circles). Path detection, as with most visual functions, declined steadily with eccentricity, with the more difficult path detection condition (alternating-phase) declining faster. Between 10° and 20° there was no abrupt loss of the ability to perform the alternating-phase condition while same-phase performance was maintained. Note the substantial difference at 20° eccentricity between our data and that of Hess and Dakin, marked by the grey vertical bar. While our subjects performed worse than Hess and Dakin on the same-phase condition they performed better on the alternating-phase condition and our data show no fundamental difference between the fovea and peripheral abilities with regards to these two tasks.

visual functions, declines steadily with eccentricity, with the more difficult path detection condition (alternating-phase) declining slightly faster, showing no fundamental difference between the two tasks.

Since we have replicated Hess and Dakin's experimental conditions, but found some different results (while replicating many), it is important to consider possible reasons for this discrepancy. Poor fixation in the eccentric viewing conditions required in this experiment as well as Experiment 1 could artificially increase detection rates. As a control experiment, we repeated a difficult viewing condition (20° eccentricity) while monitoring eye movements with an ISCAN (Burlington, MA) remote infra-red eye tracking system. There were no deviations in eye position beyond ±2° and task performance was not altered. There is no reason to expect

our subjects to lose fixation for the alternating-phase condition and not for the same-phase condition, thereby equating performance.

We conducted another experiment using visually-impaired subjects with substantial CFL. These subjects could not foveate the stimuli. Therefore, if these subjects could perform the contour integration task, then there would be no question that the paths could be detected using peripheral vision and it would confirm that the results of our normally-sighted observers were a valid test of peripheral vision. Furthermore, if the CFL subjects could detect either the same-phase or the alternating-phase paths more easily than normally-sighted subjects at an equivalent eccentricity could, then this might suggest cortical reorganization, though other reasons could be possible as well.

5. Experiment 3: contour integration by visually-impaired subjects

To further assess whether alternating-phase paths could be seen beyond 10° eccentricity, three visually-impaired subjects with large central scotomata (CFL due to ocular disease) participated in the experiment. Prior to testing, each subject's PRL and extent of the central scotoma was determined using a scanning laser ophthalmoscope (SLO). The PRL was determined by having the subject fixate on a cross-shaped target in the SLO raster (Timberlake et al., 1986). The position on the retina where the cross was overlaid, or in other words the retinal location used to attend to the cross, represented the location of the subject's PRL. The magnitude of the subject's eccentric fixation was estimated by measuring the distance from the presumed fovea to the PRL. Because the fovea of these people had been destroyed by the maculopathy, the location of the fovea was estimated indirectly using the normal average dimensions. The optic disk spans a vertical height of approximately 7.5° and a width of 5.5° (Wyszecki & Stiles, 2000), and is located approximately $15.1° \pm 1.2°$ from the fovea and approximately $2° \pm 1.2°$ above the fovea (Hu, Schuchard, & Fletcher, 1994). Using the optic disk as a calibration standard, we determined, in degrees of visual angle, the fixation eccentricity of the CFL subject. Confidence limits of the eccentricity determination were made using the variance of the normally-sighted population described by Hu et al. (1994).

One eye (generally the more severely affected eye with a larger scotoma and higher eccentricity of PRL) was used to view the paths while the alternate eye was covered with an eye patch. Subject RG was tested in both eyes, monocularly. Subjects RG and DG were presented 100 images for both same-phase and alternating-phase conditions. Images were presented for 4 s, separated by a 1 s interstimulus interval. Subjects were tested only with the 0°-path angle for both phases. Subjects sat at a viewing distance comfortable to them, as their eccentricity was fixed by their defect. It should be noted that all three subjects were allowed to scan the images. Therefore, fixational eye movements would be expected to result in the centre of the display often having a greater eccentricity during a 4-s presentation than our

estimate of the PRL eccentricity. For normally-sighted subjects (Experiments 1 and 2) eccentricity was defined as the angle between the image centre and the fovea. For CFL subjects, depending on the amount of eye movements each subject used, if any, the subjects could have used a portion of retina further away from their calculated PRL resulting in a farther eccentric fixation. Because the areas between the PRL and the fovea have been destroyed by disease, effectively, the estimated PRL represents the minimum eccentric fixation each subject could have used. A more detailed analysis of each subject's PRL and eccentric fixation is presented in Experiment 4.

Subject details are shown in Table 1. Subject RG was diagnosed with juvenile macular disease and had a rounded central lesion and a wide visual field outside that area in both eyes. Both PRLs (13.5° and 12.5° eccentricity) were located above the retinal lesion (therefore the PRL was below the scotoma in the visual field). He sat with a viewing distance of 50 cm from the monitor. In both eyes subject RG performed above chance for same-phase paths ($\geqslant 97\%$; $z \geqslant 7.5$, $p < 0.001$) and the alternating-phase paths ($\geqslant 90\%$; $z \geqslant 6.1$, $p < 0.001$). As shown in Fig. 4, for both eyes subject RG performed better in the same-phase condition than the alternating-phase condition ($z \geqslant 2.01$, $p \leqslant 0.022$) as found for the normally-sighted subjects (Fig. 3). Subject RG verbally reported seeing the same-phase and alternating-phase paths "popping out" for both eyes.

Subject DG had a small retinal "island" with residual function within the macular lesion in her worse (right) eye, with her fixation approximately 2° to the left of the location of the estimated fovea (as calculated using the above mentioned method). Central fixation with this area of subject DG's retina was possible, but subject DG could not use it for form perception. For example, when presented with the cross-shaped fixation target (1.7°), subject DG could not identify it as a cross, but only as a spot of light. When we projected a series of contour paths onto the SLO raster to determine if subject DG was using that PRL to view the paths, it was found that subject DG did not. Instead, subject DG was using a patch of retina located below the border of her lesion, approximately 14° eccentric from the fovea. She sat at a viewing distance of 25 cm from the monitor. Subject DG

Table 1
All three CFL subjects had single letter visual acuity (VA) of 20/250 or worse and a PRL that was at least 12.5° from their former fovea

Subject	Eye	Visual acuity	PRL		Scan range	
			Location	Eccentricity	Horizontal	Vertical
RG	Right	20/330	Below	13.5°	2°–5°	2°–11°
RG	Left	20/330	Below	12.5°	–	–
DG	Right	20/250	Below	14°	7°–19°	9°–12°
DS	Left	20/350	Above and left	17.5°	15°–22°	7°–18°

PRL location is the direction of the PRL relative to the (former) fovea in the visual field. The range over which they scanned when viewing various stimuli viewed with a SLO (Experiment 4) varied in a manner that seemed consistent with their scotoma(ta) size and placement.
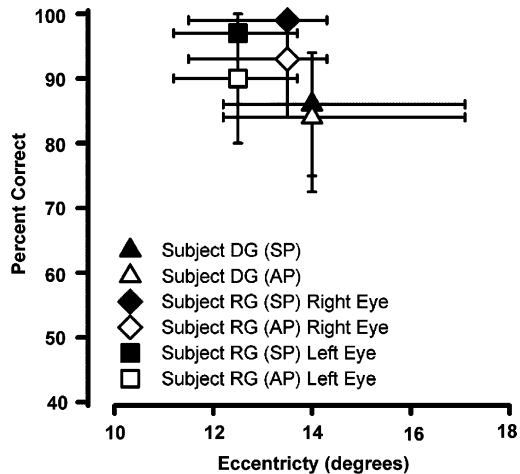
Fig. 4. Path detection performance for two subjects with CFL. Both subjects had central scotomata larger than 10° and were able to detect the alternating-phase paths. One subject, RG was tested in both eyes. Filled symbols represent same-phase conditions while unfilled symbols represent alternating-phase conditions. Error bars represent the 95% confidence intervals. SP = same-phase, AP = alternating-phase.

was able to detect the paths at a level well above chance ($z \geqslant 5.1$, $p \leqslant 0.001$). As shown in Fig. 4, subject DG's performance for the same-phase and alternating-phase, 0° path angle conditions were not significantly different (86% and 84% respectively, $z = 0.40$, $p = 0.35$). Similar to subject RG, subject DG verbally reported seeing the paths "pop out".

DS had an unusual form of juvenile macular disease with very large scotomatous regions and as a result had a very small area of residual functional retina consisting of a vertical sliver located to the left and above his optic disk in his better (left) eye (Fig. 5). His PRL was on the nasal side and diagonally below the optic disk from his macula, with an eccentricity of 17.5°. After training, subject DS was able to see some paths oriented in the vertical direction when sitting at a 30 cm viewing distance, but it took him longer than the other two CFL subjects to identify the correct path. We believe he performed better when presented with a vertical path because more of the path's elements were projected onto his remaining visual field at one time compared to a horizontal path. This was a result of the size and shape of the remaining functioning retina (Fig. 5). The largest area of functional retina was about 8° vertically and 5° horizontally. At 30 cm the distance from the centre of one patch to the centre of another was approximately 3.8°. Therefore, no more than three vertically-aligned patches could be on DS's functional retina, while only up to two horizontally-aligned patches could be seen at one fixation (Fig. 5(B)).

Even with longer viewing intervals, DS found the temporal forced-choice paradigm too difficult, so we used an alternative procedure. Stimuli that contained a path were presented for 10 s each, and DS pointed to or
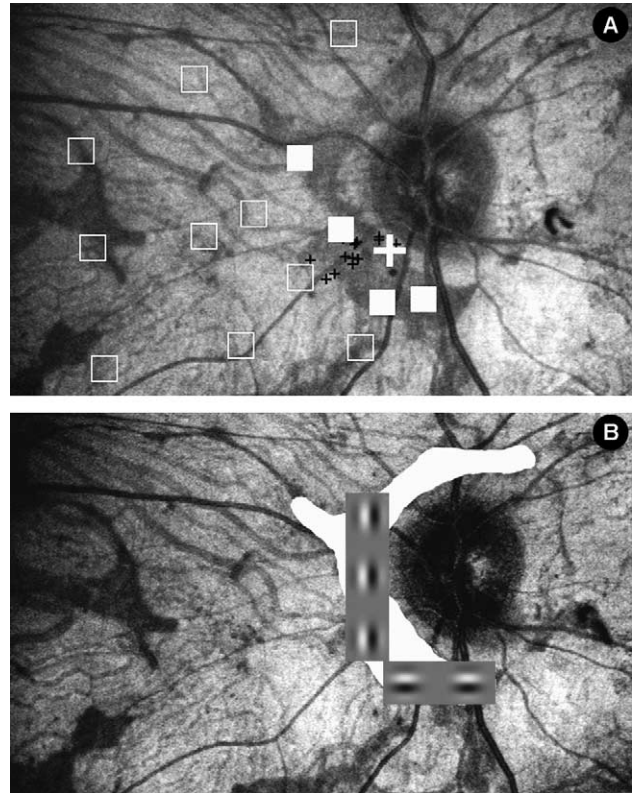

Fig. 5. (A) An SLO static microperimetry image of subject DS's left eye. Subjects fixated a cross target while a square stimulus was presented for 180 ms. Black crosses are samples of the location of the PRL during recording, illustrating shifts in location due to eye movements. His former fovea was 17.5° approximately to the right of the PRL (the optic disc is about 5.5° wide). Subjects were asked to report if the stimulus was visible. Filled squares represent retinal positions (corrected for eye movements) at which the stimulus was seen, and unfilled squares represent positions at which the stimulus was not seen. (B) An SLO image of subject DS's left eye with path segments overlaid. The filled white area represents functional retina (determined using dynamic perimetry). The largest vertical and horizontal area that a path could fall on at one time spanned approximately 8° × 5° temporally. Up to three patches could fall on the vertical area of subject DS's retina, while only up to two patches would fall on the horizontal area from his 30 cm viewing distance. Subject DS performed better when presented with a vertical path because more of the path elements were projected onto his visual field at one time, compared to a horizontal path.

traced out the path. He viewed 50 same-phase and 50 alternating-phase path stimuli in two separate blocks with the same-phase condition tested first. We could easily recognize eight distinct finger-tracing directions, i.e. 22.5° increments, in which DS could have traced out the paths. Thus, chance for tracing the paths would be 12.5%. Of the 50 same-phase and 50 alternating-phase stimuli presented to subject DS, he correctly identified and traced out 48% of the same-phase ($z = 7.7$, $p < 0.001$) and 44% of the alternating-phase images ($z = 7.0$, $p < 0.001$).

All three CFL subjects tested were able to detect the alternating-phase paths using their eccentric retinal
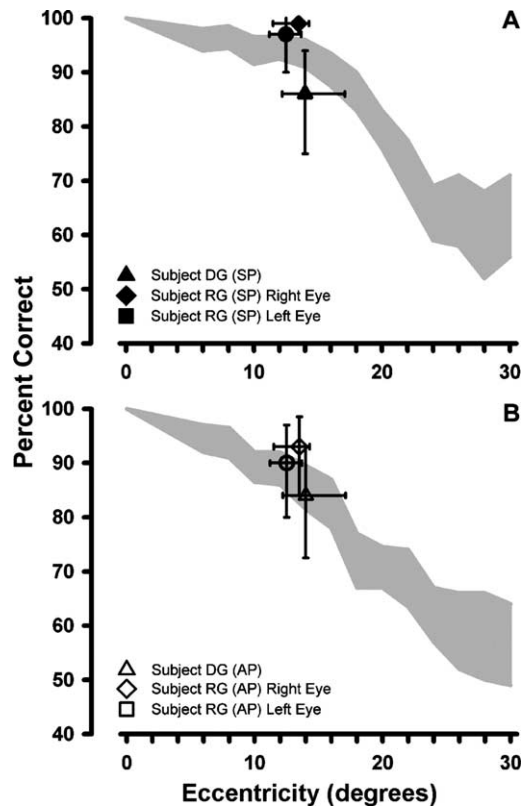
Fig. 6. Path detection performance of two CFL subjects compared to the normally-sighted subjects for (A) same-phase (SP) condition; and (B) alternating-phase (AP) condition. The confidence intervals for the CFL subjects overlapped with 95% confidence intervals for the normally-sighted subjects (shaded gray areas: Experiment 2). Thus, we found no evidence for cortical reorganization or neural adaptation using this paradigm as CFL subjects did not perform significantly better than normally-sighted subjects in either phase condition. However, the limitations to this conclusion are discussed in the text.

fixation located beyond 10° from their fovea. As shown in Fig. 6, the CFL subjects did not appear to perform differently from the normally-sighted observers for the corresponding eccentricities tested. If CFL subjects had performed better than normally-sighted subjects had, this might have suggested cortical reorganization or neural adaptation. However, the tasks performed by the normally-sighted subjects and the CFL subjects had differences that make a direct comparison difficult. Normally-sighted subjects were instructed to fixate an eccentric location, and therefore could not scan the stimulus. If the CFL subjects did scan the stimulus, parts of the stimulus would be obscured by their scotoma(ta) to different degrees at each fixation. As discussed below in Experiment 4, we were not certain of the viewing pattern of the CFL subjects. Another difference was the shorter viewing distances of the CFL subjects (consequently the stimuli subtended larger visual angles). Hess and Dakin (1997) reported scale invariance over an eightfold range, but this was for central vision. In a control experiment we found that path detection

was substantially improved when normally-sighted subjects viewed the stimulus at 25 cm. For example, detection of 0°-path angle, alternating-phase stimuli at 20° eccentricity increased from 68% to 89% for subject BP ($z = 4.0$, $p < 0.001$). This implies that the data shown in Fig. 6 for the normally-sighted subjects might be below that for conditions equivalent to the CFL subjects. However, even with eccentric viewing the normally-sighted subjects saw the entire stimulus, whereas parts were probably obscured for the CFL subjects. For example, if subject RG or DG fixated the stimulus centre, and did not scan, almost half of the stimulus would not have been visible. When normally-sighted subjects viewed with almost half of the stimulus covered (all to the right of 1° from stimulus centre was covered, as might be expected with a large scotoma and the PRL near the scotoma border), the detection rate decreased markedly. For example, covering almost half of the stimulus decreased the detection rate from 89% to 69% for subject BP ($z = 3.5$, $p = 0.001$). Again, this is not the same as for our CFL subjects who were able to scan the stimuli. Experiment 4 examined whether the subjects, in fact, did scan the stimuli.

6. Experiment 4: evaluation of viewing patterns using an SLO

Hess and Dakin used the distance between fixation and the centre of the target to define eccentricity. For the CFL subjects, stimuli subtended large visual angles due to their smaller viewing distances (up to 39° for subject DG). As our CFL subjects were allowed to scan the stimuli, we did not know their effective eccentricity. We hypothesized two potential viewing strategies:

(1) Attend to the PRL and scan. Most people with CFL have their PRL located very close to the edge of the scotoma. If the PRL was used to examine the stimulus, often this would have resulted in substantial portions of the stimuli falling on areas of non-functional retina and being obscured. If the stimulus was scanned evenly, the median PRL position would be about the centre of the stimulus (the definition of eccentricity for normally-sighted subjects), and our definition of eccentricity would be validated; or
(2) Keep the PRL (and hence scotoma border) near the edge of the stimulus but attend to more peripheral retinal location(s). The advantage being that no part of the stimulus would be obscured by the scotoma. The disadvantage being that vision reduces with increasing eccentricity. In this case the effective eccentricity would be greater than our estimate.

CFL subjects could not, of course, use loci located closer to the fovea than their PRL because this area of

retina was destroyed by disease. Therefore, to examine the eye movements made by the CFL subjects, we measured eye movements using an SLO. Also we tested normally-sighted subjects to determine the type of eye movements they made when allowed to scan the paths freely.

All three CFL and two naïve normally-sighted subjects viewed the stimuli, scaled according to their viewing distance, presented in an SLO. Our SLO was calibrated so that raster size was 34° horizontal by 21° vertical (40° diagonally; 611 by 377 pixels). Videos were made of the subjects' retina with the path overlaid (range 8.4–41.3 s per stimulus). The videotaped SLO images were digitized and eye movements were measured using a pre-selected landmark within the images (e.g. a blood vessel junction).

When presented with a stimulus that contained a path, we found that the normally-sighted subjects scanned the stimulus (range 3°–7° horizontally; 6°–8° vertically) and, at least initially, the fovea tracked along the path. The amount of scanning was nearly equivalent for stimuli that contained and did not contain a path. For each CFL subject, the median position of the PRL was approximately in the centre of the stimulus. Note that this strategy placed large segments of the stimulus on non-functional retina much of the time. Each of the three CFL subjects had slightly different patterns of eye movements that may have been related to their visual impairment (i.e. the size and shape of their remaining visual field). As shown in Table 1, subject RG made the smallest eye movements, while subject DS made the largest. Subjects RG and DG both had large central scotomata that they placed above their object of interest (i.e. PRL below). Subject RG had a very well established PRL while subject DG's PRL was not well established due to differences between the two eyes and some vestigial central vision. We suspect that subject RG's well established PRL allowed him to make smaller eye movements to more efficiently scan the stimuli. That subject DS had the largest scan range was not surprising given his very small functional visual field (Fig. 5).

For the normally-sighted subjects in Experiments 1 and 2, the eccentricity of the stimulus was defined using the centre of the stimulus. Based on our SLO analyses, we found that the CFL subjects tended to direct their PRL towards the centre of the stimulus. Therefore, our estimate of the eccentricity of their viewing in Experiment 3 (the distance from the PRL to the presumed fovea) was reasonable. Of course, we do not know if the subjects attended to the same retinal location as the PRL determined using the fixation target. However, as the median position of the PRL was located near the centre of the stimuli, it is likely that the PRL (as we defined it) was used to view the patterns.

7. Discussion

Hess and Dakin, the two normally-sighted subjects in their study, were unable to detect alternating-phase paths when presented beyond 10° (Hess & Dakin, 1997, 1999). While we were able to replicate many of their results (Fig. 2), we were unable to replicate the important finding of a growing difference in performance of the two tasks with increasing eccentricity. The normally-sighted and CFL subjects used in our study were able to detect the alternating-phase paths using eccentric loci beyond 10°. For example all three of our normally-sighted subjects were able to detect the alternating-phase paths at 20° eccentricity (Fig. 3). Unlike the abrupt loss in the ability to perform the alternating-phase condition inferred by Hess and Dakin, we found a gradual decline in performance. Performance of the alternating-phase path condition, the more difficult task, declined slightly more quickly with eccentricity than the same-phase path condition. This steady reduction in path detection performance with increasing eccentricity is similar to many other visual functions (Anderson & Thibos, 1999; Fleck, 1989; Strasburger, Harvey, & Rentschler, 1991; Thibos & Bradley, 1995). Our results could not be explained by improper fixation. Performance was the same when the eye movements of one of our normally-sighted subjects were monitored and the CFL subjects could not possibly have used central vision for the path detection. Also, our results could not be explained by superior subject performance. The subjects that participated in our study were not as experienced with path detection as Hess and Dakin. While they performed better than Hess and Dakin in the alternating-phase condition, they performed slightly worse in the same-phase condition (see Figs. 2 and 3). As far as we are aware, there was nothing in the procedure or experimental conditions that were significantly different from Hess and Dakin.

Based on their results, Hess and Dakin (1997, 1999) proposed a simple filtering model that explained their performance both in the periphery and fovea. They concluded that beyond 10°, the visual system uses only a simple filtering mechanism at independent orientations to detect contours while the fovea (or central 10°) possesses intercellular linking properties. It was this intercellular linking capability that allowed alternating-phase path detection in central vision. Our results do not support their conclusion. Our normally-sighted subjects were able to detect the alternating-phase paths in the periphery (beyond 10°). Therefore, Hess and Dakin's simple-filter model does not predict our results for the alternating-phase path detection condition (at least up to 20°). If their model of a simple-filter is correct, some mechanism other than simple filtering, such as intercellular linking in the periphery, might be required to explain our results. Recently, Lovell (2002) has reported that a simple-filter model that used filters of different

scales, unlike Hess and Dakin's model, could detect alternating-phase contours. However, Lovell's model predicts lower detection rates of relatively straight contours (<20°-path angle) than are found with human observers. Hence, a simple-filter model remains a possible explanation of path detection. Most importantly, our results demonstrate no fundamental difference between the centre and periphery in the performance of the two path detection conditions and therefore no structural difference can be inferred and needs to be modeled.

Due to a software error, experiments conducted prior to those reported as Experiments 1 and 2 were conducted without linearisation of the display monitor. At the high contrasts used in our stimuli, the non-linearised display (gamma of about 2.5) significantly affected the luminance distributions of the sine-phase Gabor patches, creating additional low spatial frequency content (Peli, 1992). Despite this, the results for two normally-sighted subjects with linearised and non-linearised data, were the same. This confirms that the path-detection task is not a threshold task.

Two of the CFL subjects tested had very small, functional visual fields around their eccentric PRL and were still able to detect the paths. As a result of their visual impairments, subjects DS and DG (when using DG's better eye for path detection, results not reported in Experiment 3, as the PRL eccentricity was less than 10°) did not have a large enough visual field to view all or most of the path in a single fixation. They could only see very small portions of the path at each fixation. They scanned the image and appeared to have temporally integrated the information to detect the path. This suggests that, at least in these subjects with restricted visual fields, the ability to detect contours might be achieved using higher visual processes. Thus the hypothetical, presumably lower-level filtering, mechanism used in peripheral vision as proposed by Hess and Dakin, may not be needed and certainly cannot account for their path detection performance. The ability to detect these paths, possibly could be due to one or more higher level systems acting at any one time, integrating the information from separate glimpses to form a perception of a continuous path.

Our CFL subjects performed no better than our normally-sighted subjects did (Fig. 6). This was the case despite having the distinct advantage of (presumably) not having to struggle with the foveation reflex since they had developed eccentric fixation. This suggests either, that our normally-sighted subjects could control their fixation with as much ease following relatively short training, or that the CFL subjects were not free of that conflict and were splitting attention even following many years of practice. The fact that these CFL subjects did not perform significantly better also contradicts the idea of brain plasticity that might develop following retinal loss. Furthermore, people who are forced to use their peripheral vision for form vision might be expected to improve higher level functions associated with such vision as it applies to the residual peripheral field even in the absence of cortical plasticity. We have found no evidence for such plasticity in this path detection task. It is still possible that such functional plasticity or improvement can be demonstrated with other tasks. However, it is difficult to envision a form detection or recognition task that requires substantially different visual skills from the path detection task.

The ability of subjects to perceive shapes in the near periphery even from a partial contour as used here and even when the polarity is alternating is encouraging with respect to visual capabilities of people with CFL. These results suggest that if contours are rendered visible (supra-threshold) they are correctly recognized even when they are incomplete. This suggests that effort in the visual rehabilitation of these people can be effective if devices or techniques can be developed that will increase the visibility of lower contrast contours to the point that they can be, at least partially, visible. It seems that such barely visible contours can be correctly perceived with the peripheral retina and possibly without much training or a need for plastic changes in the cortex.

References

Anderson, R. S., & Thibos, L. N. (1999). Relationship between acuity for gratings and for tumbling-E letters in peripheral vision. *Journal of the Optical Society of America (A), 16*, 2321–2333.

Backman, O., & Inde, K. (1979). *Low vision training.* Malmo: LiberHermods (Ostberg, A. & Voigt, J., Trans.).

Field, D. J., Hayes, A., & Hess, R. F. (1993). Contour integration by the human visual system: evidence for a local association field. *Vision Research, 33*, 173–193.

Fleck, H. J. (1989). Measurement and modeling of peripheral detection and discrimination thresholds. *Biology and Cybernetics, 61*, 437–446.

Goodrich, G. L., & Quillman, R. D. (1977). Training eccentric viewing. *Journal of Visual Impairment and Blindness, 71*, 377–381.

Hays, W. L. (1981). *Statistics* (3rd ed.). New York: CBS Publishing.

Heinen, S. J., & Skavenski, A. A. (1991). Recovery of visual responses in area VI neurons following bilateral foveal lesions in adult monkey. *Experimental Brain Research, 83*, 670–674.

Heinen, S. J., & Skavenski, A. A. (1992). Adaptation of saccades and fixation to bilateral foveal lesions in adult monkey. *Vision Research, 32*, 365–373.

Hess, R. F., & Dakin, S. C. (1997). Absence of contour linking in peripheral vision. *Nature, 390*, 602–604.

Hess, R. F., & Dakin, S. C. (1999). Contour integration in the peripheral field. *Vision Research, 39*, 947–959.

Holcomb, J. G., & Goodrich, G. L. (1976). Eccentric viewing training. *Journal of the American Optometric Association, 47*, 1438–1443.

Hu, S. Y., Schuchard, R. A., & Fletcher, D. C. (1994). Physiological blind spot characteristics and position relative to retinal locus for fixation by SLO testing. *Association for Research in Vision and Ophthalmology Annual Meeting*, Investigative Ophthalmology and Visual Science 35, S1527.

Lovell, P. G. (2002). Human contour integration: evaluating the association field theory using psychophysical and computational methods. Unpublished PhD, University of Stirling.

Nilsson, U. L. (1990). Visual rehabilitation with and without educational training in the use of optical aids and residual vision. A prospective study of patients with advanced age-related macular degeneration. *Clinical Vision Science, 6*, 3–10.

Nilsson, U. L., Frennesson, C., & Nilsson, S. E. (1998). Location and stability of a newly established eccentric retinal locus suitable for reading, achieved through training of patients with a dense central scotoma. *Optometry and Vision Science, 75*, 873–878.

Peli, E. (1992). Display nonlinearity in digital image processing for visual communications. *Optical Engineering, 31*, 2374–2382.

Strasburger, H., Harvey, L. O., Jr., & Rentschler, I. (1991). Contrast thresholds for identification of numeric characters in direct and eccentric view. *Perception and Psychophysics, 49*, 495–508.

Thibos, L. N., & Bradley, A. (1995). Modeling off-axis vision II: the effect of spatial filtering and sampling by retinal neurons. In E. Peli (Ed.), *Vision models for target detection* (vol. 13, pp. 338–379). Singapore: World Scientific.

Timberlake, G. T., Mainster, M. A., Peli, E., Augliere, R. A., Essock, E. A., & Arend, L. E. (1986). Reading with a macular scotoma. I. Retinal location of scotoma and fixation area. *Investigative Ophthalmology and Visual Science, 27*, 1137–1147.

Wyszecki, G., & Stiles, W. S. (2000). *Color science: concepts and methods, quantitative data, and formulae (Wiley classics library ed.)*. New York: John Wiley & Sons.