OPTICAL AND PERCEPTUAL CONSIDERATIONS WHEN PRESCRIBING PRISMS FOR HEMIANOPIA

A thesis presented to the graduate faculty of
New England College of Optometry in partial fulfillment
of the requirements for the degree of Master of Science

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Purpose. Prismatic glasses have been employed as a rehabilitative device for homonymous hemianopia (HH). Prisms are used to shift the image of objects located within the blind hemifield to the seeing hemiretina. Different configurations of prismatic glasses can provide either visual field substitution (exchanging visibility of parts of the blind field for parts of the seeing field) or visual field expansion (perimetrically measurable widening of the visual field). Visual field expansion is the desired effect. The unilateral peripheral prism spectacle design provides this effect. However, the use of this approach creates a number of optical and perceptual confounds. We conducted studies to systematically address these concerns with the overall aim of providing improved fitting guidelines for clinicians. The first concern is that the visual confusion may be a stimulus for binocular rivalry and suppression. If local suppression of the prism image occurs, this would limit the functionality of the glasses. Peripheral prisms are usually fitted in front of the eye ipsilateral to the side of the HH, which may not be the dominant eye. Since ocular dominance can influence binocular rivalry, we investigate whether ocular dominance should be considered when prescribing prismatic glasses. A second concern is the optical scotoma present at the apex of any prism. Although clinicians routinely prescribe prismatic corrections for patients with HH little emphasis has been placed on understanding the potential consequence of the optically-induced scotomas and how they could be mitigated by controlling prism placements.

Methods. To address our first concern (study one), detection rates of patients with HH wearing unilateral peripheral prism glasses were determined for static perimetry targets briefly presented over a complex patterned background as well as a uniform background. Detection performance in monocular and binocular viewing, and for prisms fitted to the spectacle lens ipsilateral and contralateral to the side of HH are compared. To address our second concern (study two), the position of the apical scotoma in various prismatic spectacle designs, parameters, and gaze position was calculated and compared to perimetrically measured positions. Prism placements were then modified, to reduce the impact of the apical scotoma.

Results. In study one, eight participants with normal binocularity exhibited mixed ocular dominance, demonstrated no difference in detection rates when prisms were fitted on the side of the HH or the opposite side ($p > 0.2$), and had detection rates in the expansion area that were not different for monocular and binocular viewing over both backgrounds ($p > 0.4$). However, two participants with strong ocular dominance demonstrated reduced detection in the expansion area when prisms were fitted in front of the non-dominant eye. In study two, we demonstrated that the calculated prism apical scotoma can be measured for various prismatic spectacle designs, and its impact can be eliminated or reduced from binocular view by thoughtful placement.

Conclusions. In study one, we found little evidence of local suppression for HH patients with normal binocularity. However, in cases of strong ocular dominance, we suggest fitting prisms before the dominant eye. Although these results are promising, further testing in more realistic conditions including image motion is needed. Our second study demonstrated the

importance of considering placement of the prism apex when prescribing prisms for HH. In summary, for most cases, careful placement of prism segments before one eye; ispilateral to the side of HH is preferred.

ACKNOWLEDGEMENTS.

I would like to thank my two advisors Dr. Eli Peli and Dr. Alex Bowers for their dedication to this work and to my education. I would also like to acknowledge Henry Apfelbaum and the many other members of our laboratory who contributed to this work, and to the committee members Dr. Russell Woods, Dr. Frank Thorn and Dr. Glen McCormack.

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CHAPTER 1. GENERAL INTRODUCTION AND LITERATURE REVIEW

1.1 HOMONYMOUS HEMIANOPIA: ETIOLOGY & PROGNOSIS

Homonymous hemianopia (HH) is the loss of the same half of the visual field in both eyes resulting from lesion posterior to the chiasm to the right or left optic tract or their projections (Fig1.1). The visual field loss is contralateral to the side of cortical injury. A lesion of the right optic tract will result in loss of the temporal visual field in the left eye and the nasal visual field in the right eye - a left HH. The overall prevalence of HH is 0.8% in individuals over 49 years (Gilhotra, Mitchell, Healey, Cumming & Currie, 2002). The most common etiologies include: stroke (accounting for 70% of cases of HH); followed by traumatic brain injury (13%); and cortical tumor (10%) (Pambakian & Kennard, 1997; Zhang, Kedar, Lynn, Newman & Biousse, 2006a). Incidence and prevalence rates of the above etiologies are likely to rise in coming years. The American Stroke Association indicates that the age, race and sex-adjusted prevalence of stroke among the US population 25 to 74 years of age increased by 30% in the years between 1973 and 1991 (Muntner, Garrett, Klag & Coresh, 2002). More recently, there were 6.2 million stroke survivors in the U.S. in 2010 (Schiller, Lucus & Perogoy, 2012). Estimates of the proportion of stroke survivors with HH (partial or complete) range from 30% to 50% (Townend, Sturm, Petsoglou, O'Leary, Whyte & Crimmins, 2007; Rowe, Brand, Jackson, Price, Walker, Harrison, Eccleston, Scott, Akerman, Dodridge, Howard, Shipman, Sperring, MacDiarmid & Freeman, 2009).

Spontaneous, complete recovery of HH is uncommon, occurring in less than 20% of patients. The likelihood of recovery varies with the underlying cause of the lesion: HH

resulting from ischemic or hemorrhagic stroke has a poorer prognosis for recovery than does HH resulting from traumatic brain injury (Zhang et al., 2006a). Such recovery, if any, typically occurs within the first six months (Zhang, Kedar, Lynn, Newman & Biousse, 2006b).

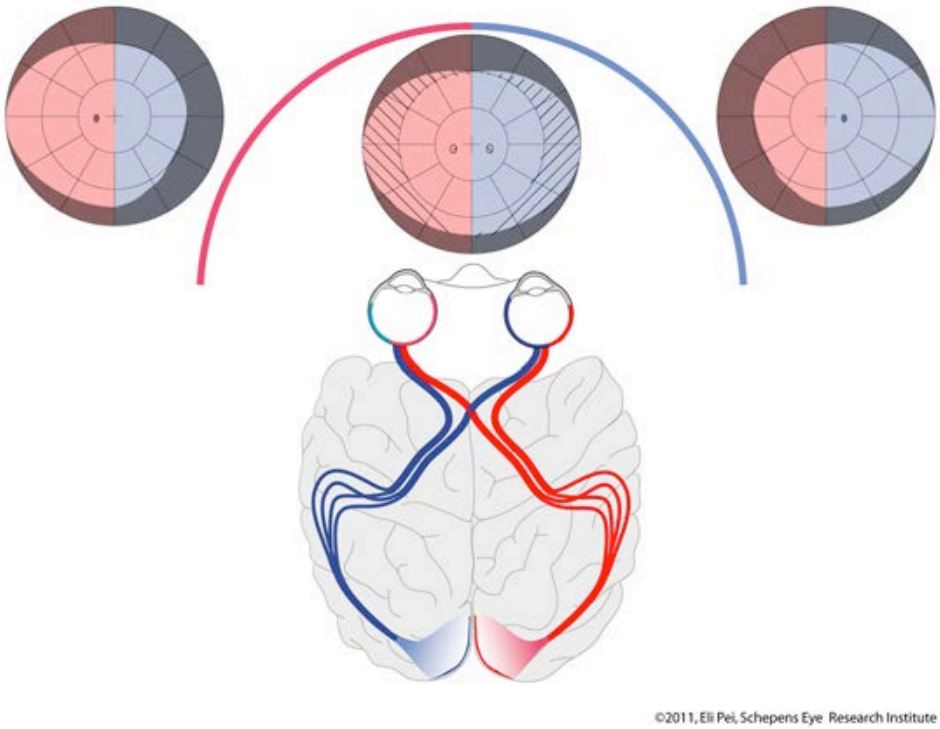


Figure 1.1. The visual pathway. The red color highlights the left visual field, which is projecting on the temporal retina of the right eye and the nasal retina of the left eye. Those areas highlighted in blue represent information from the right visual field. Hatched areas represent the portions of the visual field, which are only viewed by the nasal retina of one eye, known as the temporal crescents. At the optic chiasm, right and left visual space is segregated with fibers from each nasal hemi-retina passing into a single corresponding optic tract (left and right, respectively). Fibers in each tract pass through the lateral geniculate nucleus (not shown) and optic radiations to terminate at the striate cortex in the occipital lobe. Any lesion to the right optic tract, or any of its terminal projections, will result in a left visual field defect.

HH can significantly impair visual functioning. For example, over 90 percent of patients in one study reported difficulty detecting obstacles on the side of field loss (Warren, 2009a). Furthermore, several recent studies evaluating detection during mobility-related tasks

in virtual environments have demonstrated significant impairments in object detection on the side of the field loss (Bowers, Mandel, Higgins, Goldstein & Peli, 2005; Bowers, Mandel, Goldstein & Peli, 2009; Iorizzo, Riley, Hayhoe & Huxlin, 2011; Papageorgiou, Hardiess, Ackermann, Wiethoelter, Dietz, Mallot & Schiefer, 2011). Such detection difficulties result in impaired walking mobility (bumping into obstacles) and may impair detection of potential hazards when driving (Bowers et al., 2009). Individuals with HH are precluded from driving in the majority of U.S states (Peli & Peli, 2002; Wang, Kosinski, Schwartzberg & Shankline, 2010). Vision-related quality of life studies indicate patients with HH have a significantly reduced quality of life specifically with respect to: social functioning, role difficulties, mental health, driving and increased dependency on others (Papageorgiou, Hardiess, Schaeffel, Wiethoelter, Karnath, Mallot, Schoenfisch & Schiefer, 2007; Gall, Franke & Sabel, 2010). The consequence of driving cessation alone has significant impacts on their ability to work and maintain social networks (Marottoli, de Leon, Glass, Williams, Cooney & Berkman, 2000). Additionally, up to 48% of patients report significantly increased stress and anxiety levels when moving in crowded community environments (Warren, 2009a). Others have reported related difficulties including: reading, meal preparation, financial management, personal grooming and difficulty with visual search tasks, such as finding items on a crowded shelf. Overall, the presence of HH has been associated with significantly lower likelihood and increased time in achieving independence with walking and with instrumental activities of daily living (Rossi, Kheyfets & Reding, 1990).

1.2 STRATEGIES FOR REHABILITATION

Rehabilitation for HH broadly includes: different forms of visual training such as saccade and eye-scanning training (Kerkhoff, Munssinger & Meier, 1994; Zihl, 1995; Nelles, Esser, Eckstein, Tiede, Gerhard & Diener, 2001; Pambakian, Mannan, Hodgson & Kennard, 2004), visual restoration therapy (Kasten, Wust, Behrens-Baumann & Sabel, 1998b; Mueller, Mast & Sabel, 2007), and use of optical devices, such as prisms (Hoppe & Perlin, 1993; Cotter, 1995b; Peli, 2000), mirrors or reversed telescopes (Duszynski, 1955; Goodlaw, 1983; Dickinson, 1998a), used to expand or relocate blind areas of the visual field.

Eye Movement/Scanning Training

Eye movement and scanning training strategies arose from exploratory work analyzing the eye fixations of patients, using computer-based apparati, looking at simple patterns (Ishiai, Furukawa & Tsukagoshi, 1987) and natural images (Pambakian, 2000). HH patients concentrated gaze toward their blind side in both cases. This behavior represents a compensatory strategy; by deviating fixation into the blind field, more of the visual scene is brought into the seeing hemi-field. However, this does not seem to translate to tasks of daily living. When comparing eye movements of individuals with visual field loss to normally sighted controls when walking, there was no significant difference in eye movement patterns between these two groups (Vargas-Martin & Peli, 2006) Additionally, the saccadic eye movements and visual search techniques of HH patients when asked to find a target within their blind field, were found to be slow, and often ineffective –undershooting or overshooting the target (Meienberg, Zangemeister, Rosenberg, Hoyt & Stark, 1981). This suggests that patients with HH do not naturally nor adequately compensate for their visual field loss with

eye movements or eye scanning behaviors. From these investigations stemmed attempts to "train" patients to adopt different oculomotor strategies that may improve performance of visual search tasks, visual search area (i.e. visual search field size) and improved quality of life. These eye scanning training strategies have shown training-task specific improvements in efficiency of scan paths and a shortened response time post-training (Zihl, 1995), significant expansion of visual search field and increased effectiveness in searching for specific objects on a table (Kerkhoff et al., 1994) . Additionally, there have been subjective reports of improvements post-training with activities of daily living (Kerkhoff et al., 1994; Nelles et al., 2001; Bolognini, Rasi, Coccia & Ladavas, 2005). More recently a randomized control trail has shown exploratory saccade training is effective, resulting in a significant improvement in reaction time is a number of visual search tasks (Roth, Sokolov, Messias, Roth, Weller & Trauzettel-Klosinski, 2009).

Visual Restoration Therapy (VRT)

In their efforts to train patients with HH, some authors claimed to find evidence that their rehabilitative methods lead to restoration of part of the visual field. They hypothesize that, training reactivates surviving neurons of the partially damaged brain structure, particularly within the "border zone" the partially defective areas near the border of the seeing and non-seeing hemifields and comprises over 500 repeated presentations targets to this zone during a simple perimetry-like task in multiple training sessions (for a total of 150 hours) (Kasten, Wust, Behrens-Baumann & Sabel, 1998a). A number of studies have claimed "*restored vision*" or " a modest improvement in visual fields following three months of visual restoration therapy" (Poggel, Kasten & Sabel, 2004; Mueller et al., 2007; Marshall,

Chmayssani, O'Brian, Handy & Greenstain, 2010; Raemakers, Bergsma, van Wezel, van der Wildt & van den Berg, 2011), which extends on average 5^{o} into the blindfield (Kasten et al., 1998b). The effects of VRT remain contentious, as it is still unclear whether such visual field recovery is real, or is either measurement noise or a result of patients making occasional compensatory saccadic eye movements into their blind field (Pambakian & Kennard, 1997; Reinhard, Schreiber, Schiefer, Kasten, Sabel, Kenkel, Vonthein & Trauzettel-Klosinski, 2005). Importantly the average 5^{o} degrees of "restored" visual field found in these studies represents a very small improvement of questionable value for functional performance in activities of daily living.

1.3 OPTICAL APPROACHES TO REHABILITATION

Optical approaches to rehabilitation involve devices that provide: visual field *substitution*, sometimes referred to as visual field "enhancement" (Hoppe & Perlin, 1993; Gottlieb, Fuhr, Hatch & Wright, 1998)), or visual field *expansion*. Visual field substitution refers to swapping the visibility of parts of the blind field in exchange for parts of the seeing field, whereas expansion is an overall and perimetrically measurable widening of the visual field. The latter is the desired effect, and creates a wider available field of view with than without the device. Visual field substitution is typically achieved with bilateral sector prisms, and reflecting mirrors (discussed further below). If the prisms cover the entire field of view (as in full-field bilateral yoked prisms), field shifting, without expansion or substitution occurs.

Visual field expansion, on the other hand, can be created by creating binocular visual confusion- the placement of different objects in the same position in visual space. Confusion

is achieved by taking an image from the blind hemifield in one eye and superimposing it onto the seeing hemifield in the other, this is typically created with many unilateral prism designs, or partially reflecting or dichroic mirrors.

Mirrors

Mirrors are usually mounted nasally on the glasses on the same side as the field defect (e.g., a mirror would be placed nasally on the left spectacle lens for a patient with left HH). The information from the blind hemifield is reflected onto the seeing hemifield. However, total reflecting mirrors also occlude an area over which they are placed. In this sense they are *substituting* parts of the blind field at the cost of parts of the intact seeing hemi-field, rather than providing visual field expansion. The amount of relocation depends on the size and angle of the mirror position. If mounted unilaterally, visual field confusion is also possible.

Other attempts to provide expansion utilizing mirrors, employ partially reflecting mirrors has been proposed by several authors (Duszynski, 1955; Nerenberg, 1980; Goodlaw, 1983). In this approach, the reflected images from blind areas appear superimposed on objects seen through the mirrors, creating *visual confusion to expand the visual field*. The user of the device is able to distinguish between the images as the mirrors impart a slight silvery hue to the reflected images. Similarly, dichroic mirrors, have similarly been used, and provide color contrast between reflected images (which appear red) and transmitted images (appear green).

Limitations of this approach included poor cosmetic appearance and the fragile structure of the spectacle precluded patient acceptance. Additionally, as with any mirror, the

image is flipped/reversed along the vertical axis, which can cause difficulty interpreting image from the mirror (Goodlaw, 1983; Dickinson, 1998b).

Prisms

Spectacle-mounted prisms are the most commonly applied optical device used for rehabilitation of HH. When prescribing prisms for patients with HH the intent is to shift the image of objects located within the blind hemifield into the seeing field. Light passing through a prism is deviated toward the prism base. Consequently, as the light falls on the retina the image point from which the light rays originate appears to be displaced toward the apex of the prism (Cotter, 1995a). To achieve the intended effect, the prism is always placed with the base toward the same side as the visual field defect (i.e. base left for a patient with left HH).

1.4. PRISMATIC SPECTACLE DESIGNS FOR HEMIANOPIA

Full Yoked Bilateral Prisms

Full-field or full-aperture yoked prisms were possibly one of the first optical rehabilitative options discussed for HH (Young, 1929). In these configurations a full-aperture prism of the same power is placed before each eye with the base toward the visual field defect (e.g., base left for both eyes for left HH). Prismatic powers of 10Δ have been implemented and have thought to be the limit due to increasing edge thickness (Dickinson, 1998b). Usually this design is suggested for reading, but is also thought to be useful for mobility and navigation (though this has never been evaluated in a study). The intent is to create a shift of the field. However this approach assumes that the eyes do not re-fixate, thereby compensating for and neutralizing the effect of the prism. This prism adaptation

happens routinely, and thus, although a slight shift is created (about 5° with 10Δ prisms), there is no overall increase in the size of the visual field. The patient could achieve the same effect without yoked-prism glasses by simply shifting his/her gaze into the blind field, or by moving the book further into the seeing field. At a normal reading distance a shift of about one inch will have the same effect.

Bilateral Sector Prisms and the Prism Apical Scotoma

Yoked bilateral prisms (Fig. 1.2a) have also been fitted for patients with HH in the form of sector prism segments (covering only part of the spectacle lens). Prismatic powers of up to 30Δ (Jose & Smith, 1976; Smith, Weiner & Lucero, 1982; Hoppe & Perlin, 1993), but usually under 20Δ (Rossi et al., 1990), have been prescribed. In this design, each prism segment covers nearly one half of the spectacle lens and is offset by 1-6 mm from pupil center into the blind hemifield (Bailey, 2007). For a patient with left HH, one prism segment is placed base left (base out) into the temporal half of the left lens and the other prism segment is placed base left (base in) on the nasal half of the right lens. The patient is instructed to look into the prism segments in order to detect obstacles on the blind side. It has been suggested that the primary intent of the bilateral segment prism spectacle is to reduce the amplitude of scanning movements necessary to detect objects in the blind field (Cohen & Waiss, 1996). This design is only helpful if the patient actively looks into the prism (as the prisms are mounted on the side of the blind hemifield). There is no effect in primary gaze or when gaze is shifted to the seeing side (Bailey, 1978). The other shortcoming to the use of bilateral segment prism designs is the optical scotoma induced (in the binocular visual field) when looking into the prism. Images from the prism obscure those within the central area of

the seeing hemifield creating a scotoma in physical space. This optical scotoma is referred to as a prism apical scotoma or “Jack-in-the-Box” scotoma, and occurs at the apex of any prism (Bailey, 1978). **The impact of the prism apical scotoma in various prismatic spectacle designs is discussed further in Chapter 3.**

Unilateral Sector Prisms and the Prism Apical Scotoma

Unilaterally fitted sector prisms (Figure 2.2b) are thought to compensate for this apical scotoma by allowing the non-prism eye to see the intact seeing hemifield, while the other eye can use the sector prism to see portions of the blind hemifield. However, even in the unilateral sector prism design an optical scotoma may be present pericentrally in the binocular field in certain situations (**see Chapter 3**). Unlike bilateral sector prisms that only provide visual field substitution, unilateral sector prisms may provide visual field expansion through binocular visual confusion when looking into the prism. However, the patient will also likely experience central diplopia (Gottlieb, 2003), and may actually deter the patient from looking into the prism. While some (Gottlieb, Freeman & Williams, 1992) suggest implementing prism in this way can train and encourage a patient to scan towards the blind hemifield, no formal study or evidence has been published.

A **B**



Figure 1.2. Sector prism designs for left HH. (a) 20Δ bilateral segment prisms. (b) 20Δ unilateral segment prism design.

Peli Peripheral Prisms

Peli (2000) developed a design of prism glasses (unilateral peripheral prism glasses), for patients with HH that address some of the limitations of unilateral and bilateral sector prisms. Peripheral prisms are usually applied unilaterally in superior and inferior regions of the spectacle lens on the side of the blind hemifield at an inter-prism separation of 12mm (Bowers, Keeney & Peli, 2008) (Fig. 1.3). Like other prism designs, peripheral prisms optically shift objects from the blind side of the visual field to the seeing side. The prism-shifted images are continuously present in the patient's peripheral vision (upper and lower visual field space), creating visual confusion and thus providing visual field expansion in these areas of the visual field (Fig 1.3b). Therefore, obstacles within the blind hemifield can be detected using the patient's peripheral vision without the bothersome central diplopia present in other unilateral designs. However, while the peripheral prisms expand the accessible visual field immediately on first application, the perceived direction of objects detected through the prism is incorrect, as in all prism designs. When a patient detects an obstacle through the prism, he/she is instructed to turn his/her head and look at the object directly using the clear inter-prism area of the spectacle lens.

This design has shown promise in laboratory and multi-center clinical trials (Bowers et al., 2008; Giorgi, Woods & Peli, 2009) with approximately 74% of the patients fitted with peripheral prisms in the multicenter trial reporting benefit after 6 weeks of wear and 47% continuing wear after 12 months. A recent independent single-center study reported even higher long-term success rates (O'Neil, Connell, O'Connor, Brady, Reid & Logan, 2011). In the previous trials (Peli, 2000; Bowers et al., 2008; O'Neil et al., 2011), temporary press-on

Fresnel prisms were applied onto regular glasses used for distance vision. More recently, as described in Bowers (2008), a permanent peripheral prism design has been developed by Chadwick Optical Inc. (White River Junction VT), whereby rigid PMMA Fresnel prism segments are embedded into a carrier lens (Fig. 1.3).

Two designs of peripheral prism fitting have been used, a horizontal and an oblique design (Peli, 2000; Peli, 2008; Bowers, Keeney & Peli, 2013). In the horizontal design the prisms are placed base out on the side of visual field defect (Fig. 1.3a). Due to their placement on the spectacle lens, the peripheral prisms act on peripheral vision in the superior and inferior visual field (Fig. 1.3b). This makes the patient aware of potential obstacles on their blind side, above their line of sight (such as kitchen cupboard doors) and in the lower visual field (such as trash cans or fire hydrants on the sidewalk).

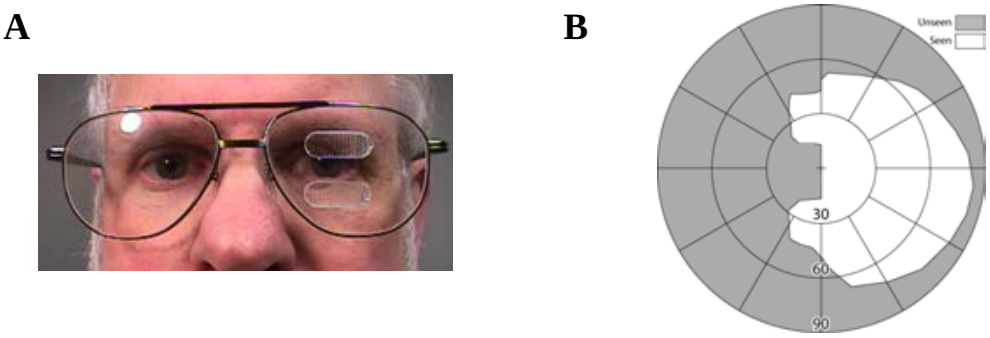


Figure 1.3. Unilateral horizontal peripheral prism design. **(a)** Peripheral prism segments (40Δ) on left spectacle lens of a left HH patient. **(b)** The binocular visual field of the same patient wearing horizontal peripheral prisms with noticeable visual field expansion of the upper and lower peripheral field by about 20 degrees

In the oblique design (Peli, 2008; Peli, Bowers & Keeney, 2009), the base-apex axes of the prisms are tilted such that the upper peripheral prism is base out and base down while the lower peripheral prism is base out and base up (Fig. 1.4). This design provides an area of expansion that is more central, which maybe more beneficial for mobility tasks that require

more awareness of the central 30 degrees of the visual field, such as looking through a car's windshield while driving. Tilting the prisms reduces the lateral expansion by a small amount provided that the angle of tilt is not too large (about 30^{o} is the maximum recommended angle of tilt before the lateral expansion is significantly reduced) (Peli et al., 2009).

A **B**

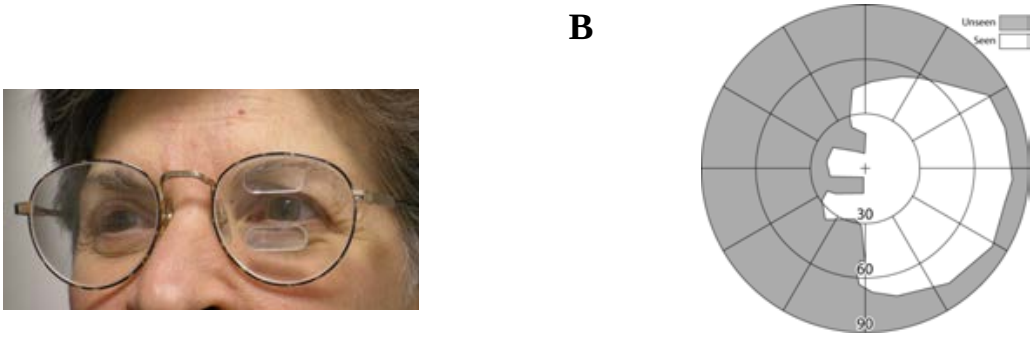


Figure 1.4. Unilateral oblique peripheral prism design**. (a)** Peripheral prism segments (57Δ) on left spectacle lens of a left HH patient. **(b)** The binocular visual field of the same patient wearing oblique peripheral prisms with visual field expansion of the upper and lower peripheral field by about 26 degrees. Although the expansion is more central with oblique prisms, the images still fall on peripheral retina, and in this case part of the field is expanded lateral to fovea despite the peripheral location of the prismatic segments.

1.5 DETECTION WITH PERIPHERAL PRISMS IN SIMPLE AND COMPLEX VISUAL CONDITIONS

The ability to detect objects in areas of visual field expansion provided by peripheral prisms has primarily been assessed using conventional kinetic perimetric techniques in very simple visual conditions (white spot on white background) (Peli, 2000; Giorgi, Woods, Goldstein, Peli, Bond & Easton, 2004; Giorgi et al., 2009; O'Neil et al., 2011). However, there are relatively little data on detection performance in more complex visual conditions, and the data that are available appear conflicting. Conventional perimetric techniques are not representative of the real world situations in which peripheral prism glasses are used. Additionally, perimetric measurements have not been illustrated for any other prismatic spectacle design. Data addressing detection performance against more visually complex

backgrounds is vital to evaluating the functionality of this device.

In a pilot driving simulator study (unpublished data), patients with HH using the peripheral prism glasses appeared (unexpectedly) to be not showing a benefit from the visual field expansion in this visually-complex environment. They were unable to detect, supra-threshold pedestrians (2m tall, appearing at a distance of 67m, thus spanning vertically 1.7^{o}) in areas of field expansion on the side of the vision loss. In contrast, these same patients were able to detect simple targets (spot of light, Goldmann V4e target- 9 mm or 3^{o}) on the side of the vision loss in a simple visual environment (Goldmann Perimeter) using the peripheral prism glasses. Furthermore, they all reported that the prism glasses were helpful for detecting obstacles on the side of the vision loss when walking in real world situations.

The driving simulator data also conflicts with the results of a recent on-road driving study in which drivers with HH had better reactions to unexpected events on the non-seeing side when wearing real oblique prisms than when wearing sham oblique prisms (Tant, 2008). A possible explanation for the inconsistencies between the subjective reports and objective assessments is that some patients may be suppressing the prism image either completely or partially in more complex or real-world viewing circumstances.

1.6 BINOCULAR PHENOMENA – RELEVANCE TO PERIPHERAL PRISM WEAR

Rivalry and Suppression

Peripheral prisms utilize visual confusion to provide visual field expansion. In visual confusion, images of different objects fall on corresponding retinal points, a situation which may result in binocular rivalry. In this case, prism-shifted objects, which are seen by the

“prism” eye, will have the same perceived visual direction as different objects seen by the “fellow” eye, which may give rise to two peripheral areas (islands) of binocular rivalry.

During binocular rivalry, perception alternate between two different images, as long as the characteristics of these images are similar. If they are dissimilar, one image may predominate –sustaining visibility for a longer duration than the alternate image, or in the extreme case, suppression may occur whereby the brain suppresses one of the two images for an extended period of time. Differences between left and right eyes in any one of a wide range of stimulus characteristics is sufficient to induce predominance of one eye, or suppression over rivalry, including differences in: color, luminance, contrast, polarity, form, size and motion velocity (Blake & Logothetis, 2002). Under these circumstances, the field with the higher contrast, the higher luminance, or the more interesting or higher contour density will dominate (Horowitz, 1949). Due to the optical image degradations of high-powered Fresnel prisms (Katz, 2004a), the prism image is of lower contrast and poorer quality than the image from the non-prism eye, and therefore more likely to have reduced predominance or to be locally suppressed under these conditions. Furthermore, exclusive visibility of only one target (ie. suppression) is more likely with increasing retinal eccentricity (Blake, O'Shea & Mueller, 1992). In the real world, with complex images, varying light levels and varying contrast it is unclear whether there may be conditions for binocular rivalry (Arnold, 2011) while wearing the prism spectacles. Reduction in predominance of the prism eye, or partial or complete suppression of the prism image, would reduce the likelihood of detecting objects in the prism-expanded vision and impair the functionality of the prism glasses.

Ocular Dominance in Rivalry

Peripheral prisms are usually placed before the eye corresponding to the side of HH (i.e. on the left lens for a patient with left HH) in order to limit the impact of the prism apical scotoma (see Chapter 3), which may not necessarily be the dominant eye. Ocular dominance is defined as the tendency to prefer the visual input from one eye over the other (Miles, 1930). Fitting prisms for patients with HH on the non-dominant eye may potentially increase the likelihood that objects seen with the prism are suppressed.

Coren and Kaplan conducted a wide variety of ocular dominance studies and classified ocular dominance into three potential categories: sighting dominance - the eye used for sighting when one looks at a distant object through an aperture; acuity dominance - the eye with better visual acuity/contrast sensitivity; and sensory dominance - the eye in which a rivaling stimulus is most often predominant (Coren & Kaplan, 1973). When using peripheral prisms as a treatment for HH we are primarily concerned with sensory dominance.

Clinicians often use tests of sighting dominance since it can be determined easily. However, the relationship has been ambiguous and contentious. Porac and Coren (Porac & Coren, 1978) reported that the sighting dominant eye predominated during binocular rivalry. Many others subsequently found the two to be independent (Ooi, Optom & He, 2001; Seijas, Gomez de Liano, Gomez de Liano, Roberts, Piedrahita & Diaz, 2007; Li, Lam, Yu, Hess, Chan, Maehara, Woo & Thompson, 2010). In Chapter 2, these issues are directly addressed as ocular dominance was assessed using a variety of sensory and sighting tests. We aimed to investigate whether sensory, or sighting dominance may affect detection performance in the blind hemi-field while wearing peripheral prism glasses. Detection performance was

compared for peripheral prisms applied to the dominant and non-dominant eye.

1.7 OVERVIEW OF RESEARCH CONDUCTED

In Chapter 2, we investigated the effects of background complexity and ocular dominance on detection performance of HH patients wearing unilateral peripheral prism glasses. Detection rates were measured for targets presented over complex, patterned backgrounds (spatial noise images) as well as a simple plain background (as used in traditional perimetry), and for prisms fitted on the side of the visual field loss and also in front of the eye on the opposite side. We expected that reduced predominance or even suppression of the prism image in binocular viewing would be more likely to occur when targets were presented on the complex background (due to binocular rivalry) than the simple background (little or no stimulus for rivalry), and when the prisms were fitted on the sensory non-dominant than the dominant eye.

In Chapter 3, we analyze the position and size of the optically-induced prism apical scotoma for various placements of peripheral prism glasses and other prismatic spectacle designs and for various positions of gaze for patients with HH. We compared the measured positions to calculated positions, and modified prism placements, based on calculation, to reduce the impact of the apical scotoma. Other confounds, such as the diplopia and visual confusion induced in some prism configurations and the non-veridical directions viewed with all designs were also considered. Our overall aim was to develop recommendations in order to advise the clinician as to how to mitigate these effects when fitting prisms for HH.

CHAPTER 2. PERIPHERAL PRISM GLASSES: EFFECTS OF DOMINANCE, SUPPRESSION, AND BACKGROUND

2.1 ABSTRACT

Purpose. Unilateral peripheral prisms for homonymous hemianopia (HH) place different images on corresponding peripheral retinal points, a rivalrous situation in which local suppression of the prism image could occur and thus limit device functionality. Detection with peripheral prisms has primarily been evaluated using conventional perimetry, where binocular rivalry is unlikely to occur. We quantified detection over more visually complex backgrounds and examined the effects of ocular dominance.

Methods. Detection rates of eight participants with HH or quadranopia and normal binocularity wearing unilateral peripheral prism glasses were determined for static perimetry targets briefly presented in the prism expansion area (in the blind hemifield) and the seeing hemifield, under monocular and binocular viewing, over uniform gray and more complex patterned backgrounds.

Results. Participants with normal binocularity had mixed sensory ocular dominance, demonstrated no difference in detection rates when prisms were fitted on the side of the HH or the opposite side ($p > 0.2$), and had detection rates in the expansion area that were not different for monocular and binocular viewing over both backgrounds ($p > 0.4$). However, two participants with abnormal binocularity and strong ocular dominance demonstrated reduced detection in the expansion area when prisms were fitted in front of the non-dominant eye.

Conclusions. We found little evidence of local suppression of the peripheral prism image for

HH patients with normal binocularity. However, in cases of strong ocular dominance, consideration should be given to fitting prisms before the dominant eye. Although these results are promising, further testing in more realistic conditions including image motion is needed.

2.2 INTRODUCTION

Homonymous hemianopia (HH) is the congruous loss of half the visual field on one side in both eyes resulting from post-chiasmal lesions. The overall prevalence of HH in individuals aged >49 years is 0.8% (Gilhotra et al., 2002). The most common etiologies are stroke (accounting for 70% of cases), followed by traumatic brain injury (13%) (Zhang et al., 2006a). Patients with HH have difficulty detecting obstacles on the side of the field loss, resulting in impaired walking, and are precluded from driving in many US states (Peli & Peli, 2002). Thus, HH can significantly impact a patient's quality of life (Vu, Keeffe, McCarty & Taylor, 2005; Warren, 2009b; O'Neil et al., 2011). Spectacle mounted prisms in a variety of unilateral and bilateral designs, aiming to expand or relocate the visual field, are a commonly applied rehabilitation treatment (Young, 1929; Cohen, 1993; Weiss & Brown, 1995; Cohen & Waiss, 1996). The prisms shift the image of objects located in the blind field into an area of the seeing field.

In 2000, Peli (Peli, 2000) described a new approach to fitting prisms for HH—peripheral prism glasses—in which two high-powered prism segments are placed above and below the line of sight on the spectacle lens (Fig. 2.1). When fitted unilaterally, the prisms create peripheral diplopia (two views of the same object at different positions in visual space) and visual confusion (the appearance of two different images in the same position). It is the

confusion that provides the visual field expansion that can be measured using perimetry. This expansion has been reported to be helpful for obstacle detection when walking (Peli, 2000; Bowers et al., 2008; Giorgi et al., 2009; O'Neil et al., 2011), and may also be helpful for detection of potential hazards when driving (Tant, 2008).



Figure 2.1. Press-on Fresnel 40 Δ prisms. Shown as fitted for the study, placed base left on the left spectacle lens of a left HH patient (the pointed edge of the prism segments indicates the direction of the base).

In visual confusion, images of different objects fall on corresponding retinal points, a situation which may result in binocular rivalry. In the case of peripheral prisms, the prism-shifted image from the prism eye and the normal image of the scene from the non-prism eye fall on peripheral corresponding points, which may give rise to two peripheral areas ("islands") of binocular rivalry. Due to the poor optical quality of high-power Fresnel prisms (Katz, 2004a), the prism image is of lower contrast than the image from the nonprism eye, and is therefore less likely to predominate during binocular rivalry (Blake, 2001). Exclusive visibility of a target (dominance/ suppression) increases with retinal eccentricity (Blake et al., 1992). In the extreme case, persistent local suppression of the prism image under binocular viewing conditions would severely reduce the utility of the peripheral prism glasses.

However, even a decrease in predominance could potentially reduce device utility to some extent.

To date, detection performance with peripheral prism glasses has primarily been measured using kinetic Goldmann perimetry, presenting a spot of light on a plain uniform background (Peli, 2000; Bowers et al., 2008; O'Neil et al., 2011). Under these conditions, local suppression of the prism image has not been found, as there is little or no stimulus for rivalry. However, these conditions are not representative of the real world where prism glasses are used to detect objects against visually complex backgrounds. By comparing detection rates for monocular and binocular viewing, we examined whether there was decreased predominance (or persistent local suppression) of the unilateral prism image, as shown by reduced detection rates, when targets were presented over complex patterned backgrounds and over uniform gray backgrounds (as used in traditional perimetry). We predicted that due to rivalry, there would be at least partial local suppression of the prism image on the patterned background, but not the gray background.

Peripheral prisms are usually placed in front of the eye ipsilateral to the blind hemifield (i.e., on the left lens for a patient with left HH), which may not necessarily be the sensory dominant eye. Decreased predominance or binocular suppression is more likely for targets presented to the sensory non-dominant eye (Handa, Uozato, Higa, Nitta, Kawamorita, Ishikawa, Shoji & Shimizu, 2006; Li et al., 2010). Previous studies of sensory ocular dominance reported that the majority of observers with normal binocular vision had no clear dominance (i.e., “mixed” dominance) (Seijas et al., 2007; Li et al., 2010). In such cases, sensory dominance would be less likely to cause local suppression of the prism images.

However, for people with strong sensory dominance (e.g., secondary to strabismus, amblyopia, or significant/pathological difference in vision), fitting the prism to the sensory non-dominant eye could result in local suppression of the prism images and reduced detection of objects of interest seen only through the prism.

Unilateral peripheral prisms were fitted on the lens ipsilateral to and contralateral to the side of the HH. We predicted that for patients with normal binocular vision and mixed ocular dominance, there would be little difference in detection rates for the two prism-fitting conditions (ipsilateral and contralateral). However, for participants with strong ocular dominance, we expected that detection rates would be lower (especially on the patterned background) when the prisms were fitted in front of the sensory nondominant eye than the dominant eye.

2.3 METHODS

This study was conducted in accordance with the tenets of the Declaration of Helsinki. All participants signed a consent form approved by the Schepens Institutional Review Board.

Participants

Participants had stable (>6 months since diagnosis) HH or quadranopic field loss. In addition, they met the following criteria: a visual acuity of 20/50 or better in each eye, no hemispatial neglect (Bells test (Gauthier, Dehaut & Joanette, 1989) and Schenkenberg line bisection test (Schenkenberg, Bradforn & Ajax, 1980)), no significant cognitive decline (a score of >24 on Mini-Mental State Examination (Folstein, Folstein & McHugh, 1975)), normal binocular vision (no amblyopia, no strabismus), and no visual field loss affecting the seeing hemifield.

Twenty potential participants were recruited and screened from local clinics, of which eight met all the criteria and were included in the main study (Table 2.1); six completed all study visits and two completed testing with the prism in front of only one eye. Three participants were current peripheral prism wearers and five were fitted with peripheral prisms for the study.

Participant Characteristics	**All Participants (n = 8)**	**Current wearer (n = 3)**	**New wearer (n = 5)**
Male, n (%)	5 (63%)	2 (67%)	3 (60%)
Age in years, median (range)	47 (15-69)	54 (35-61)	39 (15-69)
Snellen Binocular BCVA*, median (range)	20/16 (20/13-20/25)	20/16 (20/13-20/16)	20/16 (20/13-20/25)
MMSE^ score, median (range)	30 (29-30)	30 (30-30)	30 (29-30)
Time in months since onset of HH, median (range)	92 (28-160)	61 (28-90)	104 (45-160)
Number with complete HH, n (%)	4 (50%)	2 (67%)	2 (40%)
Number with left sided loss, n (%)	4 (50%)	3 (100%)	1 (20%)
Stroke etiology of HH, n (%)	7 (88%)	3 (100%)	4 (80%)
Continued wear after study, n (%)	5 (63%)	3 (100%)	2 (40%)

Table 2.1. Characteristics of the eight participants in the main study, *BCVA = Best corrected visual acuity. ^MMSE = Mini-Mental State Examination

In addition, to evaluate the effect of strong ocular dominance (and/or suppression), two participants with left HH who did not meet the criteria for visual acuity and normal binocularity participated. Their data were not included in the main analyses and are presented separately. One was a current wearer, and the other was fitted with peripheral prisms for the study.

In addition to the screening vision measures (visual acuity, refraction, Goldmann perimetry, and binocular vision testing), sensory dominance was evaluated using a test battery (Seijas et al., 2007; Li et al., 2010) including the Worth 4 dot test, plus lens test, Randot polarized suppression test, and the polarized mirror test (Peli, 2002).

Peripheral Prisms

Peripheral prism segments were fit unilaterally, first to one lens and then the other of participants' glasses, primarily used for distance vision. The segments were 8 mm (vertical) by 22 mm, with a standard 12 mm interprism separation (Bowers et al., 2008) (Fig. 2.1). The prism base was always placed toward the side of the HH and was therefore in the same direction (right or left) irrespective of which spectacle lens was used. When the prism was on the lens on the side of the HH, current peripheral prism wearers used their own prism glasses for testing (either 40 Δ press-on or, in one case, 57Δ permanent prism glasses); a second equivalent pair was provided for testing with prisms on the opposite side. New wearers were provided with study glasses with 40Δ press-on Fresnel prisms, and the side of the first prism fitting (the side of HH or the opposite) was counterbalanced. With the exception of one current peripheral prism wearer (who would not permit us to change the press-on prisms on his glasses), all participants using press-on prisms were fitted with new prisms for the study. Subjects were encouraged to wear the prism glasses as much as possible between visits (except during prolonged near work or when driving).

Detection Test: Backgrounds and Targets

A computerized tangent-screen perimeter (Woods, Apfelbaum & Peli, 2010) was used to perform kinetic and static perimetry, presenting targets on a large 1.6 × 1 m rear-

projection screen at a 1 m viewing distance. The dichoptic measurement capability of this system (using liquid crystal goggles) (Doherty, Bowers, Luo & Peli, 2010; Woods et al., 2010) was not applied in this study. Instead, for monocular viewing conditions, an eye patch was used to occlude the eye not being tested.

Viewing Backgrounds

Two backgrounds were used: a simple uniform gray background and a more visually complex patterned background. For the latter, $1/f^{0.75}$ noise images (Doherty et al., 2010) (Fig. 2.2) were used that had spatial frequency (f) radially averaged spectra similar to natural scenes (Field, 1987), but more stationary distributions of luminance and contrast (which may vary considerably in natural scenes causing large local variations in target visibility). The patterned background changed after each target presentation, and, on average, the contrast between the background and the target remained uniform despite changes in target position on the screen. Testing on a normally sighted participant wearing peripheral prism glasses confirmed that the noise images created a detectable rivalry (using the color-marking technique).

Targets

Targets were 1° square checkerboards (two-by-two black-and white 0.5° squares; Fig. 2.2) of 60, 75, or 95% internal Michelson contrast. Target contrast was determined separately for each participant before experimental trials began. A contrast level was selected for which detection rates during monocular viewing with peripheral prism glasses were high on the uniform gray background in the seeing hemifield test zone (described later in the text) and were still > 20% on the patterned background in the prism expansion test zone. Targets were

presented for 250 ms, followed by a grace period of 600 ms to allow a subject's response (a button press). To avoid anticipation of the onset of the next target, a randomized delay of 1000 to 1950 ms occurred after the button press (or grace period if no response) before the next target presentation.

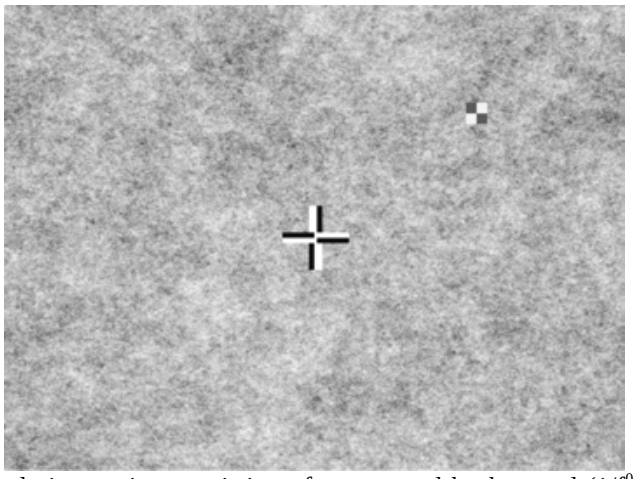


Figure 2.2. Patient's view during testing consisting of a patterned background ($1/f^{0.75}$ spatial noise), a bipolar fixation cross, and a peripheral bipolar checkerboard target (shown here at high 95% contrast). Only the central portion of the screen is shown.

Test Zones

Two main test zones were used: a zone in the blind hemifield to evaluate detection in one prism expansion area (either upper or lower) and a zone within the seeing hemifield in an area where both the prism eye and the fellow eye would be able to detect targets in monocular and binocular conditions (Fig. 2.3). In addition, a third test zone in the seeing hemifield, but under the optical apical scotoma caused by the unilateral prism (Ross, Bowers & Peli, 2009), was used (Fig. 2.3A). In monocular prism-eye-only viewing, we expected that no targets would be detected in this area (thus acting as a fixation check); however, in binocular viewing, we expected that the fellow eye would compensate for the apical scotoma.

All test zones were 3° (vertically) by 8°, deliberately smaller than the expansion areas

(of approximately 24° by 22°), to ensure that, even if there was some head movement during testing, the test targets would be presented within the expansion area. Forty targets (two repetitions of 20 targets) were shown in each of the test zones. In addition, 40 targets (two repetitions of 20 targets) were presented outside the test zones at arbitrary positions covering a wide area in the seeing and non-seeing hemifields (Fig. 2.3). These targets ensured that the participants did not expect targets to appear in only specific areas of the visual field; they were not included in analyses of detection performance. Eight additional targets (two repetitions of four targets) to monitor fixation losses were presented in non-prism areas of the blind hemifield, close to the border with the seeing visual field; median fixation losses were 0% {interquartile range (IQR): 0–4%}.

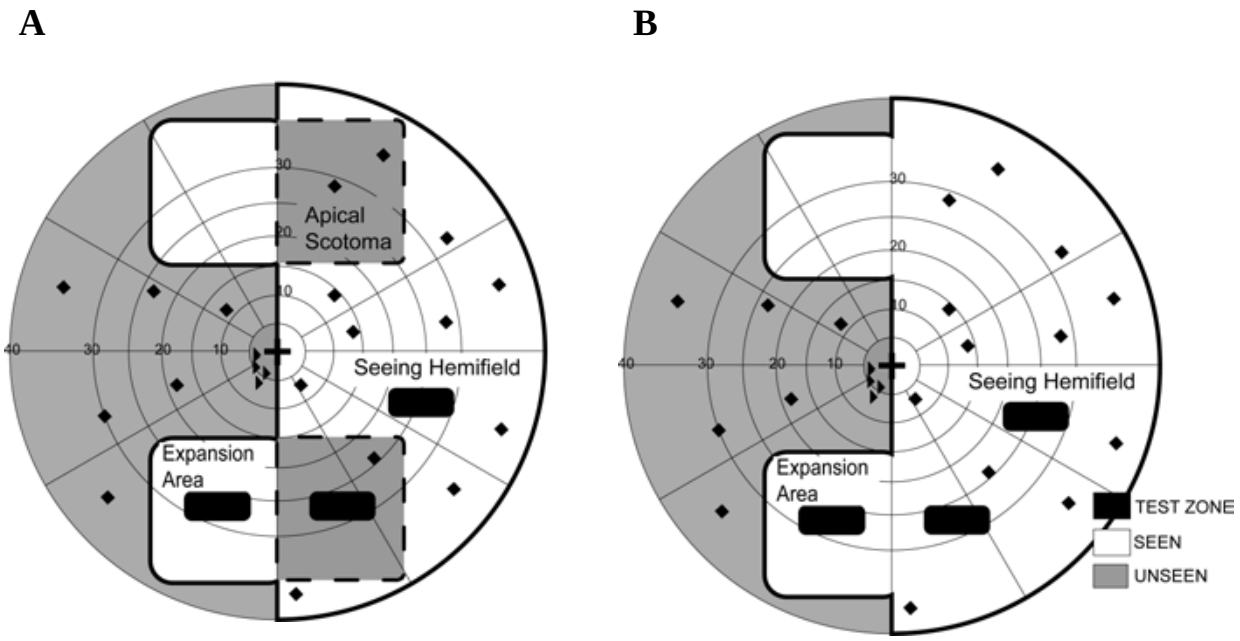


Figure 2.3. Schematic visual field plots and static detection test zones for a patient with left HH wearing peripheral prism glasses. (A) Prism-eye-only viewing; (B) binocular viewing. Thick black lines mark the kinetic isopter. Dashed lines outline the prism apical scotoma mapped in the prism-eye-only condition. Black-filled rounded-corner rectangles represent test zones (20 targets per zone). Black diamonds represent arbitrary positions of additional targets (20) included to prevent anticipation of a target's location. Black triangles are targets used to monitor fixation.

Detection Test Conditions and Procedures

For each of the prism fittings (side of HH and opposite side), detection performance was evaluated on two backgrounds (complex patterned and uniform gray) and in two viewing conditions (prism-eye only and binocular). All the tests for one fitting (usually two sessions) were completed before the prisms were swapped to the other eye. For each fitting, participants wore the prisms as much as possible every day for at least 2 weeks before testing (median: 3.0 h/d, range: 1.25–18 h/d). Order of backgrounds and viewing conditions were counterbalanced as much as possible across participants, but the order was the same for the two fittings for each participant.

During the detection tests, participants were instructed to maintain fixation on the central cross and to press a hand-held response button, connected to the computer, whenever a target was seen. Participants practiced the task before experimental trials began and were allowed to take breaks whenever needed. Kinetic perimetry was used at the start of every test condition to ensure that the test zones were within the intended areas of the visual field. When necessary, participants were optically corrected for the 1 m test distance either with study glasses prescribed for that distance or with clip-on +1 D lenses.

Questionnaires and Clinical Decision

After wearing each prism fitting for at least 2 weeks, all participants completed a short questionnaire addressing their experiences of using that prism fitting (Bowers et al., 2008). At the end of the study, preference for one prism fitting over the other was determined. Based on subjective preferences and quantitative detection data, a clinical decision regarding continued use of the prism glasses (and which side fitting) was made.

Data Analysis

Because the detection rate data were not normally distributed, even after a probit transform (Pearson, 1904; Winer, Brown & Michels, 1991), statistical analyses of group data were conducted on the raw percentages using the non-parametric Wilcoxon signed rank test. A significance level of $\alpha = 0.05$ was used.

2.4 RESULTS

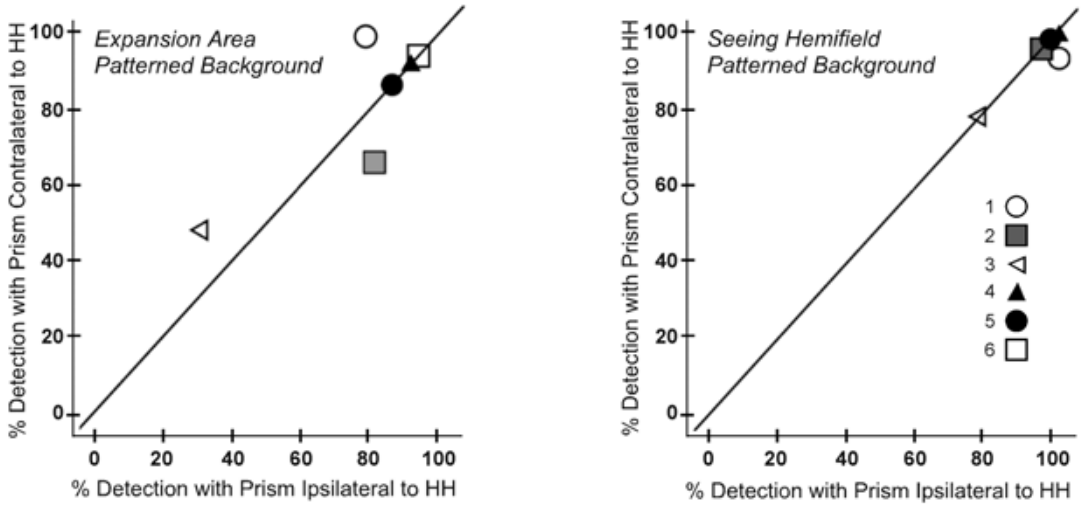
Participants with Normal Binocular Vision

Sensory Dominance

The majority of participants with normal binocular vision (seven of eight) had no clear dominance; only one demonstrated consistent sensory ocular dominance on the test battery (same eye dominant on three of the four tests).

Side of Prism Fitting

For the six participants who completed testing with both fittings, we compared detection rates for binocular viewing when the prism was fitted in front of the eye corresponding to the side of HH and in front of the opposite eye. For the expansion area, there were no significant differences in detection rates between the two prism fittings for both the patterned background (Fig. 2.4A) and the uniform gray background ($p = 0.285$ and 0.713, respectively). For the seeing hemifield area (Fig. 2.4B), there were also no significant differences in detection rates between the two prism fittings for both backgrounds ($p = 0.180$ and 0.414, respectively). Therefore, subsequent data analyses were performed with the data collapsed across the two fittings for these six participants. In addition, data were included from the two participants who only completed testing for fitting on the side of the HH.



A **B**

Figure 2.4. Detection rates for each participant under binocular viewing on the patterned background when peripheral prism segments were fit ipsilateral and contralateral to the side of HH: (A) prism expansion area test zone and (B) seeing hemifield test zone. In both test zones, detection rates were not significantly different for the two fittings (p _ 0.2). The y = x reference line is plotted to assist interpretation; data points falling on the reference line indicate no difference between the ipsilateral and contralateral fittings.

Seeing Hemifield Zone Under the Apical Scotoma

As expected, for monocular prism-eye-only viewing, very few targets were detected in the seeing hemifield zone under the apical scotoma; median detection rates were only 1% (IQR: 0–5%). However, in binocular viewing, the fellow eye compensated for the monocular apical scotoma, and detection rates in the main seeing hemifield zone and the seeing hemifield zone under the apical scotoma were not significantly different ($p > 0.5$). Only results for the main seeing hemifield zone are reported below.

Suppression of Prism Image Under Binocular Viewing?

To evaluate whether there was decreased predominance or local suppression of the prism image, detection rates in the expansion test zone were compared for monocular and binocular viewing. As expected, there was no significant difference in detection between monocular and binocular viewing on the uniform gray background ($p = 0.893$; Fig. 2.5A). However, contrary to our prediction, there was also no significant difference between monocular and binocular viewing on the patterned background ($p = 0.483$; Fig. 2.5B). Median detection performance on the patterned background was 78% for monocular viewing (IQR: 69–78%) and 86% for binocular viewing (IQR: 64–91%).

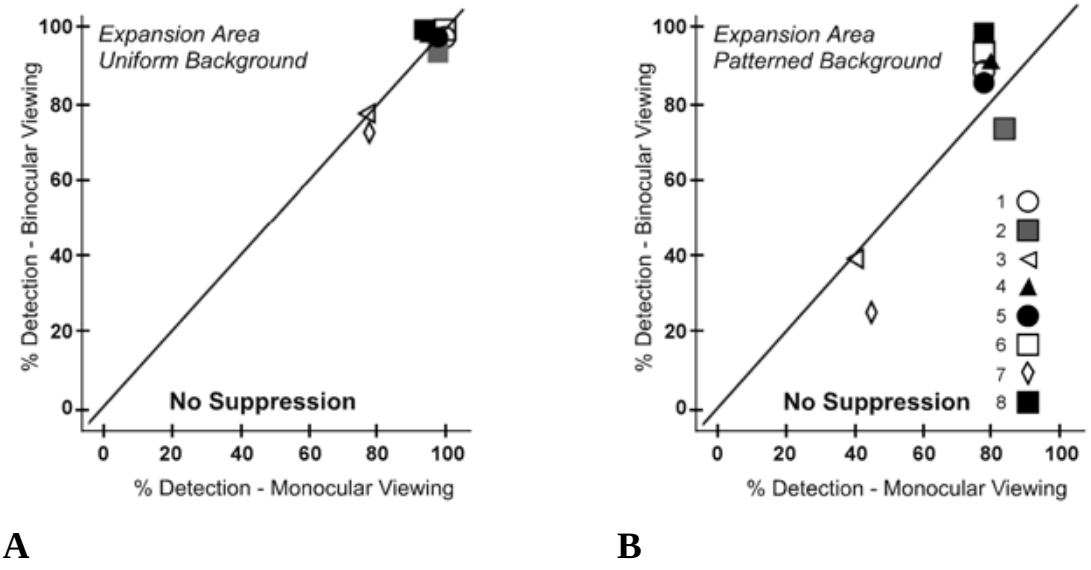
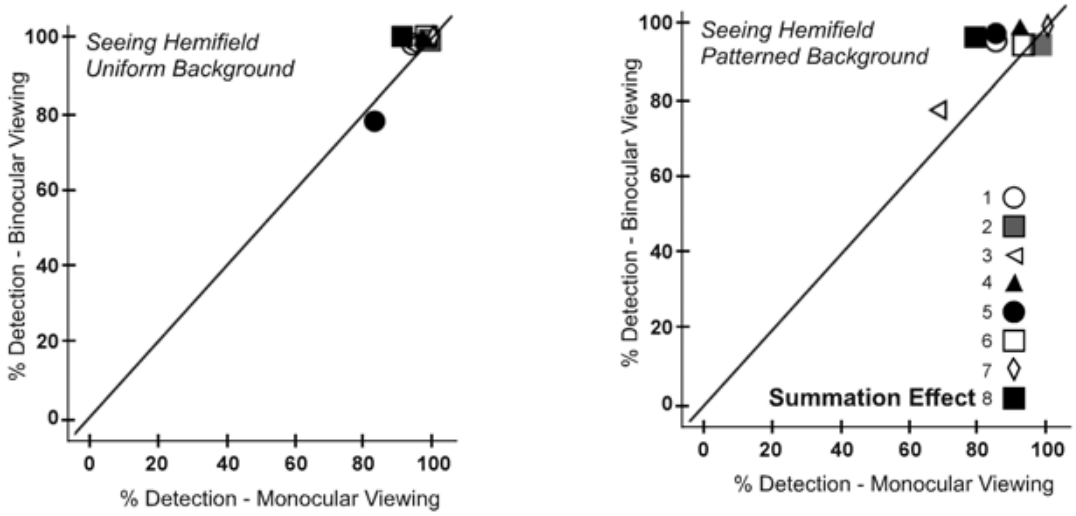


Figure 2.5. Detection rates for each participant in the expansion area test zone for monocular and binocular viewing for (A) the uniform and (B) the patterned background. There were no significant differences in detection rates between monocular and binocular viewing on either background, suggesting no reduction in predominance or local suppression of the prism image in binocular viewing.

We did, however, find an effect of binocular summation in the seeing hemifield. Although this effect was not observed with the uniform background (as expected; p = 0.246; Fig. 2.6A), there were significantly higher detection rates for binocular than monocular viewing on the patterned background (p = 0.043; Fig. 2.6B).



A **B**

Figure 2.6. Detection rates for each participant in the main seeing hemifield area test zone for monocular and binocular viewing for (A) the uniform and (B) the patterned background. On the patterned background, detection was better under binocular than monocular viewing, consistent with a binocular summation effect, which was not evident on the uniform background (as expected).

Effect of Background

As expected, detection rates for the patterned background were lower than for the uniform gray background. This trend was apparent in both the expansion and the seeing hemifield test zones for both monocular and binocular viewing. However, the reduction was greater in the prism expansion area (97–82%, p = 0.012; Fig. 2.7A; data pooled across monocular and binocular viewing) than the seeing hemifield (97–93%, p = 0.175; Fig. 2.7B). This difference was likely due to the degradation in image quality induced by the high-power Fresnel prism, as shown in the next section.

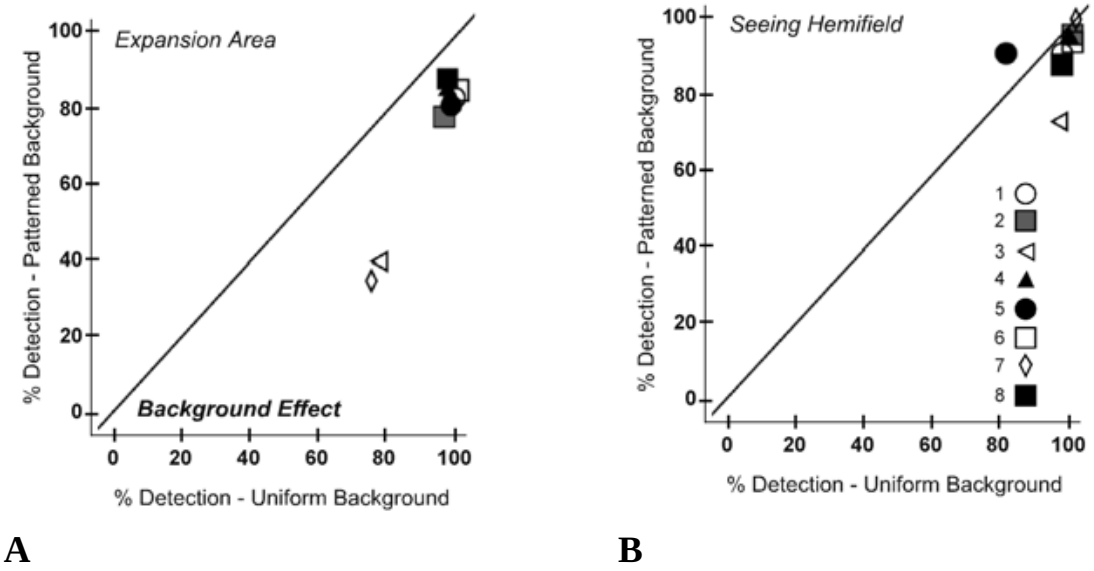


Figure 2.7. Detection rates for each participant on the uniform and patterned backgrounds for (A) the prism expansion area and (B) the seeing hemifield test zones. In the prism expansion area, detection rates were significantly lower on the patterned than the uniform gray background ($p = 0.012$). Data are pooled across monocular and binocular viewing.

Effect of Prism Alone

The effect of the prism alone on detection (without the possible confound of binocular rivalry) was examined by comparing detection rates in the expansion and seeing hemifield zones for monocular (prism-eye only) viewing. On the uniform gray background, there was little difference in monocular detection rates between the expansion and seeing hemifield areas (median difference: only 3%; Fig. 2.8A). By comparison, on the patterned background, monocular detection in the prism expansion area was 10% (median) lower than in the seeing hemifield ($p = 0.012$; Fig. 2.8B).

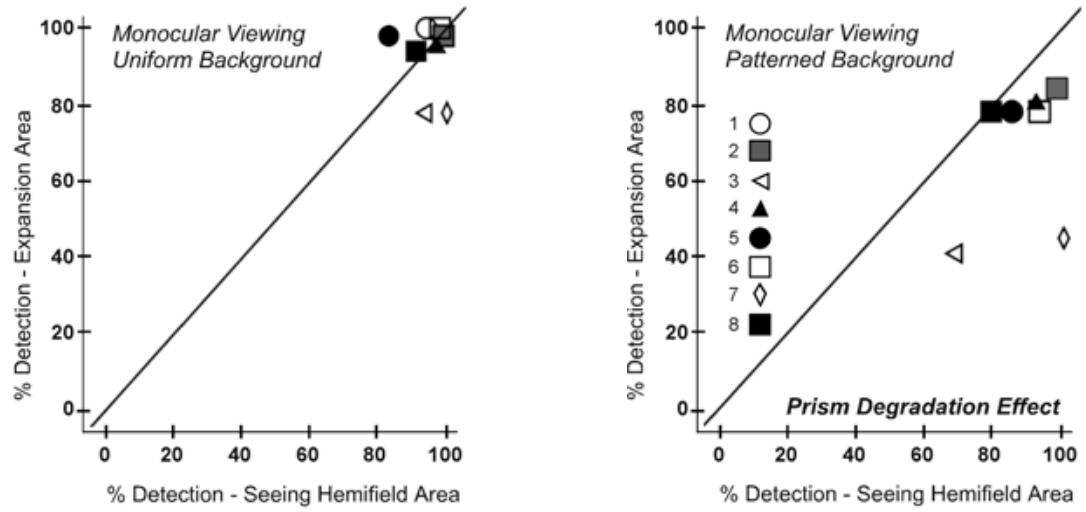


Figure 2.8. The degrading effect of the Fresnel prism was measured by comparing detection rates for each participant in the seeing hemifield and expansion area test zones under monocular viewing for (A) the uniform and (B) the patterned background. The poor optical quality of the prisms reduced detection rates by approximately 10% (median) on the patterned background, but had little effect on detection rates on the uniform background.

Long-Term Wear and Clinical Decision

Of the eight participants who participated in the main study, five continued to wear the prisms at the conclusion of the study (three with complete HH and two with quadranopia; Table 2.1), reporting that they used the prism glasses mostly when moving about outdoors or in unfamiliar environments. Participants ranked the helpfulness of the prism glasses in these circumstances; the median reported score was 2.5 out of a possible score of 5 (somewhat to moderately helpful) for detecting obstacles on their blind side. Of the six participants who completed testing with both prism fittings, two continued wearing the peripheral prisms on the side of HH (one current wearer with complete HH and one new wearer with quadranopia), and one new wearer with complete HH continued wearing on the opposite side.

Participants with Abnormal Binocular Vision and Strong Ocular Dominance

Two participants with HH, who did not meet the main study inclusion criteria for visual acuity, normal binocularity and in one case, integrity of the seeing hemifield, were included as cases of strong ocular dominance. Participant 9 (left HH; age: 96 years, had not worn peripheral prisms before the study) had significant ocular pathology (primary open-angle glaucoma, and geographic atrophy) in the right eye only, and consistently showed left eye preference on all dominance tests (OD:20/63, OS:20/32). Although there was glaucomatous visual field loss in the right eye, there was still sufficient remaining field to encompass the prism- shifted images from the blind hemifield when the prisms were fitted in front of that eye. However, there was insufficient remaining field to place a seeing hemifield test zone in an area outside the apical scotoma where both the prism eye and the fellow eye would be able to detect targets in monocular and binocular conditions; therefore, only results for the expansion zone are reported. On the patterned background, detection in the prism expansion area was lower when the prism was fit before the non-dominant eye than the dominant eye; this difference was statistically significant (Newcombe & Altman, 2006) in both monocular and binocular viewing ($p = 0.01$ and $p = 0.0001$, respectively; Fig. 2.9). The same was also true for the gray background for binocular viewing ($p = 0.0001$), but not monocular viewing ($p = 0.50$). Consistent with these findings, this participant reported that the peripheral prism segments were helpful for detecting obstacles on the blind side when fitted in front of the dominant left eye, but less helpful when fitted in front of the non-dominant eye. She reported they were especially helpful when navigating in church or in the shopping mall and requested to continue to wear the prism segments (on the dominant eye) in

these situations at the conclusion of the study.

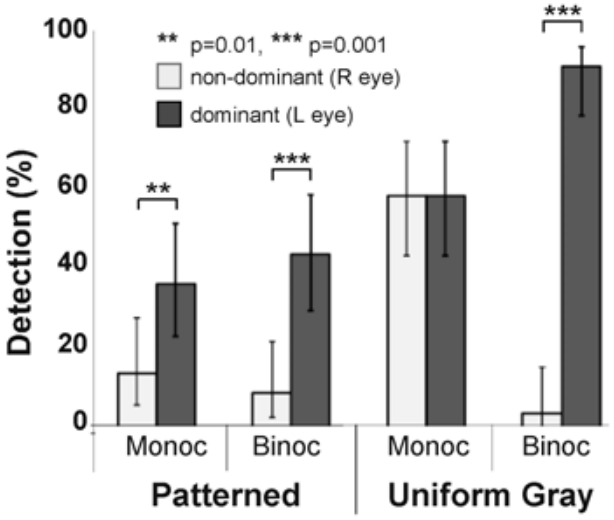


Figure 2.9. Detection performance in the expansion area for participant 9 with left HH and a strongly dominant left eye due to unilateral (right eye) ocular pathology. Detection rates were significantly higher in the prism expansion area when the prism was fit to the left than the right eye for both viewing conditions on the patterned background and for the binocular condition on the uniform background. Error bars are 95% confidence limits.

Participant 10 (left HH; age: 81 years), with left small-angle exotropia, reported crossed diplopia on the Worth 4 dot test, and was right-eye dominant on all other ocular dominance tests (OD:20/16, OS: 20/60). This participant had worn peripheral prisms, fitted elsewhere, in front of the left non-dominant eye for 6 years before participating in the study. Owing to transportation difficulties, detection tests were completed for only the habitual (left eye) prism fitting; we were unable to arrange subsequent visits to fit prisms in front of the right dominant eye. On the patterned background, monocular detection performance in the expansion zone for the left-eye prism fitting was very low (25%), and significantly worse under binocular viewing (8%, $p = 0.0001$; Fig. 2.10), suggesting reduced predominance or partial local suppression of the prism image from the non-dominant eye. In the seeing

hemifield on the patterned background, monocular (prism-eye only) detection was also reduced relative to binocular detection ($p = 0.0001$), indicating overall poorer visual function in the prism eye. Detection on the gray background was higher for all viewing conditions, with minimal differences between monocular and binocular viewing ($p > 0.1$). After the study, this participant elected to continue wearing the prism glasses with the habitual left-eye prism fitting for occasional use when walking outside. However, he reported that the glasses were not helpful for detecting obstacles in crowded situations.

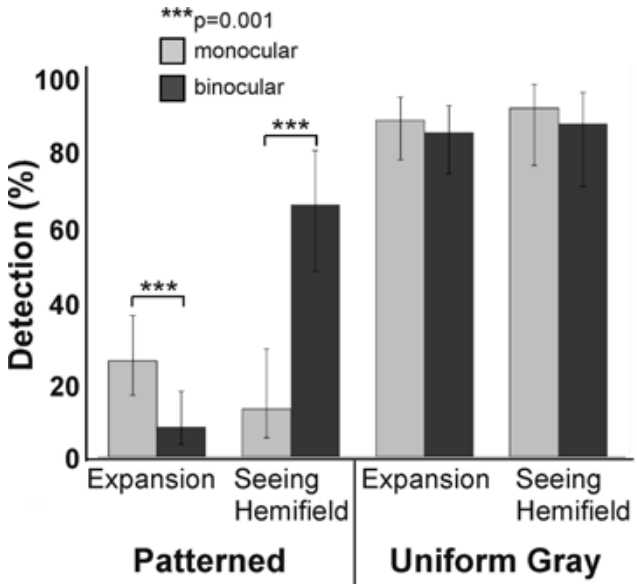


Figure 2.10. Detection rates when peripheral prisms were fit in front of the nondominant left eye of participant 10 with left HH and left exotropia. On the patterned background, monocular (prism-eye only) detection was significantly reduced in both the expansion and the seeing hemifield zones (compared with the binocular seeing hemifield condition), indicating overall poor visual function of the prism eye. In the expansion zone, detection rates on the patterned background were significantly lower in binocular than monocular viewing, suggesting partial local suppression of the prism image from the non-dominant prism eye. Error bars are 95% confidence limits.

2.5 DISCUSSION

Consistent with our predictions, for participants with normal binocularity, detection rates in the prism expansion area were similar in binocular and monocular viewing on both the patterned and uniform gray backgrounds. These findings suggest that there was no reduced predominance or local suppression of the prism image in binocular viewing, even in the more complex pattern-viewing condition where there was a stimulus for binocular rivalry (Shen, Peli & Bowers, 2011). As expected, overall detection rates were lower on the patterned (masking) background than the uniform gray background, with a greater reduction in the prism-affected expansion area than the prism-free seeing hemifield. These results suggest that the reduction was caused by the contrast degradation and poor optical quality of the Fresnel prism images (Katz, 2004a) rather than by local suppression of the lower-contrast prism image on the more complex background.

Median detection rates were only 10% lower in the prism expansion area than the seeing hemifield zone on the patterned background in both monocular and binocular viewing, which is promising for the utility of the prisms in real-world conditions. Nevertheless, there was a high degree of between-subject variability in detection rates for the prism expansion area (ranging from 25 to 98% for binocular viewing on the patterned background; Fig. 2.5B). There were two participants with noticeably lower detection rates (participants 3 and 7 in Fig. 2.5B). One was the participant who would not permit us to place new press-on prisms on his glasses; therefore, detection rates may have been affected by deterioration in the optical quality of the old prisms. The other participant had a moderate myopic prescription (spherical equivalent OD: -4.87 D, OS: -5.25 D) and used permanent prism glasses without any

refractive correction in the area of the lens occupied by the prism segments that may have contributed to the lower detection rates.

In agreement with previous studies (Seijas et al., 2007; Li et al., 2010), the majority of participants with normal binocular vision demonstrated mixed results on sensory ocular dominance testing, exhibiting no truly dominant eye, and little overall difference in detection rates when prisms were fitted on the side of the HH or the opposite side. However, as expected, strong ocular dominance did affect detection performance in the prism expansion area (and the seeing hemifield area). Participant 9, with strong left-eye dominance, demonstrated significantly decreased monocular and binocular detection in the expansion area when the prism segments were fit to the non-dominant right eye as opposed to the dominant left eye. Participant 10, who only wore prisms on the non-dominant eye, exhibited significantly reduced detection in the expansion area in binocular compared with monocular viewing on the complex background. This may be indicative of reduced predominance (or partial local suppression) of the expansion area under binocular viewing.

Our results suggest that for patients with normal binocularity and without strong ocular dominance, peripheral prisms can be fitted in front of either eye. However, fitting in front of the eye on the side of the hemianopia is generally recommended, especially if fitting press-on segments that extend across the entire lens, as in the original design (Fig. 2 in Peli or Fig. 1 in Bowers et al.), rather than the smaller precut segments that are now widely used (Fig. 2.1). If prism segments that extend across the whole lens are fitted in front of the eye on the side opposite to the HH, there is a possibility that the optical (apical) scotoma caused by the prism could reduce the temporal visual field, as the apex of the prism will be in the

monocular temporal crescent region of the field and thus will not be compensated by the other eye's field (Ross et al., 2009). However, if a prism segment spanning the full width of the lens is fitted in front of the eye on the side of the HH, the prism apex will be placed nasally and the apical scotoma will likely be compensated by the normal hemifield of the other eye. With both the smaller 22-mm-wide precut press-on and permanent segments, the apical scotoma usually falls within the area of the binocular overlap of the seeing hemifields and is compensated for by the non-prism eye, as was the case in this study.

For patients with abnormal binocularity and/or strong ocular dominance, the likelihood of reduced predominance or local suppression of the prism image needs to be considered. Therefore, preference should be given to fitting peripheral prisms in front of the dominant eye, while still considering the possible impact of the apical scotoma (Ross et al., 2009). It is also important to ensure that the eye in front of which the prism is fitted has sufficient remaining visual field to encompass the prism-shifted images from the blind hemifield.

This study is a first step in evaluating detection performance with peripheral prism glasses using more complex patterned backgrounds than the uniform backgrounds typically used in conventional perimetry. The results from participant 10 clearly demonstrate the advantage of using a rivalrous background rather than a plain uniform gray background when the goal of the perimetry assessment is to predict functional performance in real-world situations. On the uniform gray background, detection rates were similar in the prism expansion area and the seeing hemifield for both monocular and binocular viewing. However, on the patterned background, there was evidence of reduced predominance (or local

suppression) of the prism image in binocular viewing.

Our results suggest that, in binocular viewing conditions, neither reduced predominance nor exclusive local suppression of the prism expansion area occurs for patients with normal binocularity. Comparable results were recently reported for a similar paradigm, but using natural image backgrounds rather than patterned backgrounds (Shen et al., 2011). These findings are confirmatory of the subjective reports of the utility of the peripheral prism glasses in real-world situations (Peli, 2000; Bowers et al., 2008; Giorgi et al., 2009; O'Neil et al., 2011). In future studies, we will increase the reality of the test conditions to bring them closer to those experienced in everyday dynamic environments by using motion video backgrounds (Shen et al., 2011).

CHAPTER 3. CONSIDERING APICAL SCOTOMAS, CONFUSION, AND DIPLOPIA WHEN PRESCRIBING PRISMS FOR HOMONYMOUS HEMIANOPIA

3.1 ABSTRACT

Purpose. While prisms are commonly prescribed for homonymous hemianopia (HH) to extend or expand the visual field, they cause potentially troubling visual side effects, including non-veridical location of perceived images, diplopia, and visual confusion. In addition, field behind a prism at its apex is lost to an apical scotoma equal in magnitude to the amount of prism shift. The perceptual consequences of apical scotomas and the other effects of various designs were examined in detail and quantitatively to consider parameters and designs that can mitigate the impact of these effects.

Methods. Various configurations of sector and of peripheral prisms were analyzed, in various directions of gaze, and their visual effects were illustrated using simulated perimetry. A novel diagram (the percept diagram) is introduced that yields insights into the patient's view through the prisms. The predictions were verified using perimetry with HH patients wearing the various designs.

Results and Conclusions. The diagrams distinguish between the potentially beneficial field expansion effect of visual confusion (different images seen in the same apparent direction) and the disturbing (pericentrally) and useless effect of diplopia (same image seen in two places), and their relationship to prism powers and gaze directions. They also illustrate the non-expanding substitution of field segments of some popular prism designs. Yoked sector prisms have no effect at primary gaze or when gaze is directed toward the seeing hemifield,

and they introduce pericentral field loss when gaze is shifted into them. When fitted unilaterally, these sector prisms also have an effect only when the gaze is directed into the prism and may cause a pericentral scotoma and/or central diplopia. Peripheral prisms are effective at essentially all gaze angles. Since gaze is not directed into them, they avoid problematic pericentral effects. We derive useful recommendations for prism power and position parameters, including novel ways of fitting prisms asymmetrically.

Translational Relevance. Clinicians will find these novel diagrams, diagramming techniques, and analyses valuable when prescribing prismatic aids for HH and when designing new prism devices for patients with various types of field loss

3.2 INTRODUCTION

Homonymous hemianopia (HH), the loss of half the visual field in both eyes on the same side and to similar extent, results from postchiasmatic lesions typically caused by stroke, tumor, or trauma (Zhang et al., 2006b). Hemianopic visual field loss reduces detection of objects in the blind hemifield and impacts the ability to avoid obstacles while walking and driving (Papageorgiou et al., 2007; Bowers et al., 2009; Gall et al., 2010).

Spectacle-mounted prisms are the most commonly used rehabilitation devices for HH. There are various designs and methods for fitting prism spectacles. All involve tradeoffs between the access to otherwise invisible areas of the visual scene and the various potentially troubling visual side effects the prisms introduce. While the prism apical scotoma has been mentioned in the literature (Bailey, 1978; Perlin & Dziadul, 1991; Cotter, 1995b; Cohen & Waiss, 1996; Dickinson, 1998b), its functional significance has not been addressed, nor has its impact on the residual visual field been illustrated. This paper examines common prism

configurations used for HH, and primarily analyzes the oft-ignored, but important, effect of prism apical scotomas. Other effects, such as the diplopia and visual confusion induced in some configurations and the non-veridical views created by all designs are also addressed, and their impact is illustrated in a novel way. Careful fitting design based on the parameters and diagrams provided here can mitigate these effects. The analyses will also provide practitioners insights into why some configurations may be accepted and valued more than others by their patients. Novel designs emerged from these analyses, described in the sections on offset sector and peripheral prism placement.

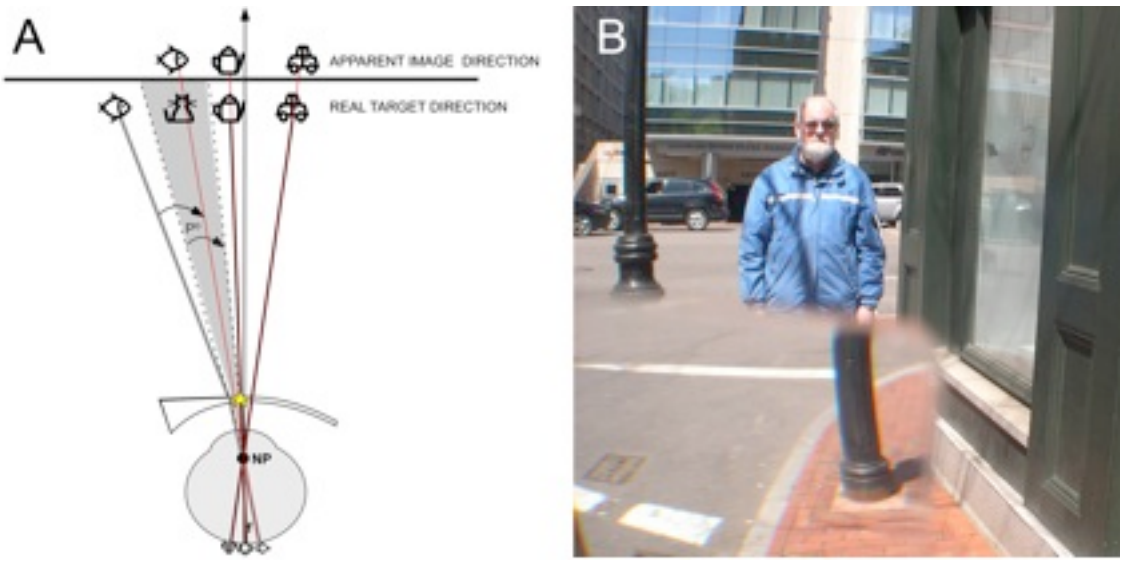


Figure 3.1. Apical prism scotoma. (A) Schematic ray diagram of the apical scotoma of a sector prism. The apical scotoma occurs between the last undeviated ray and the first adjacent light ray which is deviated by the prism (prism apex highlighted by yellow star). The angle between these two light rays is equivalent to the prism power in degrees. In this example, the cat is not visible through the prism, since it is located within the prism's apical scotoma, indicated by the gray shading. (B) Photograph taken with a 30Δ prism with base to the left covering most of the lower left quadrant of the frame. The prism extends the camera's field of view to the left, revealing crosswalk left of the lamppost, but loses field at its apex, as the lower half of the man is now missing. Had the prism extended the full height of the image, the man would be lost completely to the apical scotoma. The aperture of the camera lens creates vignetting at the prism edges.

The bending of light rays by a prism creates a gap in the visible field of view between the last undeviated ray just outside the prism, at its apex, and the first ray deviated by the prism (Dickinson, 1998b). The angular extent of that gap is equal to the prism power in degrees (Fig 3.1A). That gap is referred to as the apical scotoma. The perceived (retinal) field of view is still fully covered by rays from portions of the external field, but the view from within the scotoma is missing, obscured by the prism itself. Thus, this ‘‘scotoma’’ is a gap in the portion of the external world view that is seen, not a blind retinal area. The retinal image is discontinuous, but has no blanks. (If a prism is replaced by an opaque occluder, visual field equal in width to the visual angle the occluder subtends would be lost behind the occluder. With a prism, the field blocked by the prism beyond the apical scotoma is seen at the prism apex; hence, the apical scotoma is the only loss.) The effect is illustrated photographically by holding a prism in front of a camera lens (Fig 3.1B).

All of the prism configurations to be discussed cause portions of the world view to appear in nonveridical directions; the apparent location through the prism is displaced from the true direction (e.g., the lower portion of the lamppost in Fig. 3.1B).

When prisms are placed bilaterally for HH, with essentially the same position and coverage for each eye, the prism apical scotomas induce a gap in the visual field. When placed monocularly (or at different relative positions on each carrier lens), it is possible for the view of one eye to include field portions missing to the apical scotoma of the fellow eye. These configurations produce areas of visual confusion, in which two different views are seen at the same apparent direction by the two eyes, and some produce diplopia, wherein a given object or portion of the scene is seen in two different directions simultaneously. We

avoid using the term ‘‘double vision,’’ as it has been ambiguously applied in the literature to include or exclude confusion and diplopia.

If the total field area available (at a given direction of gaze) is larger than the hemifield available without prisms, we deem this to be true field expansion. Semitransparent mirrors have been used to provide true expansion (Goodlaw, 1982), but they are bulky, unsightly, and add the disorientation of a reversed view to the visual confusion. They are now rarely used and are not discussed further here. As will be seen below, true expansion is possible with prisms, but only if they are fit asymmetrically, or monocularly, so that different portions of the field are available to each eye (albeit with some visual confusion).

Most bilateral prism designs provide field substitution rather than expansion: The total area visible at any time is no greater than without prisms; the area shifted into view displaces an equal amount of the unaided view, creating an optical scotoma in the field—the apical scotoma. We also avoid the term ‘‘field enhancement’’, as it is ambiguous with respect to these important distinctions.

If prisms cover the entire field of view (as happens with bilateral full-field yoked prisms (Cohen, 1993; Cotter, 1995b; Cohen & Waiss, 1996)), field shifting, without expansion or substitution, occurs. Field shifting is of no value for patients with HH, as normal fixation, head, and eye movements will negate it to bring the view straight ahead into primary gaze. The prism configurations discussed here (sector and peripheral prisms) do not span the full field horizontally, so the placement of the prism apices becomes a critical design element, affecting the role the apical scotomas play in the patient’s experience, as well as the location of regions of visual confusion and diplopia. (The prism bases are set far into the

blind side, where they are rarely in view.) Visual confusion is a necessary consequence of prismatic field expansion. It is more readily tolerated in the periphery than in central vision. Confusion and diplopia are very disturbing centrally (parafoveally), while they are normal in the periphery (Bishop, 1998). Prism-induced diplopia anywhere, however, represents a waste of prism power that could be better used for expansion (or substitution), as will become apparent below.

In the subsequent sections, we identify the parameters that affect optimal positioning and power for each of the common methods of fitting prisms, and discuss their implications in terms of field expansion or substitution and troublesome perceptual effects including apical scotomas, diplopia, and visual confusion. Often confusion and diplopia are thought to coexist, but these analyses make clear how independent these phenomena can be. The examples are illustrated using predicted/calculated and actual visual field diagrams from patients, and we introduce a new visual field representation technique, the percept diagram, to describe the patient's binocular view through the prism spectacles.

3.3 METHODS

Calculations used to predict Goldmann visual field diagrams and the associated percept diagrams for each prism configuration, as well as to manufacture the corresponding spectacles used, assume that the nodal point distance (NPD) between an eye's nodal point and the cornea is 7.1 mm (Gullstrand's Schematic Eye (Fannin & Grosvenor, 1996)) and the back vertex distance (BVD) between the cornea and the carrier lens is 13 mm. Formulas used for these calculations are provided below. The visual angle (A^o) between primary gaze and the prism apex is given by *Equation 3.1*, where L is the distance (mm) on the carrier lens

from the intersection of the visual axis (in primary gaze) to the prism apex. Nodal point is used when calculating visual field angles, while center of rotation (*CR*, assumed to be 13.5 mm from the cornea) is substituted for *NPD* when calculating eye rotations. The conversion of prism power from prism diopters (P^{Δ}) to degrees (P^{o}) is given by *Equation 3.2*.

Equation 3.1

$$A^{o} = \tan^{-1}\left(\frac{L}{BVD + NP\ D}\right)$$

Equation 3.2

$$P^{o} = \tan^{-1}\left(\frac{P^{\Delta}}{100}\right)$$

A conventional Goldmann visual field diagram provides information about which portions of the external visual field are detected by the visual system (in primary gaze). In this paper, we use Goldmann visual field measurements to identify the portions of the external field that are seen (and unseen) when various prism configurations are used and in various directions of gaze, not to map visual system status. To cover the range of configurations tested (not for between–subject comparisons), prism spectacles were worn by three individuals with complete HH. The spectacles were fit according to common clinical practice for each of the designs.

We also introduce a synthetic variant of the Goldmann diagram to illustrate the visual field as it would be seen by the prism wearer. We call this a percept diagram (although, to be precise, it shows what is available on the retinas to be perceived, not necessarily what is perceived, as binocular post-retinal factors such as suppression may intercede). A percept diagram illustrates what the world would look like if the world were a Goldmann grid; as if

the patient is inside a huge sphere marked with radial lines and concentric circles originating at primary gaze. Figure 3.2A is the percept diagram for the prism photo in Figure 3.1B. The percept diagram is a handy way to understand the nonveridical views that prisms introduce. The percept diagrams make it easier to see where visual confusion is introduced and the nonveridical perceived directions of objects, while the Goldmann perimetry diagrams make it easy to note field substitution or expansion, diplopia, and field-of-view losses due to apical scotomas. Figure 3.2B gives the simulated Goldmann diagram that corresponds to this percept diagram. It is the diagram, which would result if the camera could respond to Goldmann stimuli with the prism configuration of Figure 3.1B interposed. The simulated Goldmann diagram gives a clear understanding of the field substitution the prism provides as well as the loss of field at the prism apex. The diagrams below illustrating the effects of various prism configurations will, of course, show the limits of a subject's visual fields, not the camera's. Details of many of the diagrams will benefit from the magnification provided by viewing this document at full screen width.

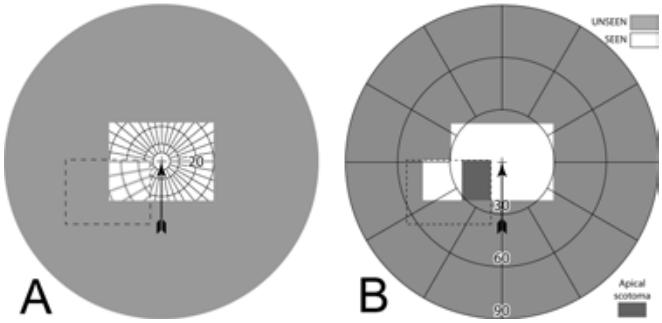


Figure 3.2. Introduction to the percept diagram. (A) This percept diagram represents the way a Goldmann grid would be captured by a camera with a 30Δ prism interposed as in Fig. 1B. The area outside the camera's field of view is shaded. The arrow points to the center of the field of view (the fixation or "gaze point"). The arrow is not included in subsequent percept diagrams, as fixation is always in the center, although the grid cross will appear off center when diagramming averted gaze views. A dashed line (not part of the percept) outlines the prism location. Its left and lower edges are outside of the camera's field. The base-left prism has allowed a portion of the grid otherwise outside the camera's field on the left to be visible to the camera. The lines in the prism view have been blurred slightly, not just to represent the loss of quality that occurs through prisms, but

also as a diagramming aid to differentiate the shifted and unshifted areas. The wider spacing in that area is due to its view of more peripheral grid, not magnification. A 16.7° wide rectangular patch of grid is missing at the prism apex. That is the apical scotoma. (b) The Goldmann diagram that would result if the camera could respond to Goldmann stimuli with a prism similarly interposed. The simulated Goldmann diagram clearly shows the effect of the apical scotoma, shaded in darker gray for emphasis. The prism has substituted the field of view to the left, with a resulting loss of pericentral view.

All calculated diagrams assume a pinhole pupil, so they do not include the transition vignetting effect of a larger pupil (exaggerated by the larger camera aperture in Fig.3.1B), nor do they include the fringes of color or the other known optical distortions that prisms induce, as these are not generally factors considered when fitting prisms for HH(Morgan, 1963; Katz, 2004b). The simulated Goldmann diagrams, and those of patients wearing the prisms, are dichoptic, representing separately what each eye sees when both are viewing. Although we have developed perimetry systems that actually measure dichoptically (Woods et al., 2010; Satgunam, Apfelbaum & Peli, 2012), most patient diagrams here are actually a synthesis of three separate diagrams, with OD, OS, and OU measured separately and then combined (the OU diagrams were necessary to identify diplopia and confirm binocular scotomas). This technique provided wider plots than are possible when wearing the goggles used in our dichoptic perimeters. Figure 3.3 illustrates the diagram notations and the distinction between binocular and dichoptic perimetry.

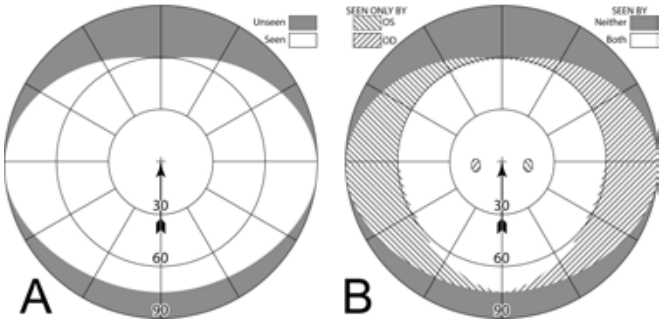


Figure 3.3. Simulated normal Goldmann fields. (A) Binocular (B) Dichoptic (or superimposed separate OD and OS)

All procedures were conducted according to the tenets of the Declaration of Helsinki, and the protocol was approved by the Schepens Eye Research Institute Institutional Review Board. Informed consent was obtained from all subjects.

3.4 SECTOR PRISM SPECTACLES FOR HEMIANOPIA

3.4.1 Bilateral Sector Prisms

Yoked bilateral sector prisms, up to 20Δ (Rossi et al., 1990) (and rarely 30Δ) (Jose & Smith, 1976; Smith et al., 1982; Hoppe & Perlin, 1993), were one of the first designs of prism spectacles prescribed for hemianopia (Wiener, 1925; Young, 1929), and have been prescribed frequently since (Weiss, 1972; Perlin & Dziadul, 1991; Dickinson, 1998b; Lee & Perez, 1999; Somani, Brent & Markowitz, 2006). In this design, prisms usually extend the full height of the carrier lens, covering about a full half of each lens on the side of the blind hemifield (Fig. 3.4A,B). For this patient with left hemianopia, the prism bases are directed toward the left, so that when looking into the prisms, images of objects in the blind hemifield are shifted into the right seeing field.

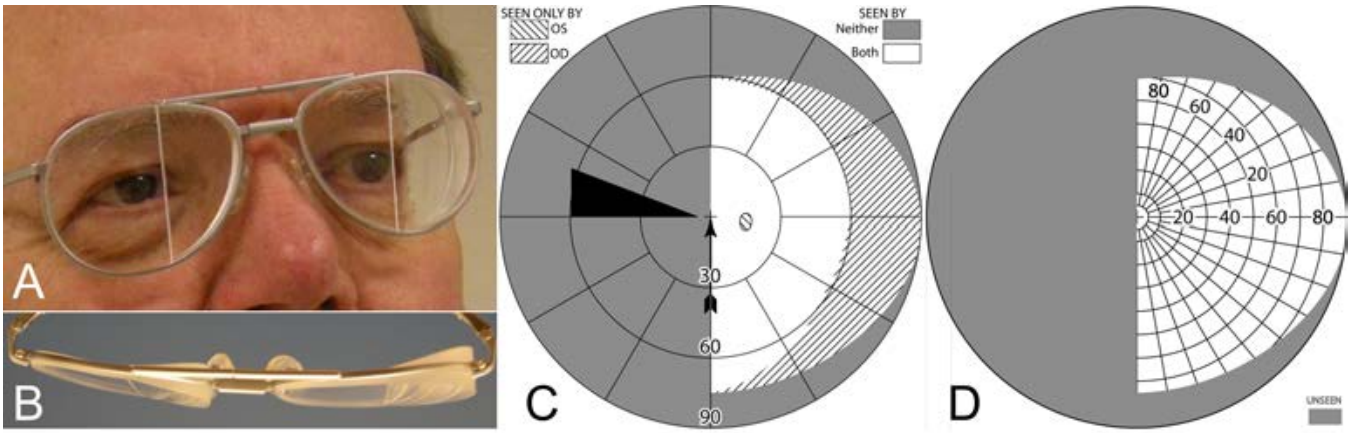


Figure 3.4. Bilateral sector prisms. (A & B) The prism bases are placed toward the blind side, shown here with base left. The prism apices are placed left of primary gaze by 2.1 mm. (C) Dichoptic simulated Goldmann diagram at primary gaze with these bilateral 20Δ sector prisms. The prisms have no effect, as they are entirely in the blind hemifield, so this is simply the same as a diagram of a left hemianope without prisms. The black triangle is included to indicate the prism orientation and apex location, but not its size. The arrowhead indicates the gaze point. (D) Corresponding percept diagram. It, too, is exactly the same as a diagram of a left hemianope without prisms.

The prism apices are typically offset away from the seeing field, although the recommended offset varies considerably, from 1.5 mm (Cotter, 1995b) to 6 mm (Bailey, 2007). Often clinicians offset the prisms, such that a 58^{o} ocular rotation into the blind side is required to reach the prism segment (Perlin & Dziadul, 1991) (~ 2.3 mm). As a result of that placement, the prisms are not visible to the wearer at primary gaze (or when gazing in the direction of the seeing hemifield), and do not alter the normal hemianopic Goldmann visual field diagram (Fig.3.4C). When the wearer glances into the prisms, objects may be viewed through the prisms with less of an angular eye shift than would otherwise be needed. Since high-power prisms can be quite bulky, prisms are generally limited to 20Δ (Perlin & Dziadul, 1991; Bailey, 2007), yielding a field shift of about 118. Less bulky press-on Fresnel prisms are also available, but their poorer optical quality (Katz, 2004a) and need for frequent replacement limit their application to temporary fitting, allowing a patient to experience prisms before more expensive prism spectacles are prescribed.

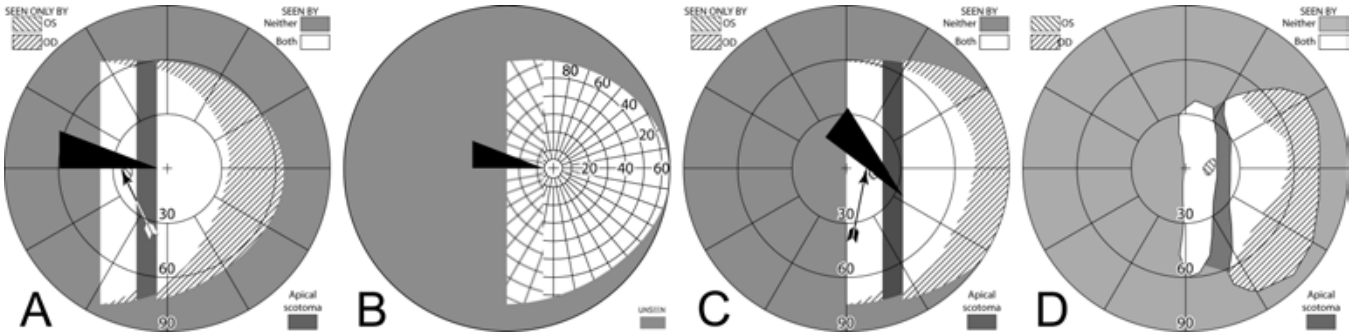


Figure 3.5. Gazing 20° into bilateral 20Δ sector prisms. (A) Simulated Goldmann diagram with the prism configuration of Fig. 4 and the patient facing the fixation target but gazing left into the prisms by 20°, for a total gaze shift of 26°. The arrow is rotated counterclockwise at the gaze point into the prism to indicate the 26° angle of incidence (from perpendicular) of the gaze. A 20°-wide region of field from 17° into the blind hemifield is visible (6° to the prism apex plus 11° of prism shift), but the 11° just left of the prism apex is missing due to the apical scotomas. Since the gaze is shifted left, some of the right far periphery has been lost from view. (B) The corresponding percept diagram shows that the patient sees 20° of field shifted from 11° farther left, but there is a discontinuity where 11° of pericentral view has been lost to the apical scotomas. The triangle is also shown here to indicate the location of the prism apex. Fixation is at the lower intersection of the triangle and the hemifield margin. (c) In order to provide a fixation reference when gazing into the prism, it is necessary to perform Goldmann perimetry with the patient's head turned right so that the gaze falls on the shifted view of the perimeter's fixation target. A simulation of a field diagram taken that way is shown in (C). We have rotated the prism symbol clockwise about the gaze point to indicate the magnitude of head rotation to the right needed to see the fixation target with a 20° gaze into the prism (37°; 6° to the prism plus 20° into the prism plus 11° of prism shift). The arrow rotation indicates the gaze incidence at the prism. (D) An actual Goldmann visual field diagram taken this way. This patient has overall restricted peripheral fields on the seeing side in addition to the hemianopia. The measured apical scotoma is highlighted in dark gray.

Figure 3.5A simulates the Goldmann diagram that would result if the patient is facing the Goldmann perimeter's fixation target but gazing left 20^{o} into 20Δ (~ 11^{o}) prisms with apices shifted left 2.1 mm (~ 6^{o}). In this and all subsequent diagrams illustrating averted gaze, eye rotation would move the eye's nodal point slightly away from the center of the Goldmann bowl. To avoid the complexities in interpretation (and diagramming) that change induces, the diagrams are based on rotations about the nodal point, not the center of rotation. In actuality, only 20.3^{o} of ocular rotation is needed to achieve the 26^{o} view change. We provide diagrams with gaze shifts this large as an upper limit; saccades larger than 15^{o} are infrequent (Bahill, Adler & Stark, 1975; Luo, Vargas-Martin & Peli, 2008), and we have

found no reports documenting an ability of scan training to alter this. Averted gaze representations are provided as an aid to estimating effects of eye (but not head) movements.

To the immediate right of the gaze point the patient sees the 20^{o} wide section of the Goldmann perimeter that is shifted from a region 11^{o} farther left. Eleven degrees of the perimeter to the left of the prism apices is unseen (the apical scotomas) while the 6^{o} between the prism apices and the fixation target are seen directly, as is the remaining portion of the patient's field to the right of that. Since the patient is gazing left a total of 26^{o}, portions of the Goldmann hemifield beyond 64^{o} (nominally) at the extreme right are invisible. The corresponding percept diagram is shown in Figure 3.5B. The field substitution through the prisms is apparent, as is discontinuity and partial loss of field behind the prisms (due to the apical scotomas).

However, it is not practical to perform actual Goldmann perimetry this way. Since the patient is gazing into the prism, away from the fixation target, there is no reference point on the blank Goldmann dome to serve as a target and stabilize fixation. Instead, we had the patient turn his head (and the prism-bearing spectacles) sufficiently to the right so that the fixation target was viewed through the prisms when gazing $20^{\mathbf{o}}$ (in this example) into the prisms. The calculated Goldmann diagram in that situation is shown in Figure 3.5C. (It may be easier to think of this as having the patient maintain a fixed head position, while the Goldmann perimeter is rotated until the fixation target is foveated with gaze averted $26^{\mathbf{o}}$ (Good, Fogt, Daum & Mitchell, 2005). Of course, it is more practical for the patient to turn within the chin rest.) A binocular Goldmann diagram with the patient's head turned in this way is shown in Figure 3.5D. Note that the measured apical scotoma does not appear as large

as the calculated scotoma, likely due to a combination of measurement error, vignetting, and slight misalignment of the prism apices between the eyes when the head is turned in this direction (but see Fig.3.9 for a way that ‘‘misalignment’’ can be an advantage).

A similar set of diagrams is given in Figure 3.6, with gaze shifted only 5^{o} into the prisms (requiring 11^{o} shift from primary gaze). Since the amount of eye movement is smaller, the apical scotoma is closer to the center of gaze, where it may have a more deleterious impact.

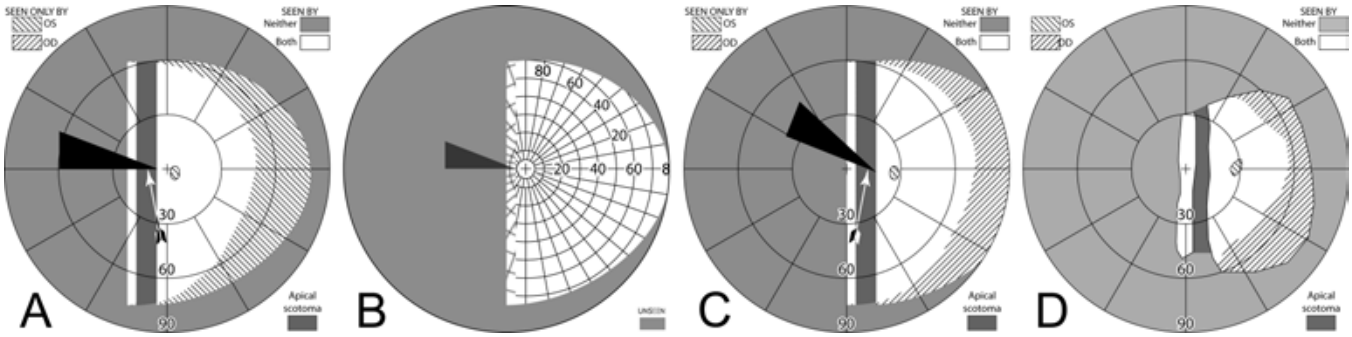


Figure 3.6. Gazing 5^{o} into bilateral 20Δ sector prisms Diagrams corresponding to those in Fig. 3.5, but with a gaze of only 5° into the prisms. (A) Simulated Goldmann with head straight. (B) Percept diagram. (C) Simulated Goldmann with head turned 22° (6° to the prism plus 5° into the prism plus 11° of prism shift) so that a gaze shift of 11° (6° to the prism and 5° into the prism) enables the Goldmann fixation target foveation through the prism. (D) Actual Goldmann visual field measured that way. Although the gaze had to be averted 11° to achieve a 5° sliver of field substitution, 11° are still missed pericentrally (the apical scotoma).

Thus, bilateral sector prisms provide no benefit at primary gaze, but provide access to portions of the blind hemifield with less eye rotation (by the amount of prism power in degrees) than would be required without prisms. However, while gazing into the prisms, a vertical swath of visual field, also the width of the prism shift, is missed between the shifted and unshifted views due to the apical scotomas. The field thus lost includes pericentral areas important for safe mobility (Lovie-Kitchin, Mainstone, Robinson & Brown, 1990). The apical scotomas and large gaze shifts needed to achieve field substitution (but not expansion)

likely account for the paucity of reports of long term acceptance of this prism configuration. Some clinicians suggest that these prisms are training the patient to become aware of the blind area ‘‘by looking further into the prism or turning their head and viewing the object through the carrier portion of the spectacle,’’(Perlin & Dziadul, 1991) but we are not aware of any studies demonstrating a training effect.

In order to mitigate the effects of the apical scotomas, we next consider two alternatives to the common bilateral fitting of sector prisms. The first, unilateral fitting, has been used previously (Bailey, 1978; Gottlieb et al., 1992; Cotter, 1995b). The second, offset bilateral placement, is new and as yet untested clinically. It arises directly from our analyses of scotoma effects presented here. Neither of these configurations overcomes the lack of field expansion or substitution at primary gaze (or any gaze in the direction of the sighted hemifield), and they induce central and pericentral visual confusion when gaze is directed into them. Peripheral prisms, discussed later, overcome those limitations.

3.4.2 Unilateral Sector Prisms

If a sector prism of the type described above is fit on only one carrier lens (typically ipsilateral to the field defect; OS for a patient with left hemianopia), the nonprism eye can see some or all of the area lost to the prism eye’s apical scotoma. The region between the gaze point into the prism and the prism apex is seen unblocked by the prism by the nonprism eye, and is, thus, not lost in the binocular field to the scotoma. If the angle of gaze into the prism is less than the prism power, some scotoma will remain. If the angle of gaze into the prism is larger, there is an area of diplopia equal in width to the excess of the gaze angle beyond the prism power. In this and subsequent discussions, we assume that the patient is

orthophoric. Because the unilateral prism can dissociate binocularity, the actual binocular field results may vary with patient's phoria and eye dominance. Note, in this unilateral sector design too, the prism has no effect in primary position of gaze or when the patient gazes towards the sighted hemifield.

Figure 3.7 builds the percept diagram for the case in which the gaze angle into the prism is larger than the prism power. The fitting parameters are as above (gazing 20^{o} into a 20D prism offset 6^{o} from primary gaze). The fellow eye now sees the region lost to the apical scotoma of the prism eye, although there is visual confusion in that area and a 9^{o} wide area of diplopia. Confusion and diplopia around the gaze point can make it difficult for the patient to quickly interpret the view, and may result in suppression; thus, eye dominance and the overall binocular status of the patient may be important factors.

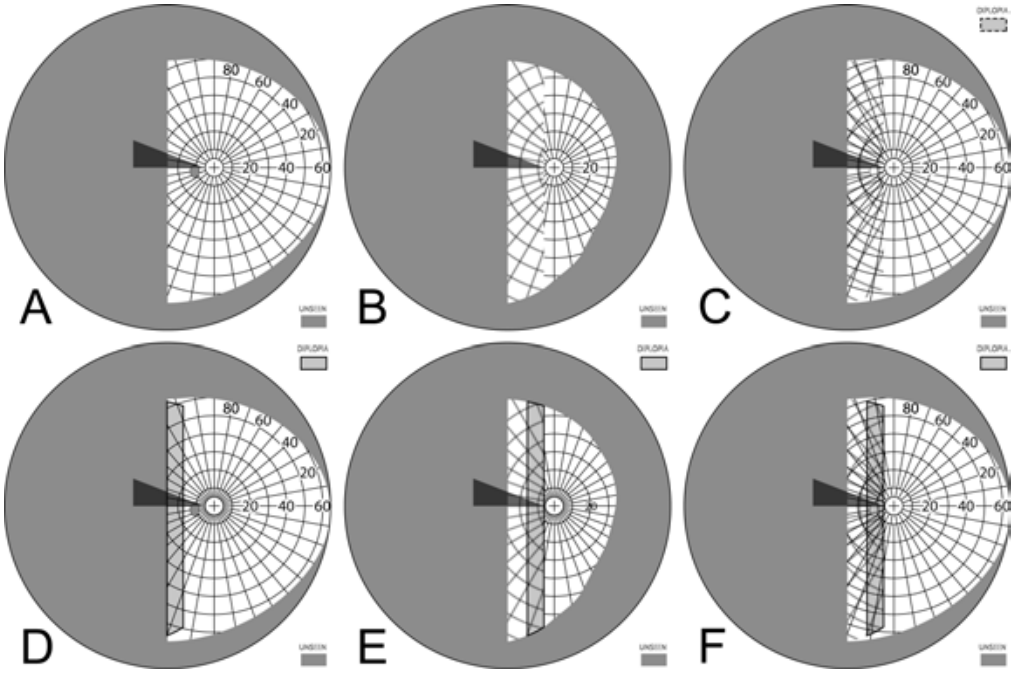


Figure 3.7. Building a percept diagram with confusion and diplopia. (A) The OD view, when the patient is gazing 20º into a 20Δ OS-only sector prism, is unaffected by the prism. (B) OS view. The view shifted through the prism brings 11º of the grid from the blind hemifield into view, while losing view of an 11º section at the apical scotoma. (C) Combined percept. There is visual confusion in the 20° section where OS sees through the

prism and OD does not. Although OS views 20° of field through the prism, only the leftmost 11° provide expansion. The remaining 9° seen by OS at the prism apex side are visible to OD, but are seen in a different apparent direction, and thus diplopic. At the prism apex OD sees the 11º degrees of field lost to OS by the apical scotoma. (The OD optic nerve head is outlined for clarity, but not likely perceived.) The OD-only view in (d) shades the portion of the OD field behind the OS prism that is seen diplopically, and the OS-only view in (e) shades the corresponding portion of the OS field. The field of view covered by the outlined areas in (D) and (E) is identical, but separated in the patient's view by the 11° prism power. In the final diagram (F), the outline for the diplopic region of only the prism view is shown, as that is the area in which diplopia is present without adding any expansion benefit, while the remaining areas of visual confusion are a necessary consequence of true field expansion. Central diplopia and confusion are annoying and confusing and thus poorly tolerated.

Figure 3.8A is the computed Goldmann visual field diagram analogous to Figure 3.5A, with the patient facing straight at the fixation light and gaze shifted 20^{o} into the prism. Figure 3.8C gives the calculated diagram analogous to Figure 3.5C, with the head rotated 26^{o} right, so that the left eye is gazing 20^{o} into the prism when the right eye is gazing at the fixation target. Figure 3.8D gives the actual patient results under that condition. As noted above, the calculated diagrams are created as if the nodal points of both eyes are at the perimeter origin; clearly impossible to actually achieve. However, in the mobility situations where these diagrams are relevant, the distance to the targets of interest are so large that the distance between the eyes is inconsequential.

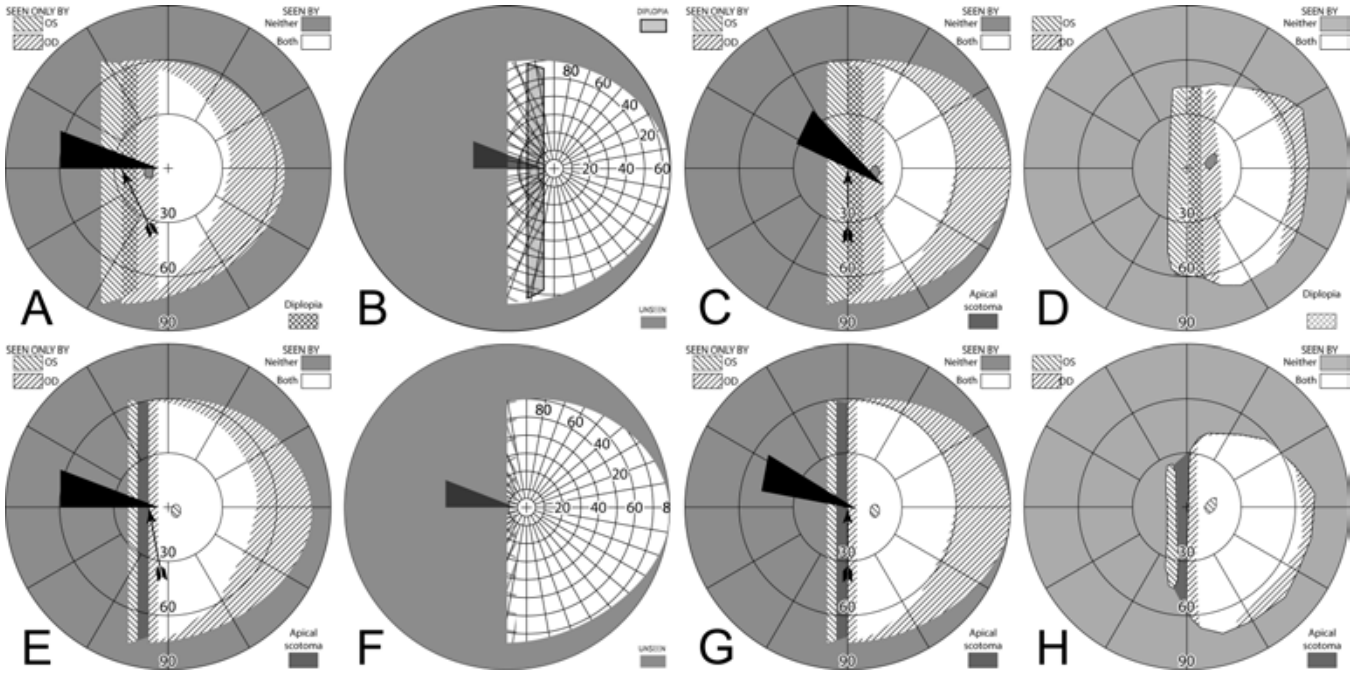


Figure 3.8. Unilateral sector prism. With a sector prism (of the type in Fig. 3.5) fitted on just one eye, the fellow eye sees some of or the entire region lost to the apical scotoma, albeit with visual confusion. (A-D) The calculated head straight Goldmann diagram, percept (from Fig. 3.7), and calculated head turned and actual Goldmann diagrams, respectively, when gazing 20° into the prism. 20° of field is shifted into view by the prism. The 11° prism scotoma region is visible to the fellow eye, but with 20° of visual confusion and 9° (20°-11°) of diplopia. In the Goldmann diagrams the diplopic area is cross-hatched. (E-H) Corresponding diagrams when gazing just 5° into the prism (yet 11° away from primary gaze, so 11° of field at the right periphery is lost); 5° of shifted field are viewed through the prism, and there is 5° of visual confusion, but no diplopia and only 5° of the apical scotoma has become visible to the non-prism eye.

Figures 3.8E through H are the corresponding diagrams when gaze is shifted just 5^o into the prism, where the amount of eye movement in degrees is less than the amount of prismatic shift. For a 5^o gaze shift into the prism segment (total 6^o + 5^o = 11^o shift from primary gaze), there is no diplopia, but the apical scotoma is present in the binocular view, as the nonprism eye sees only 5^o of the 11^o apical scotoma region, and that part is seen with visual confusion.

Thus, the unilateral sector prism design can reduce or eliminate the apical scotoma and provide some true binocular field expansion, not just substitution. However, the apical

scotoma does appear in the binocular view as the eye crosses the prism segment, until the amount of gaze shift is equivalent to or greater than the prism power in degrees. Furthermore, central and peripheral field confusion around the gaze point do occur, and as the gaze is shifted farther into the prism, central and peripheral diplopia ensue. The percept diagram shows these effects. Since this is the first example with confusion and diplopia, Figure 3.7 builds the diagram a step at a time, so the component effects are clearer. Subsequent diagrams will only show the compounded final effect. To best represent the situation the patient experiences, we do not use color to distinguish the OD and OS contributions to visual confusion. However, where this may be particularly hard for the reader to interpret, we have also provided magnified detail views with color. Nonetheless, since the perceived location of prism-induced diplopia is not readily identified in the Goldmann diagrams, we highlight it in the percept diagrams, even though that delineation, of course, is not apparent to the patient.

The Gottlieb prism design (Gottlieb et al., 1992) differs from unilateral sector prisms, in that only a circular cutout of the sector prism is used. The prism apex is placed at the limbus, and is, thus, offset by about 6 mm ($\sim 13^{o} = \tan^{-1}(6/(CR+BVD))$), which is a larger angle than 97% of natural saccades (Bahill et al., 1975; Luo et al., 2008). The prism is intended to be used during brief glances to aid in locating objects of interest. Its smaller size makes it lighter weight and perhaps less conspicuous (better cosmetics), losing some peripheral areas of a full sector prism that are arguably less important. The main optical effects, however, are identical to those of a unilateral sector prism within the coverage area of the Gottlieb prism.

3.4.3 Offset Bilateral Sector Prisms

To avoid the pericentral and central diplopia that accompanies unilateral sector prisms (when in gaze), bilateral prisms can be offset so that the apical scotoma for each prism lies in a different portion of the binocular visual field. If the offset is exactly equal to the prism power, no portion of the field will be completely lost within the apical scotomas of both prisms simultaneously, as illustrated in Figure 3.9. The extent of coverage is identical to that provided by the unilateral and conventional bilateral configurations. There is true binocular field expansion when the eyes are turned far enough to be gazing into one or both prisms. Visual confusion is substituted for the apical scotomas of the conventional bilateral configuration and the diplopia of unilateral fitting. There is still no field expansion at primary gaze, making this (as yet untested) configuration less desirable than the peripheral placement of prisms described next. The central confusion that remains with this design, though preferable to diplopia that does not contribute anything to field expansion, is not less annoying or bothersome than central diplopia.

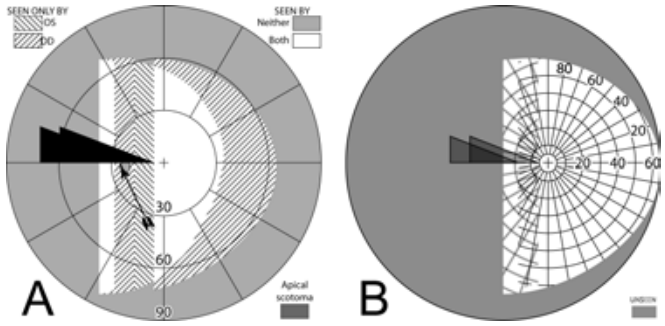


Figure 3.9. Offset placement of bilateral sector prisms can avoid diplopia. This is illustrated for a gaze 20° into 20Δ sector prisms. The OD prism has the conventional 6° offset from primary gaze, while the OS prism is offset the additional 11° of the prism power. Although field extent is identical, the pericentral scotoma of the conventional bilateral fitting (Fig. 3.5) is gone, as is the diplopic area of unilateral fitting (Fig. 3.8), though central confusion remains. (A) Simulated Goldmann (with head straight). (B) The percept diagram shows that a region of visual confusion exists where OD is viewing through a prism and OS is not. The apex of the leftmost triangle in each diagram identifies the location of the OS prism apex.

3.5. PERIPHERALLY-PLACED PRISM SPECTACLES FOR HEMIANOPIA

Also known as EP Prisms or Peli Prisms(Peli, 2000), the peripheral prism spectacle design uses high power prism inserts placed in upper and lower peripheral parts of a carrier spectacle lens (usually in Fresnel format), with a clear central area in between (Fig.3.10A). The commercially available rigid permanent prism segments extend 22 mm across and 8 mm high, with the center of the prisms generally placed above and below the patient's pupil center when in primary gaze. A typical interprism separation of 12 mm34 leaves a clear central field approximately 17^{o} ($\tan^{-1}(6/(NPD+BVD))$) above and below primary gaze.

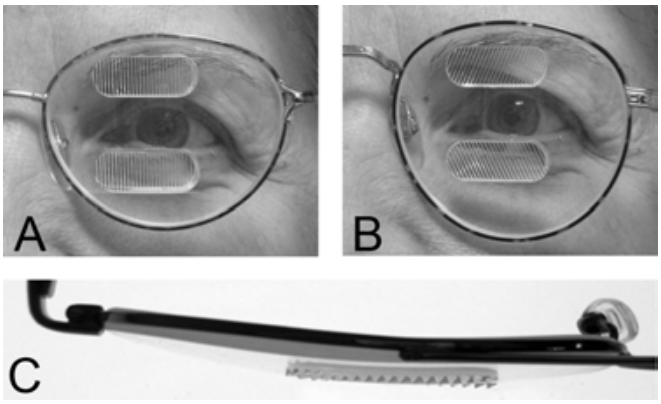


Figure 3.10. 57Δ horizontal EP Prism glasses (A) have a horizontal apex-base axis, while 57Δ oblique EP Prism glasses (B) tilt the apex-base axis approximately 25°. (C) A bird's-eye view of the horizontal EP.

Since the prisms extend left and right of primary gaze, prism-shifted images are continuously present in the patient's superior and inferior peripheral vision, providing visual field expansion in these areas at essentially all directions of lateral gaze; thus, augmenting the natural ability of peripheral vision to capture attention on the blind side. This differs from the sector designs, where the prism-shifted images are only visible when the patient's gaze is shifted into the prism segment. Since the prisms do not block pericentral vision (and gaze is not intentionally directed into the prisms), any diplopia, visual confusion, and scotomas that

the prisms may induce are confined to the upper and lower peripheral retina, where they are more readily tolerated (Blake, 2001). Binocular foveal fusion is maintained; thus, this design is not affected by patient's phoria or binocular status. The peripheral prisms design was found to be effective in single (Giorgi et al., 2009; O'Neil et al., 2011) and multicenter (Bowers et al., 2008; Bowers et al., 2013) clinical trials. Since Fresnel prisms are thinner and lighter than regular ophthalmic sector prisms, and the reduced optical quality is not as disturbing in the periphery as it would be in the fovea, prism powers (and the concomitant benefits) can be much greater, with 40Δ or even 57Δ typically used. They can be fit in either a horizontal (Peli, 2000) or in an oblique design (Peli et al., 2009; Bowers, Tant & Peli, 2012) (Fig.3.10).

3.5.1 Horizontal Peripheral Prism Spectacles

The bases of horizontal peripheral prisms are placed toward the blind hemifield to provide field access to areas in the blind hemifield horizontally in line with the prisms. (Like the sector prisms, the apex base axis is horizontal, parallel to the 180^{o} meridian.) Prisms of 40Δ and 57Δ provide shifts of 22^{o} and 30^{o}, respectively, and prisms can be fit unilaterally or bilaterally. While it is preferable to fit patients with the 57Δ peripheral prisms, as they provide more field expansion, press-on temporary prisms are only available up to 40Δ. Thus, 40Δ press-on Fresnel prisms (available precut to the same size as permanent prisms) are recommended for initial prescription by the clinician on a trial basis before prescribing higher powered permanent Fresnel prisms. Higher prism powers have correspondingly larger apical scotomas, but as shown below for unilateral fitting, that can be turned into an advantage.

3.5.2 Unilateral Horizontal Peripheral Prisms

Peripheral prisms are more commonly fit unilaterally, usually placing the prism on the lens ipsilateral to the side of visual field loss and with the base always to that side. One eye has access to portions of the blind hemifield (via the prisms), while the other eye can still see objects within the intact seeing hemifield that may otherwise not be seen due to the apical scotomas.

When fitting a patient with unilateral peripheral prisms, an apical scotoma is not present in the binocular visual field. If the prisms are fit as recommended, with the center of the prism segment aligned with the patient's pupil center, the field lost to the apical scotomas will be located within an area of the patient's seeing hemifield; thus, visible to the fellow nonprism eye. The 11 mm half-width of an EP Prism subtends about 29^{o}, closely matching the 57Δ apical scotoma of 29.7^{o}. Figure 3.11 illustrates the percept and predicted visual field diagrams for a patient with left hemianopia wearing unilateral horizontal peripheral prisms. The lateral extents of the prism expansion areas in the left visual field are determined by the prism power, while the vertical extents are determined by the height of the prism segments. The prisms result in two areas in the seeing hemifield that are seen by the right (nonprism) eye only; the prism apical scotomas. With 40Δ prisms, there is also an area of the visual field in the seeing hemifield that is visible to both the prism eye and the fellow eye, resulting in peripheral diplopia.

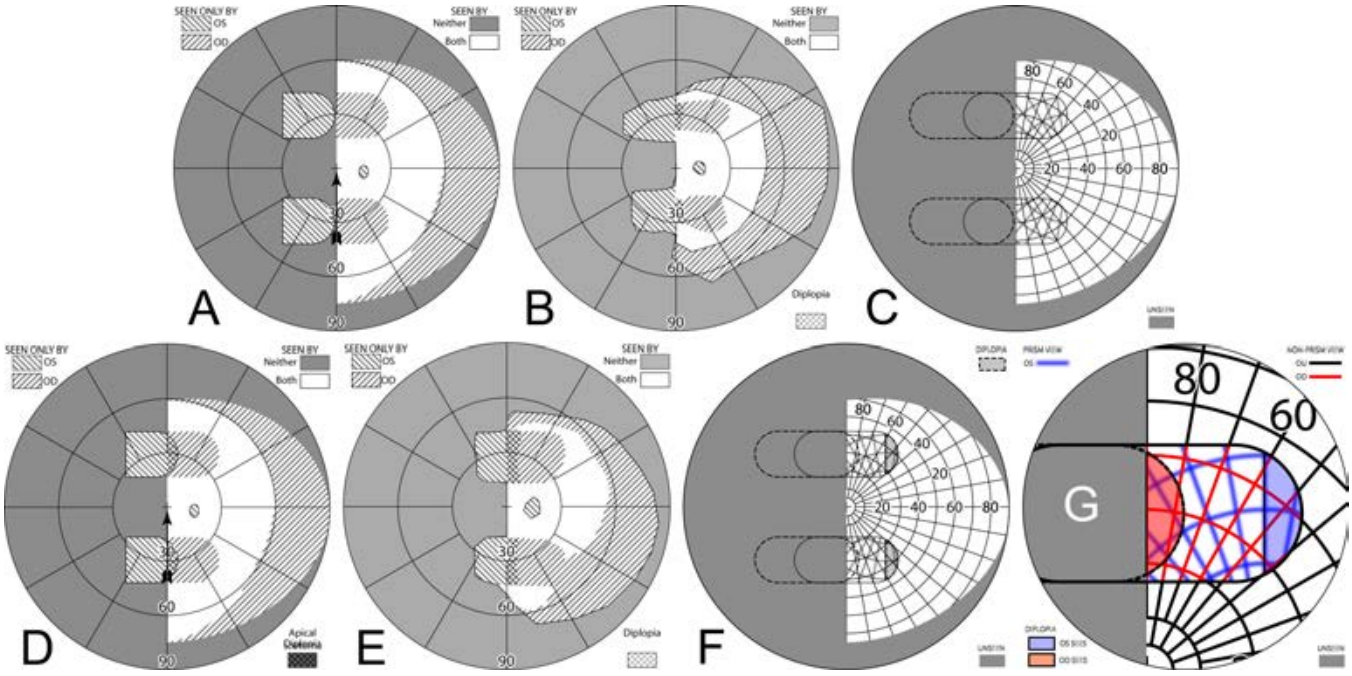


Figure 3.11. Unilateral peripheral prisms. **(**A–C) Forward gaze with unilateral 57Δ EP Prism glasses. (D–F) The corresponding diagrams with 40Δ prisms. (A) Simulated Goldmann visual field. The left eye sees regions shifted from 30° left, while the right eye maintains a view of the regions blocked by the left eye's prisms' apical scotomas. Since the monocularly-viewed regions do not overlap, there is confusion but no diplopia, and there is a small gap between the expansion area and the normal seeing hemifield. (B) Actual composite field diagram from a patient. Imprecision in measurements or different fitting parameters result in a small region of apparent diplopia. (C) The corresponding percept diagram shows that there is visual confusion in the peripheral prism regions (where it is reasonably tolerated). The patient does not intentionally gaze into the prisms, but activity or objects there can alert the user and cause a gaze shift into the blind hemifield, possibly adjusting head direction slightly to view the area of interest centrally and not through the prisms. Dashed outlines indicate the source of the prism views. For simplicity and clarity, we plot rounded rectangles as the projected shape of the prisms. In actuality, they would appear slightly trapezoidal, with slightly curved horizontal edges. (D-F) With the lower-power prisms, the diplopic area, where the prism view includes portions of the normal seeing hemifield, is larger, since the prism power is less than the angular size of the visible portion of the prisms. Diplopia crosshatching in the clinical perimetry is based on the overlap found in monocular OS and OD diagrams, but was not actually reported by the subjects, which we take as another indication of its inconsequence peripherally. Diplopia in the percept diagram is outlined and lightly shaded in prism view locations where it offers no expansion benefit. (G) Annotated detail of the upper prism area of (f), with color coding to identify the contribution of each eye to the visual confusion and diplopia. The area behind the prism shaded in red (and its red grid lines) is seen directly by OD, while the same area (blue shading and blurred blue grid lines) is seen by OS shifted to a different location by the prism (diplopia).

Figures 3.12A and 3.12B illustrate the expanding visual field when the patient's gaze is shifted into the blind field (in this case left) by about 15**°**. Since the gaze of the patient has shifted, the entire field is shifted to the left by 15° and the areas of expansion have also shifted farther to the left by this amount. As the gaze of the patient is shifted toward the blind

field, more of the prism segment is now acting in the periphery of the patient's seeing hemifield; thus, there is more diplopia and visual confusion, created by the presence of the prismatically shifted and nonshifted views of the same region. Since the gaze is not directly into the prisms, the diplopia is peripheral and easily tolerated.

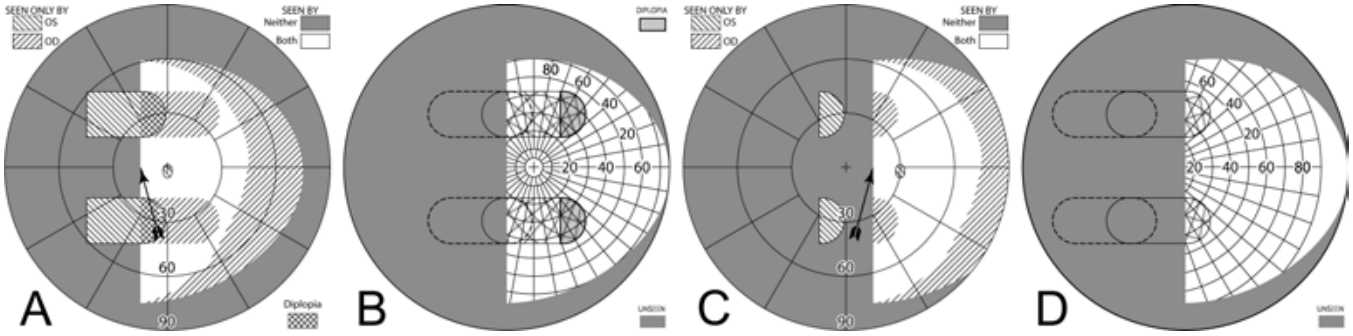


Figure 3.12. Unilateral horizontal 57Δ peripheral prisms, with gaze shift. (A) With gaze shifted left 15°, more of the blind hemifield is visible in the prisms. Since the prism shift is less than the visible width of the prisms, there is diplopia in the overlap regions (crosshatched). (B) The corresponding percept diagram shows the visual confusion in the prism regions, combined with diplopia (outlined and lightly shaded in the prism view location). (C-D) Unlike sector prisms, when gaze is shifted 15° *away* from the blind side, the prisms still provide field expansion, providing some continued access to activity in the important region ahead of the wearer. Diagrams for 40Δ prisms are included in Fig. S1 of the supplemental material. They show more diplopia during gaze to the left and a smaller gap with gaze to the right

When the patient's gaze is shifted right (away from the blind side), the prisms remain in the seeing periphery and provide field expansion that provides information from areas directly ahead of the patient while the gaze is averted (Figs. 3.12C–D). This, of course, is in contrast to sector prisms, which provide no expansion at primary gaze, let alone gazes directed away from the blind side. Continuing to monitor the straight ahead direction when looking to the side, as done with normal vision, may be particularly important during mobility.

3.5.3 Considering Prism Size and Power

Patients sometimes ask for the prisms to be shifted farther to their blind side to provide even greater expansion. At primary gaze, the extent of expansion is determined (and limited by) the prism power, not the prism edge positions. The prism base edge is almost always in the blind hemifield, except for extreme (and uncomfortable) gaze angles. Shifting the prism toward the blind side simply limits the availability of prism on the seeing side, where it is needed when gazing away from the blind side, as shown in Figure 3.13.

At primary gaze, if the prism power is less than the angular extent of the visible portion of the prism, diplopia will be present (Figs. 3.11A, 3.11D). If the power is greater, the apical scotoma creates a gap between the expansion area and the seeing side at primary gaze (as occurs with averted gaze in Fig.3.12C). Peripheral diplopia, while not necessarily disturbing, represents a lost opportunity for further expansion, as the diplopic view through the prism would be more productively directed to a nonoverlapping region. Since it makes sense to optimize the prism effect at primary gaze, where the users spend most of their time (Vargas-Martin & Peli, 2002; Iorizzo et al., 2011), minimizing diplopia and any gap between the expansion area and the midline strikes the best balance, and this occurs when the prism power equals the prism half-width (when both are expressed in degrees).

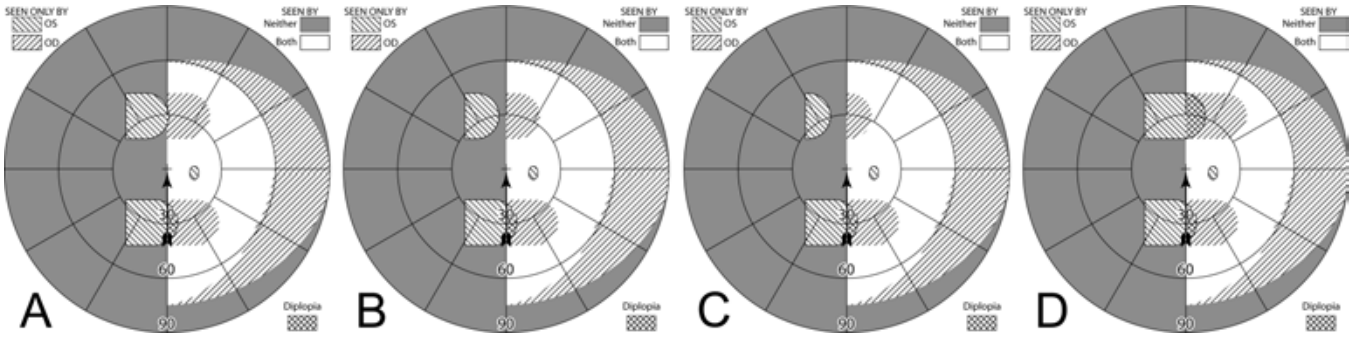


Figure 3.13. Examples of altering the **upper** 40Δ prism position of Fig. 3.11d. (A–C) Temporal shifts of 5°, 10°, and 15°, respectively, open an increasing gap between the expansion area and the midline, decreasing, not increasing, the expansion. (D) A 5° nasal shift only increases the amount of peripheral diplopia.

3.5.4 Bilateral Horizontal Peripheral Prisms

Although peripheral prisms are typically applied unilaterally, they can also be fitted bilaterally and yoked, all bases in the direction of the field loss. When each prism center is aligned with the pupil position at primary gaze there is no visual confusion, but apical scotomas are present in the binocular field (Fig. 3.14), as was the case for sector prisms. This is also the case if a patient with only one functional eye is fitted with peripheral prisms. Unlike sector prisms, however, objects not completely blocked vertically by the prisms can still be detected (as is the upper half of the man in Fig. 3.1B).

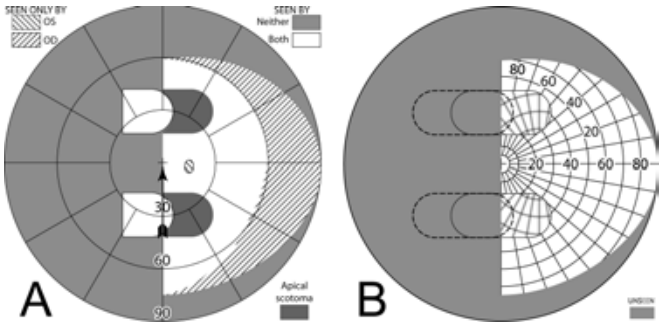


Figure 3.14. Bilateral horizontal 40Δ peripheral prisms. Since both eyes have the same prism views, the prism apical scotomas remain in the binocular view. (A) Simulated Goldmann diagram shows field *substitution*, not expansion. (B) The corresponding percept diagram shows no visual confusion, as the view from each eye is the same. Images from the blind side are merely shifted to displace an area of the seeing hemifield

3.5.5 Offset Bilateral Horizontal Peripheral Prisms

The apical scotomas of bilateral fitting can be mitigated by offset placement of the prisms relative to the line of sight. If both eyes' prisms are moved nasally, the left and right apical scotomas can be made to fall in non-overlapping areas of the visual field. Since both bases are on the blind side, one prism apex (contralateral to the field loss) moves toward the line of primary gaze, and the other (on the lens ipsilateral to the field loss) moves away (Fig. 3.15). Shifting the prisms relative to each other by an angular shift equal to the prism power accomplishes that (Fig. 3.15B). The figure also shows that less shift leaves partial scotomas, while more leads to peripheral diplopia at primary gaze. Of course, having different views through each prism does create visual confusion in peripheral regions proportional to the amount of prism offset, but, unlike unilateral placement, the true expansion area is seen binocularly without confusion. Portions of the seeing hemifield are now viewed with visual confusion, but hazards which exceed the prism height would be partially seen binocularly and without confusion on the seeing side. Although as yet untested clinically, this is likely to be preferable over unilateral placement and clearly avoids the apical scotomas of non-offset bilateral placement.

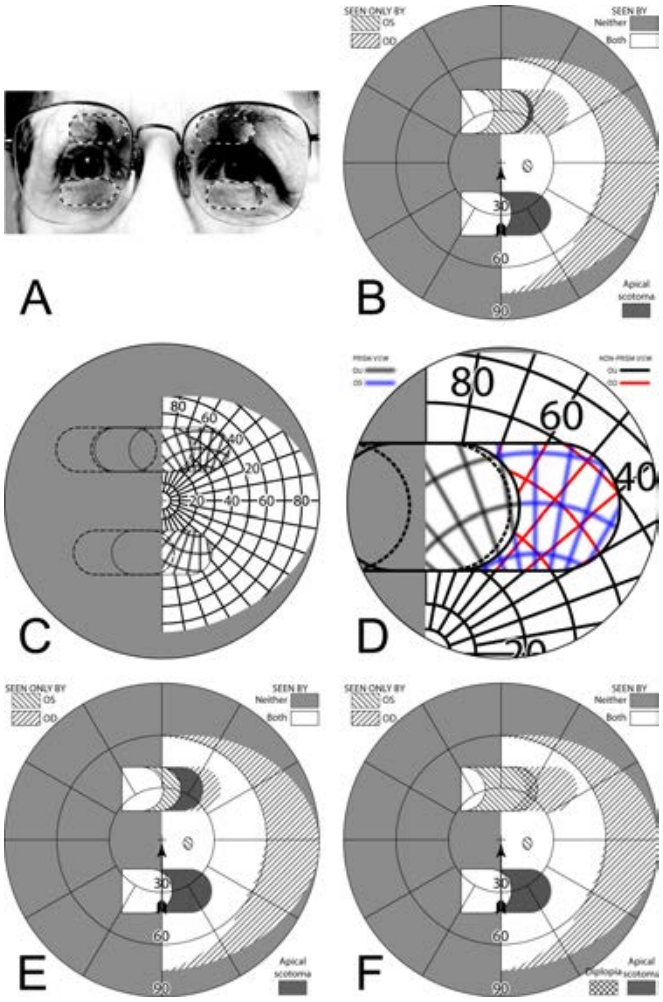


Figure 3.15. Offset bilateral horizontal 40Δ peripheral prisms. (A) Spectacles with the upper prisms offset nasally (and outlined for clarity), shown for left hemianopia, though only the direction of the base (illustrated with the sharp points) will be different for right hemianopia. While the lower prisms could also be shifted, many spectacle frames do not provide much room for that, as the lens shape accommodates the flaring of the nose at the bottom. (B) Moving each of the upper prisms 10° (3.5mm) nasally on its carrier lens (for a difference between them of 20°) essentially eliminates the 22° scotomas in the binocular field. (C) The percept diagram shows that even though the upper prisms are placed differently for each eye, they provide the same view where they overlap, since they have the same power. The view lost to the upper OD apical scotoma is seen in the OS prism, while the area of the OS apical scotoma is seen in the OD non-prism view. (D) Magnified detail of the upper prism area has the monocular views coded in color to more clearly identify the area of visual confusion possibly subject to suppression or rivalry. (E) Shifting each prism only 5° nasally (1.8mm) still leaves significant scotomas. (F) Shifting each prism 15° (5.4mm) introduces diplopia and needlessly extends the region of visual confusion. A total relative shift equal to the prism power is optimal

3.6 TILTING THE PRISM BASE-APEX AXIS: THE OBLIQUE PERIPHERAL PRISM DESIGN

The field expansion provided by horizontal peripheral prisms provides access to many of the obstacles, hazards, and orientation cues important for pedestrian mobility and common daily activities. Many states do not prohibit hemianopes from driving, in which case the prisms may be of help. However, as the vertical extent of a car's windshield is limited, the area of expansion provided by horizontal peripheral prisms falls mostly outside of the visual field typically used when driving. Moving the prisms vertically closer to primary gaze to increase the view through a windshield is not an acceptable option, as head bobbing due to car motion (that shifts the prisms into the gaze) could create the central confusion and diplopia that plague sector prisms. Leaving the prism location unchanged, but tilting the prism apex-base axes, provides a solution (Peli et al., 2009). This ‘‘oblique’’ design gives peripheral access to pericentral regions critical for driving, without blocking the central view. The apical scotomas (or visual confusion) with this design mostly fall in areas inside the car, on the visor and dashboard. In an on-road study of people with hemianopia, use of the oblique prisms improved hazard detection on the blind side and reduced the number of interventions needed by the driving examiner (Bowers et al., 2012).

An oblique prism has the same effect as the superposition of a vertical and horizontal prism, as illustrated in Supplementary Figure S2.

3.6.1 Unilateral Oblique Peripheral Prisms

An apex-base angle of about 30° provides a good compromise between vertical shift and the resulting loss of some horizontal expansion. An oblique prism of 57Δ and 30° tilt

provides 26° of horizontal shift and 15° vertical shift. Figure 3.16 diagrams the effects of this configuration. The supplemental material has diagrams illustrating the effects of the same design with gazes to the right and left (Fig. S3), as well as those for 40Δ prisms (Fig. S4).

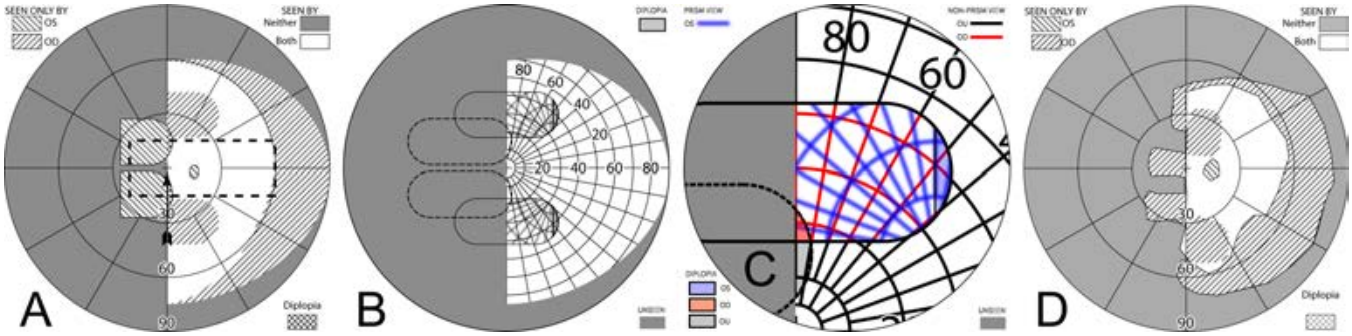


Figure 3.16. Unilateral oblique 57Δ peripheral prisms, ±30° apex-base angle at 12mm inter-prism separation, provide access to pericentral regions. (A) Simulated Goldmann visual field diagram shows true expansion with no remaining apical scotomas. The dashed rectangle outlines the typical view area through a car's windshield.(Vargas-Martin & Garcia-Perez, 2005) When driving, the prisms' expansion regions fall outside the direct road view, lessening any effect of visual confusion against the bland interior background. (B) The percept diagram shows the areas of visual confusion associated with unilateral fitting. (C) The magnified view of the upper prism area of (B) color-codes the monocular portions and shades the diplopic correspondence as in Fig. 3.11. A portion of the small region of interocular diplopia is also seen as monocular diplopia by OS; inconsequential, but an interesting wrinkle. (Monocular diplopia occurs when the visual angle of the effective prism base-apex distance is less than the prism power.) When gaze is directed to the left (Supplement Fig. S3 A & B) the diplopic region increases. Although partially seen foveally, patients have not reported noticing it. (D) Actual patient visual field diagram.

Thus, unilateral oblique peripheral prisms provide awareness of areas closer to the horizontal meridian, as might benefit a driver. Unlike sector prisms, they do this without actually impinging on the pericentral region and thus maintain binocular foveal fusion and avoid central confusion. With unilateral fitting there is peripheral confusion, but apical scotomas are avoided in the binocular field. With the bland design of most visors and dashboards, the outside road view on the blind side, with its dynamic nature, is likely to predominate under this rivalrous condition.

3.6.2 Bilateral Oblique Peripheral Prisms

Oblique prisms can be fitted bilaterally (Fig. 3.17) to avoid the visual confusion associated with unilateral fitting. However, the apical scotomas are significant, and there is a small area of pericentral diplopia that increases as gaze is shifted toward the blind hemifield, rendering this a trade-off of questionable added value. Lower-power prisms increase the diplopia, as shown in Fig. S5 of the supplemental material. However, apical scotomas in the driving situation are mostly located outside the field of view through the windshield and thus may have lower impact on performance or safety. The view through the prisms is binocular and free of confusion or rivalry. This yet-untested design may prove especially useful when driving.

As with the horizontal prisms, offset placement can provide some mitigation of the apical scotomas in the binocular field. However, since only the horizontal component of the prisms is offset, the vertical component of the scotomas remains. Figure S6 of the supplemental material has diagrams of the offset bilateral oblique prisms.

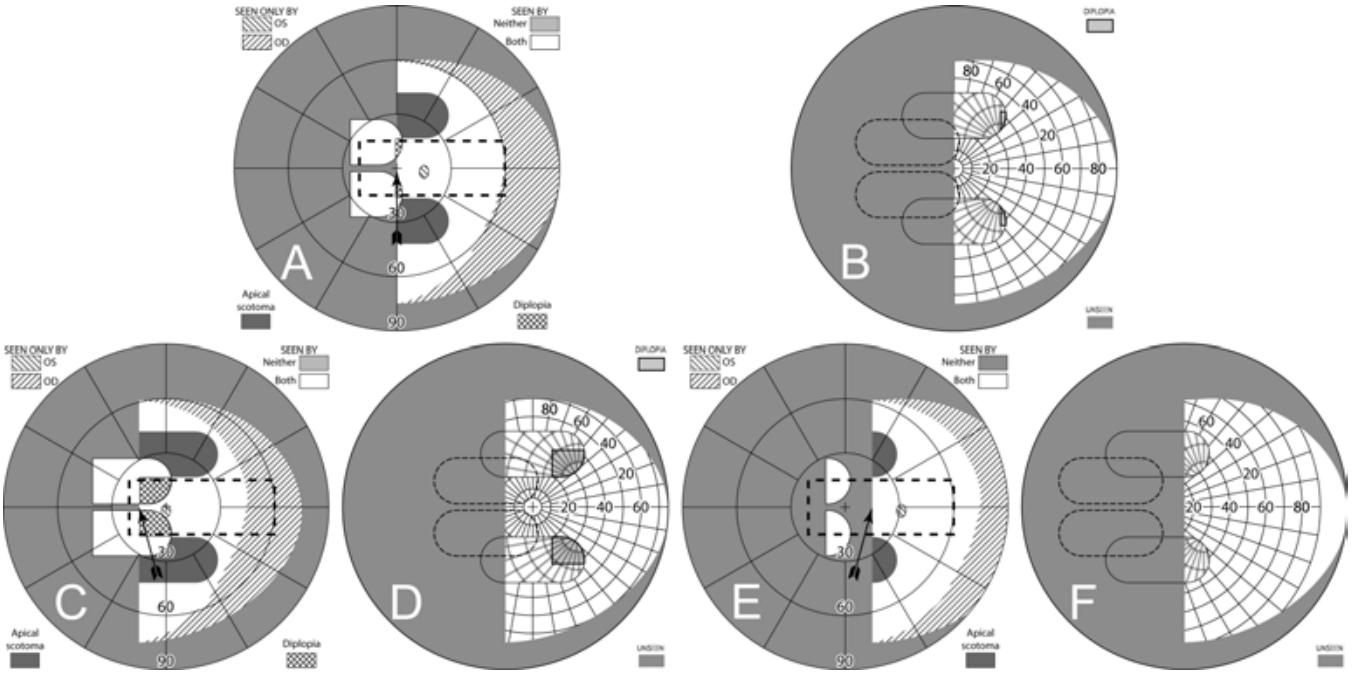


Figure 3.17. Bilateral oblique 57Δ peripheral prisms, ±30° apex-base angle. With gaze forward (A, B) there is a bit of diplopia and significant peripheral apical binocular scotomas. With gaze shifted left (C, D), since the prism views include larger portions of the seeing hemifield, there is a larger area of pericentral diplopia, while areas behind the prisms are still lost to the apical scotomas. With gaze shifted right (E, F) there is some field *substitution* (but not *expansion*) without confusion or diplopia. The dashed rectangles in A, C, and E outline the typical view area through a car's windshield. When driving, most of the peripheral scotoma is inside the car, not detracting from the view of the road.

3.7 CONCLUSIONS & RECOMMENDATIONS

Prisms are often prescribed to provide access to portions of the field of view lost to hemianopia. Failure to consider the pericentral view that is lost to prism apical scotomas can lead to deficits potentially more harmful than those the prisms are intended to resolve, yet reports of prism use frequently include discussions or diagrams that omit these scotomas (Smith et al., 1982; Woo & Mandelman, 1983; Rossi et al., 1990; Cardenal, Hoban & Toffel, 2012; van Waveren, Jagle & Besch, 2012). If the fellow eye does not have a scotoma in the same location, the effect can be mitigated. Unilateral fitting, or bilateral fitting of prisms offset so that their apical scotomas block different portions of the binocular visual field, can

accomplish that, albeit by introducing regions of visual confusion and possibly also creating diplopia.

Visual confusion and diplopia are particularly objectionable if in central or pericentral view, while they are well tolerated in the periphery, where in some sense they are normal. Visual confusion is the mechanism by which field expansion with prisms is made possible. Without confusion, prisms can only shift the view, trading one scotomatous location with another. Diplopia, on the other hand, has no beneficial effect in these treatments and should be avoided or reduced when possible. Direct foveation through prisms reduces acuity and contrast sensitivity and introduces other disturbing and noticeable spatial and chromatic distortions. Peripherally-placed prisms are much less disturbing in these regards, and yet are effective in attracting attention that can cause the wearer to shift gaze centrally to the alerted direction, similar to the natural role of peripheral vision.

These observations lead us to conclude that traditional sector prisms, which provide no field substitution or expansion at primary gaze and induce central and pericentral scotomas when the gaze is shifted into them, are of questionable value. The claim that they serve to train the users to fixate in their direction (Perlin & Dziadul, 1991; Perez & Jose, 2003), has not been supported with any documentation. The peripheral prisms developed in our lab avoid those shortcomings and have been met with considerable patient acceptance. They have been found useful in single and multicenter clinical trials, both open label (Bowers et al., 2008) and randomized controlled (Bowers et al., 2012; Bowers et al., 2013). The peripheral prisms provide true field expansion at most horizontal gaze directions, including primary. Although operating in the periphery, the oblique design can provide

pericentral field expansion. This effect is particularly important for patients who are permitted to drive. The prisms access important regions of the road view, while the confusion in unilateral fit and apical scotomas in bilateral fit fall in the bland interior of the car and thus are less likely to be deleterious. Although the peripheral prisms are generally fit unilaterally, as this is easier and less expensive, offset bilateral fitting provides another option for dealing with the apical scotomas. Oblique bilateral fitting may prove more beneficial for driving than unilateral fitting.

Despite the long history of sector prisms, we found only three controlled sector prism trials (Rossi et al., 1990; Gottlieb et al., 1992; Szlyk, Seiple, Stelmack & McMahon, 2005), and each had limitations. Rossi et al. used a parallel arm trial to evaluate bilateral 15Δ sector prisms against a no treatment control in patients undergoing an inpatient stroke rehabilitation program. The study (which found no advantage for the prisms in activities of daily living) recruited patients with either HH or spatial neglect (without HH) during the acute post stroke period, in which spontaneous recovery in neglect and visual field is common. Much of the improvement in the treatment group occurred on spatial neglect tests. However, the way sector prisms may be affecting neglect is not known and beyond the scope of this paper. ‘‘Expansion’’ occurred in both the treatment and control groups and did not include measurements in the seeing hemifield where the apical scotomas lay. As the prisms were fitted 2 mm into the blind hemifield, they should have had no effect on the perimetry results; thus, the improvements recorded were most likely due to spontaneous recovery. Gottlieb et al. evaluated their unilateral 18.5Δ sector prisms against a control device, which appeared similar, but included a ‘‘plano lens without prism power.’’ Methodology was not well

described, but all subjects tried the real prisms before the shams. They reported increased ‘‘awareness’’ of the visual field ranging from 10^{o} to 45^{o} in binocular (but not monocular) viewing with the real prisms; however, a 45^{o} increase in visual field from a 10.5^{o} prism is physically impossible. Szlyk et al., used a counterbalanced crossover trial to evaluate the Gottlieb unilateral 18.5Δ ophthalmic sector prisms against similarly shaped and positioned press-on 20Δ Fresnel prisms (Szlyk et al., 2005). The aim was to evaluate the relative efficacy of the two types of prisms when combined with an intensive 3-month training program. Unsurprisingly, improvements in performance on a wide range of tests were similar for the two prism types, as they had similar prismatic powers and differed only in optical quality and cosmetics. Unfortunately, the study design did not permit an evaluation of the benefits of the prisms alone (without training) relative to no prisms. The importance of including a sham control treatment in detecting placebo effects was highlighted in our clinical trial of real versus sham peripheral prisms (Bowers et al., 2013) in which 26% of subjects selected the sham control over no glasses or the real prisms.

Attention to the principles and diagrams we provided can avoid prescription mistakes. Moving peripheral prisms temporally will not increase their effect; rather it exacerbates the apical scotoma effects and wastes much of the prism extent where it is not likely to be used, robbing it from where it does provide benefit. Similarly, increasing the power of sector prisms increases the region lost to the apical scotomas, requiring even larger gaze shifts for pericentral views into the blind hemifield.

Our analyses and illustrations of the effects of apical scotomas have yielded subtle insights into the many ways prisms can both aid and hinder vision. Conventional wisdom and our own intuition were proved wrong or incomplete on numerous occasions by this analysis and diagramming.

CHAPTER 4. GENERAL DISCUSSION & CONCLUSIONS

There are multiple visual and optical considerations that could affect detection performance and clinical success when using prismatic spectacles as a rehabilitative device for hemianopia. In study 1, the effects of ocular dominance and background complexity were examined. In study 2, the effects of the position of the prism apex, the optical scotoma present there and the areas of visual confusion and diplopia in the visual field were addressed.

4.1 Study 1- Effects of dominance and background complexity

With any vision rehabilitative device that changes the quality, size or retinal location of an image presented to one eye relative to another, the potential for binocular rivalry to occur and for one image to predominant over the other must be considered. A patient's own ocular dominance could affect the frequency of this predominance, in addition to the quality and characteristics of the images themselves.

With respect to ocular dominance, we found that, consistent with other studies (Ooi et al., 2001; Seijas et al., 2007; Li et al., 2010), most patients with normal binocular vision did not exhibit repeatable ocular dominance rather they displayed mixed ocular dominance with no preference for either eye. Consequently, as expected, detection rates in the prism expansion area were not significantly different when the prism was fit to the spectacle lens ipsilateral or contralateral to the side of visual field loss. Therefore, for most patients, a clinician could fit the prism lens before either eye with careful consideration of the position of the prism apex.

With respect to concerns of possible partial suppression of the prism image due to its low contrast and peripheral retinal location, the results were quite promising. Although detection rates in the prism expansion area were lower on the patterned than the uniform background, contrary to our predictions, there was no significant difference in detection rates in the prism expansion area between monocular and binocular viewing. This indicated no local suppression of the prism image under binocular conditions, even in complex viewing circumstances where the conditions for rivalry exist.

While these results are positive for the majority of the patient population with normal binocular vision, two patients with strong ocular dominance demonstrated significantly decreased monocular and binocular detection rates in the prism expansion area when the prism segments were fit to the non-dominant eye. Specifically, one strabismic patient, who was only tested with the prisms on the non-dominant eye, exhibited significantly reduced detection in the prism expansion area in binocular compared to monocular viewing on the patterned background. This is suggestive of local binocular suppression of the expansion area under binocular, complex viewing conditions. Therefore, for patients with strong ocular dominance (due to amblyopia and/or pathology), the likelihood of local suppression of the prism image needs to be considered, and prisms should be carefully placed on the dominant eye.

4.2 Study 2 - Optical Scotomas at the Prism Apex and Maximizing Visual Confusion

In considering the patient with strong ocular dominance, the second study illustrates to us that we must carefully consider the position and placement of the prism apex. In these cases, fitting the peripheral prism segments to the dominant eye is recommended to avoid partial suppression of the prism image. However, once the prism is fit to the dominant eye, the capability of the non-dominant eye to detect targets within the prism apical scotoma may also be compromised. Therefore careful consideration of prism placement must be given to limit the impact of the prism apical scotoma, and maximize detection within the prism expansion area.

In considering the various optical confounds of commonly prescribed prism spectacle designs, each has its limitations that the clinician must carefully consider when fitting and prescribing these devices. The optimal design is one whereby the prism apical scotoma can be compensated entirely by the unaided view of the fellow eye. Whether, this is achieved by unilateral (with careful placement) or off-set bilateral designs, the net effect is visual field expansion via the use of visual confusion.

Considerations for prism fitting as it relates to maximizing visual confusion over diplopia should also be addressed. Visual field expansion via visual confusion can be most easily be provided by a unilateral sector or peripheral prism design. However, visual confusion is particularly objectionable if in the central or pericentral view, and is better tolerated in the periphery where we are somewhat accustomed to it, as this is the case in normal physiologic diplopia. This is a distinct advantage of the peripheral prism design in addition to the fact that higher prismatic powers can be used.

With peripheral prisms and careful consideration of prismatic power and placement, we can maximize visual confusion over diplopia. Diplopia has no beneficial effect and should be avoided or reduced when possible. This is obvious, as the prisms benefit the patient with HH only when a different, otherwise undetectable obstacle can be detected when wearing the prisms, rather than two images of the same object that would have otherwise been detected without the prism spectacles. Ideal prismatic placement occurs when both the apical scotoma and diplopia are absent from the binocular view in primary gaze. This occurs when the prism power equals the prism half-width (when both are expressed in degrees).

4.3 Sample size considerations

Finding and recruiting participants for these types of investigations is challenging. In the first study, of the twenty potential participants with HH recruited from local clinics, only eight met the inclusion criteria (visual acuity of 20/50 or better in each eye, no hemi-spatial neglect, no significant cognitive decline, and normal binocular vision). Additionally, many of these participants reported having other health issues which affected their stamina, and extended the number of study visits. Participants completed an average of four to six, three-hour study visits, in each of the studies. In the future, one should consider limiting the number of testing conditions in order to reduce the duration and number of study visits. While small sample sizes may introduce concerns regarding statistical power, significant effects were found, including a significant effect of binocular summation, which is typically small in magnitude (Blake, 2001). Furthermore, the first study employed a within-subjects design and analysis; therefore, the high degree of between subject variability in detection rates was not a concern.

4.4 Fitting Recommendations for Unilateral Peripheral Prism Glasses

Monocular visual fields should always be plotted before fitting peripheral prisms to ensure sufficient visual field is present in the prism eye to encompass the prism-shifted images from the blind hemifield and sufficient visual field is present in the fellow eye to compensate for the prism apical scotoma so that true visual field expansion is possible. When fitting peripheral prisms for patients without strong ocular dominance, it is generally better to place the prisms on the lens on the side of the hemianopia (see discussion, Chapter 2). However, in cases where there is likely to be strong ocular dominance, including patients with history of strabismus, amblyopia or different acuities between the two eyes (such as those due to macular pathology), the prisms should be fitted on the dominant eye, while still considering the possible effect of the apical scotoma.

Study two provided a detailed exposition of the effects of the apical scotoma and how they could be mitigated by careful consideration of the placement of the prism apex and its relationship to the line of sight. Peripheral prism segments should ideally be placed on the spectacle lens so that the center of the prism segment is in line with the center of the pupil when the eye is in the primary gaze position. Moving prism segments temporally will not increase the visual expansion effect (a misconception held by some patients and clinicians). If moved too far nasally, this will increase the amount of diplopia, limiting the area available for visual confusion. In terms of the prismatic segment power and size, it is optimal for the prism power to equal the prism half-width in degrees. If centered, this minimizes unnecessary diplopia and maximizes visual confusion (i.e., visual field expansion).

4.5 Conclusions

In summary, the results are promising, suggesting that, in binocular viewing conditions, neither reduced predominance nor exclusive local suppression of the prism expansion area occurs for patients with normal binocularity wearing unilateral peripheral prism glasses. These findings are confirmatory of the subjective reports of the utility of the peripheral prism glasses in real-world situations (Tant, 2008) . With careful consideration of prismatic power and placement, we can maximize visual confusion (field expansion) over diplopia and avoided unwanted apical scotoma effects. In future studies, we will increase the reality of the test conditions to bring them closer to those experienced in everyday dynamic environments by using more realistic targets and motion video backgrounds (Shen et al., 2011).

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APPENDIX 1. SUPPLEMENT TO CHAPTER 3

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Supplement to

Considering Apical Scotomas, Confusion, and Diplopia When Prescribing Prisms for Homonymous Hemianopia

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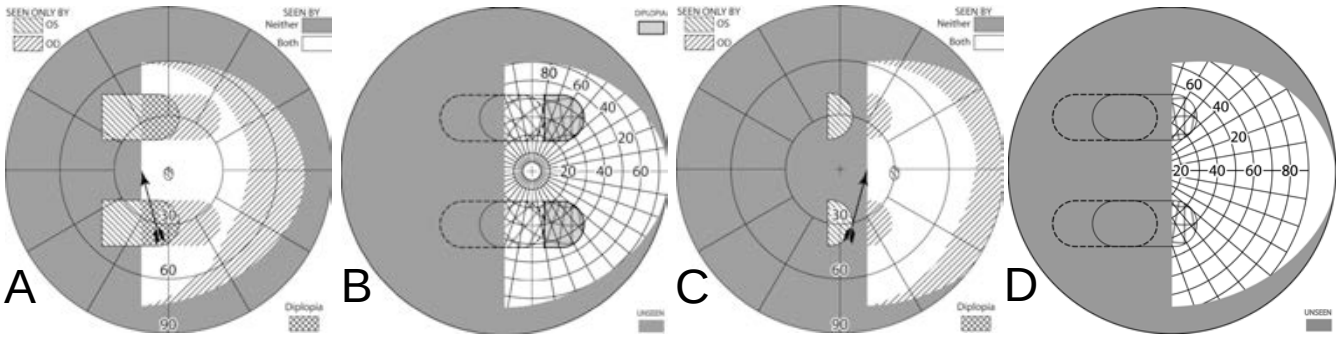


Figure S1. Unilateral Horizontal 40Δ Peripheral Prisms, with gaze shifted. With the lower power the prisms show more diplopia when gazing to the left and a smaller gap when gazing to the right than the 57Δ prisms of Figure 12. (A) With gaze shifted left 15°, more of the blind hemifield is visible in the prisms. Since the prism shift is less than the visible width of the prisms, there is diplopia in the overlap regions (crosshatched). (B) The corresponding percept diagram shows the visual confusion in the prism regions, combined with diplopia (outlined and lightly shaded in prism view locations where it offers no expansion benefit). (C-D) Unlike sector prisms, when gaze is shifted 15° away from the blind side, the prisms still provide field expansion, providing some continued access to activity in the important region straight ahead of the wearer.

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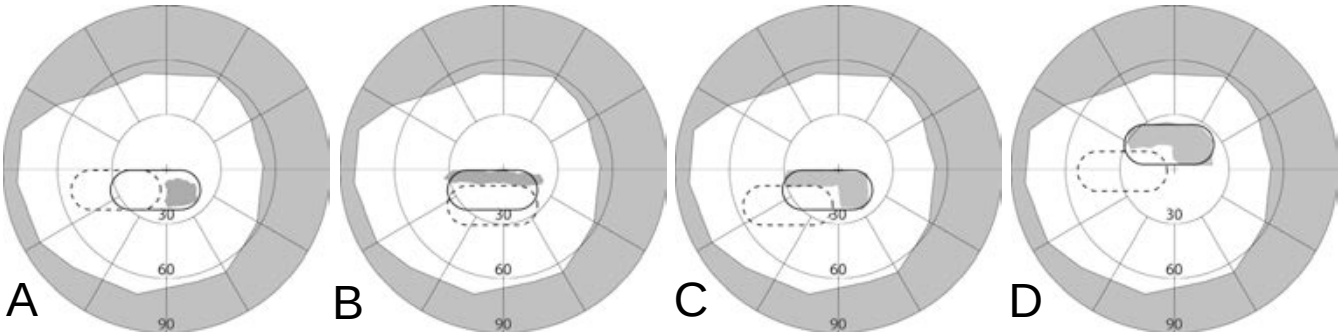


Figure S2. An oblique 57Δ prism with power 29.7 degrees and apex-base angle 30° is equivalent to combining a vertical prism with power 29.7×sin(30) = 14.8° (26.5Δ) and a horizontal prism with power 29.7×cos(30) = 25.7° (48.1Δ). Press -On prisms (3M, Minneapolis. MN) used in this figure are all the same shape and size and are centered (except for d) on the left lens of a normally-sighted subject, with OD patched. The solid outlines indicate the approximate prism locations, while the dashed outlines indicate the field seen in the prisms. (A) Visual field diagram with a 40Δ base left (horizontal) prism on the rear of the carrier lens, showing an apical scotoma the height of the prism and the width of the prism power (21.8°). (B) Diagram with a 15Δ base down (vertical) prism on the front of the carrier lens, showing an apical scotoma the width of the prism and the height of the prism power (8.5°). (C) Diagram with both prisms in place, showing the combined scotoma. (D) Diagram using an upper segment 57Δ oblique peripheral prism with apex-base angle 30°, showing a similar scotoma

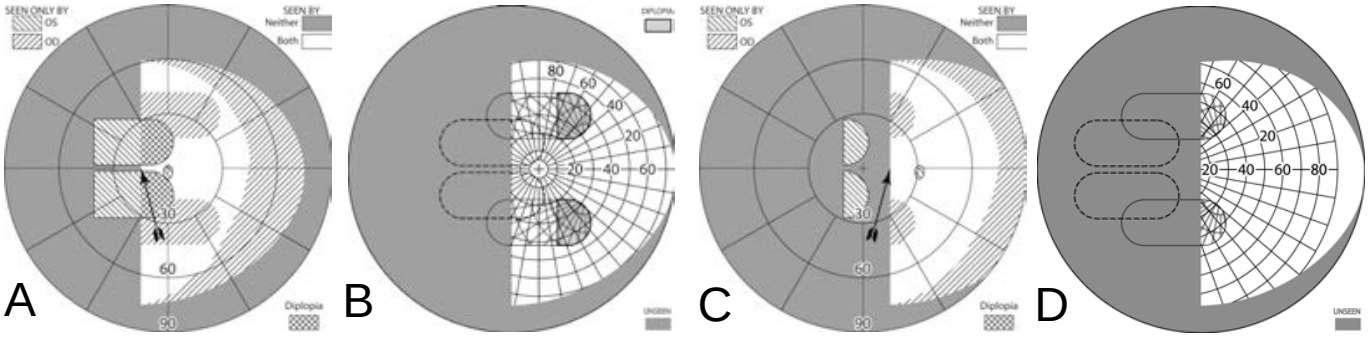


Figure S3. Unilateral oblique 57Δ peripheral prisms provide access to pericentral regions even when gaze is shifted from primary. (A) Simulated Goldmann visual field diagram with gaze shifted 15° left. (B) The corresponding percept diagram shades the diplopic portion of the prism view that does not contribute expansion. There is peripheral (retinal), but not central, diplopia. (C-D) With gaze shifted right 15°, some pericentral expansion is still provided, with no diplopia.

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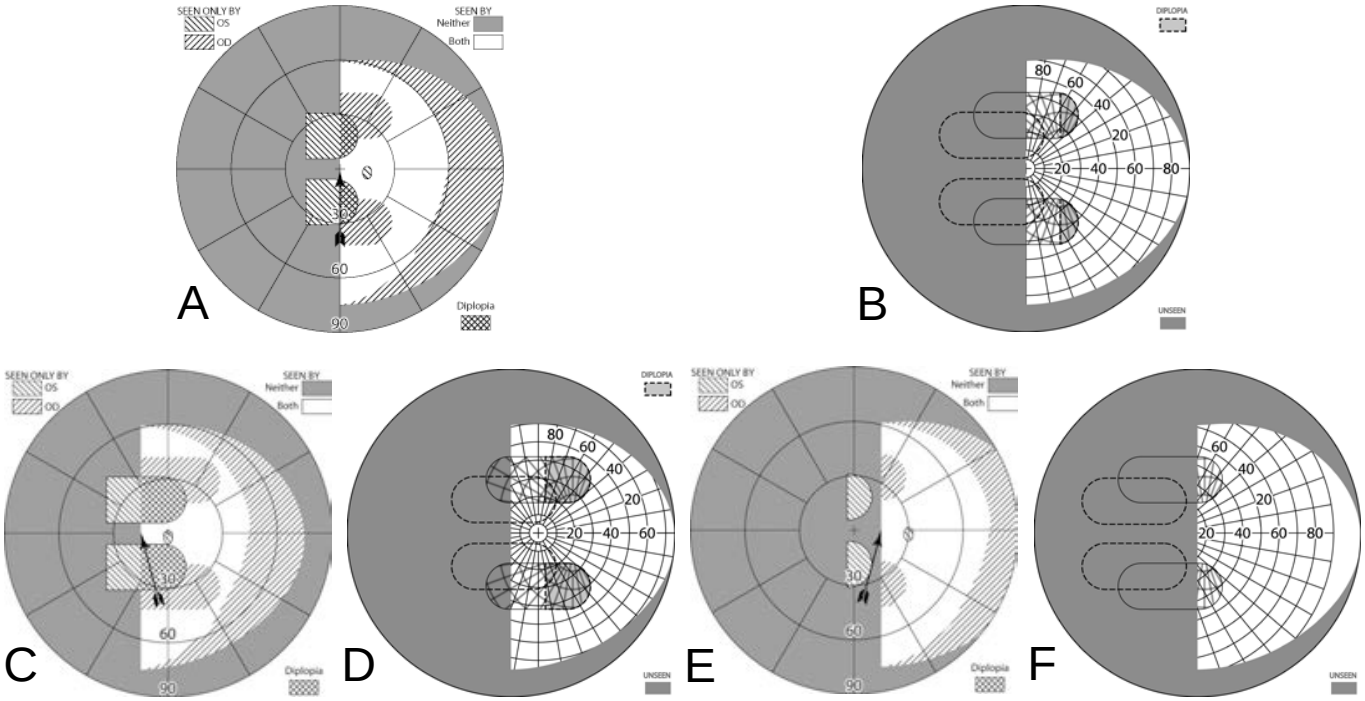


Figure S4. Unilateral oblique 40Δ peripheral prisms, ±30° apex-base angle, provide access to pericentral regions. (A) Simulated Goldmann visual field diagram shows true expansion with no apical scotomas at primary gaze, but there is some peripheral diplopia. (B) The percept diagram shows the areas of visual confusion associated with unilateral fitting, and the shading indicates the (peripheral) diplopic regions that do not contribute to expansion. (C-F) Corresponding calculated diagrams with gaze shifted 15° left and right, respectively, as shown by the arrows.

Considering Apical Scotomas, Confusion, and Diplopia When Prescribing Prisms for Homonymous Hemianopia

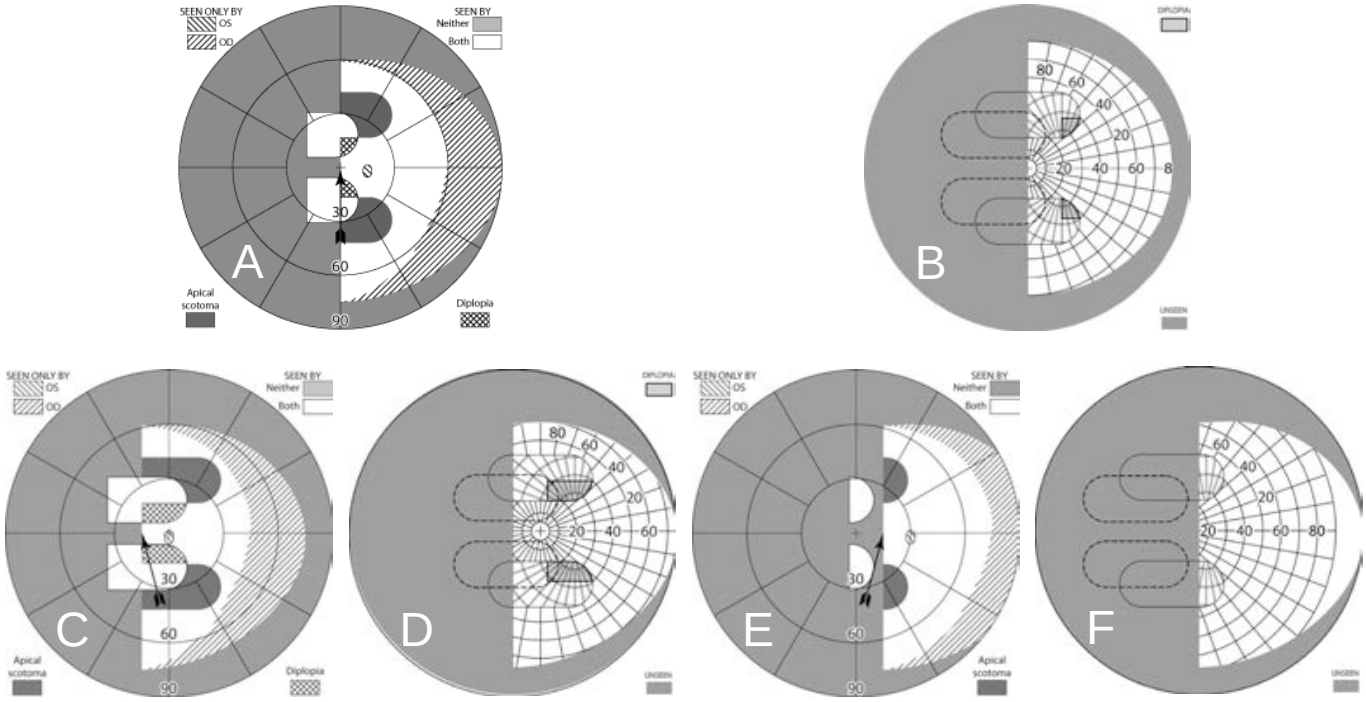


Figure S5. Diagrams similar to those in Figure 17, with 40Δ rather than 57Δ prisms. Lower power results in larger areas of diplopia.

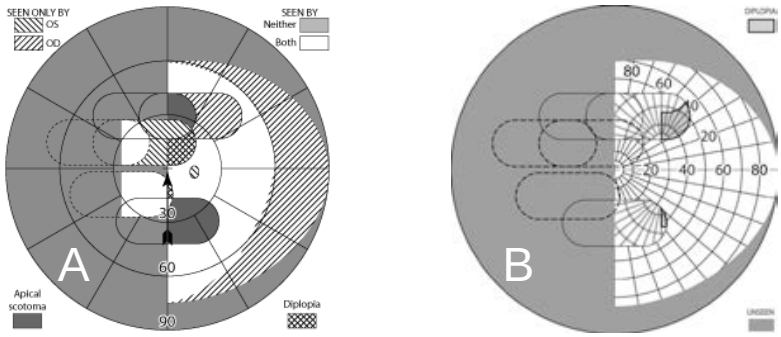


Figure S6. In this example, 57Δ prisms are fit bilaterally, with the upper prisms offset temporally with respect to each other. Offsetting oblique prisms horizontally does not compensate for the vertical component of the apical scotomas and results in wasteful peripheral diplopia. Unilateral fitting is preferable.