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Mini-review: Far Peripheral Vision

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Abstract

The region of far peripheral vision, beyond 60 degrees of visual angle, is important to the evaluation of peripheral dark shadows (negative dysphotopsia) seen by some intraocular lens (IOL) patients. Theoretical calculations show that the limited diameter of an IOL affects ray paths at large angles, leading to a dimming of the main image for small pupils, and to peripheral illumination by light bypassing the IOL for larger pupils. These effects are rarely bothersome, and cataract surgery is highly successful, but there is a need to improve the characterization of far peripheral vision, for both pseudophakic and phakic eyes. Perimetry is the main quantitative test, but the purpose is to evaluate pathologies rather than characterize vision (and object and image regions are no longer uniquely related in the pseudophakic eye). The maximum visual angle is approximately 105^0, but there is limited information about variations with age, race, or refractive error (in case there is an unexpected link with the development of myopia), or about how clear cornea, iris location, and the limiting retina are related. Also, the detection of peripheral motion is widely recognized to be important, yet rarely evaluated. Overall, people rarely complain specifically about this visual region, but with "normal" vision including an IOL for >5% of people, and increasing interest in virtual reality and augmented reality, there are new reasons to characterize peripheral vision more completely.

Keywords

Far peripheral vision. Peripheral vision. Perimetry. Negative dysphotopsia. Intraocular lenses.

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Mini-review: Far Peripheral Vision

1. Introduction

This mini-review of "far peripheral vision" was stimulated by an evaluation into the cause of "dark shadows" that are seen by some intraocular lens (IOL) patients in their temporal visual fields (Davison, 2000; Henderson & Geneva, 2015; Holladay & Simpson, 2017; Holladay, Zhao, & Reisin, 2012; Simpson, 2014, 2015a, 2015b). It gradually became clear that vision at very large visual angles was not really thought of as being a particular field of study, with little active research, apart from topics related to perimetry and the measurement of visual fields (Anderson, 1987). Perimetry is probably perceived to be capturing everything about peripheral vision that is important, but although it is very successful, the reason for the measurement is typically because of concern about the potential loss of central vision, or to evaluate visual pathways, and not to evaluate far peripheral vision for its own sake. Measurements are rarely made at large visual angles, and modern equipment cannot even measure the limiting temporal visual field because measurements only go up to 90 degrees.

The research into vision with IOLs has led to what may be new questions about far peripheral vision, relating not only to the use of IOLs by older cataract patients, but also to the phakic eye, including the youthful eye as it develops. It is also possible that the IOL patients who are bothered by "negative dysphotopsia", which is the more formal name given to the perception of peripheral dark shadows, might be experiencing a characteristic of vision that has not been previously reported. The theoretical evaluations reviewed here show that the far peripheral vision of the pseudophakic eye has different imaging properties to those of the phakic eye anyway, whether or not dark shadows are seen (Holladay & Simpson, 2017). Even if there were no complaints about dark shadows, these evaluations raise questions about vision characteristics in the far periphery. Some IOL patients have also been bothered by "positive dysphotopsia", where they see bright arcs or flashes of light at night. These are primarily caused by light reflected from within the lens hitting the foveal region, and they are not evaluated here.

This mini-review does not review the many papers that have discussed negative dysphotopsia with IOLs, which are already covered in review papers and the recent literature (Holladay et al., 2012) (Henderson & Geneva, 2015; Holladay & Simpson, 2017) (Makhotkina, Berendschot, & Nuijts, 2016) (Makhotkina et al., 2017). It starts instead with the observation that it is just not possible for an IOL to create an image at very large visual angles because it has a diameter that is much smaller than the natural lens. This perspective was not included in most of the earlier papers on the topic. IOLs had already been used for decades with no clinical observations of peripheral shadows, but there seem to have been no published theoretical calculations about imaging in this visual region for either phakic or pseudophakic eyes. The new theoretical calculations show that "vignetting" occurs because the IOL is much smaller than the natural crystalline lens (Simpson, 2015b), and this creates shadowlike regions that are very similar to the clinical reports of negative dysphotopsia. However, light can also bypass the IOL, and light can be scattered, and these can illuminate the retina and affect the perception of a shadow. There is no consensus in the literature yet about the primary cause of negative dysphotopsia, and the discussion is at the point where additional clinical data need to be recorded to confirm the cause, particularly because the visual angle at which the phenomenon is perceived has not been recorded in most of the clinical reports. However, the fundamental nature of the difference in the basic imaging properties of the pseudophakic eye in the periphery, compared to the phakic eye, has led to the questions about vision that are addressed in this mini-review.

The initial discussion about IOLs is followed by broader questions about far peripheral vision. People rarely seem to complain specifically about the quality of their vision in the far periphery, and this may have contributed to there being limited research into the "value" to the user of this visual region. Deficits may be measured by a clinician, but they are typically concerned about losses later at lower visual angles, rather than about the quality of far peripheral vision itself. This might be the case for glaucoma, for example, where initial losses in the periphery might be noted, and the concern would be that this would spread to more central visual angles. There seem to be no simple routine objective tests for either the total limit of the visual field, or for detecting motion in the far periphery. The observation of fingers may be the main data, using a confrontational test, with no detailed objective measurement of the visual angle or of motion characteristics. Other questions here relate to the structure of the eye, such as the extent of the retina, and the clear diameter of the cornea, while others relate to the way that signals from the periphery are processed. The limiting visual field is specifically addressed because it represents an upper limit for the visual field.

The main functional use of far peripheral vision is perhaps assumed to be self-evident because it is a continuous feature of everyday life. If something moves in the far periphery then it attracts attention, and the eye can be moved to look in that direction with a higher resolution portion of the retina. Peripheral vision is also thought to be important for lane tracking when driving (Huisingh, Wood, & Owsley, 2015; Owsley & McGwin, 2010), and for orienting an airplane relative to the ground when flying, but published evaluations do not typically extend to very large visual angles. A recent paper also evaluates optic flow at very large angles in a simulator (Mcmanus, Amour, & Harris, 2017), indicating that the far peripheral region is beneficial when walking. Questions about peripheral vision are also included in questionnaires (Sloane et al., 1992), but although these address both walking and driving situations, very large angles are not specifically evaluated.

The intent of this mini-review is to emphasize areas where little is known, but where there is increasing interest. This is particularly relevant to topics relating to ocular surgery and intraocular implants, but it may also be relevant to progress with virtual reality, augmented reality, and visual displays, where there is increasing interaction with the surrounding visual regions.

2. Defining the visual angles for "far peripheral vision"

There does not appear to be a clear definition in the formal scientific literature about the visual angles that would be included in the "far" peripheral vision region. Visual angles above 60^0 degrees are assumed here to be the region of "far peripheral vision", which is the value used in a Wikipedia article on peripheral vision (Peripheral Vision, 2017). The article includes a clear figure for different visual regions that is not published elsewhere, which uses round numbers of 8^0-30^0 for near peripheral vison, 30^0- 60^0 for mid-peripheral vision, and then taking everything above 60^0 as far peripheral vision, up to the limiting visual angle. This 60^0 angle seems appropriate, since this is an approximate value for occlusion by the nose and eyebrow, and also where light entering the eye will be incident on the retina near the equator (so the corresponding retinal region is in the anterior portion of the eye). Clinical measurements rarely include visual angles as high as this, however, and with this definition the far peripheral vision region exists mostly temporally, with the greatest extent infero-temporally.

3. Negative dysphotopsia with IOLs

Reports that a small number of intraocular lens (IOL) patients were bothered by peripheral dark shadows (negative dysphotopsia) first began in about 2000, many years after IOL surgery became a common surgical solution for cataracts (Davison, 2000; Henderson & Geneva, 2015). It is highly likely that this is actually an imaging phenomenon, rather than a shadow phenomenon, with the primary cause being that the IOL is much smaller than the natural crystalline lens that it replaces. This is illustrated in Figure 1 where preoperative and postoperative OCT images for the same eye are superimposed (Simpson & Muzyka-Wozniak, 2017). The preoperative lens thickness is not measured by OCT, but it is illustrated here to have a thickness of 5 mm, which is a typical value for an eye over 70 years old (Atchison et al., 2008). Preoperatively the iris is in contact with the crystalline lens, and all the light that passes through the pupil creates a single image on the retina. After cataract surgery, the iris moves posteriorly, but the IOL is much thinner than the natural crystalline lens, and there is a gap between the posterior iris surface and the IOL surface. The IOL thickness is only about 0.8 mm in Figure 1, with a lens diameter of 6mm, compared to the 5 mm thickness and 9.5 mm diameter of a natural crystalline lens.

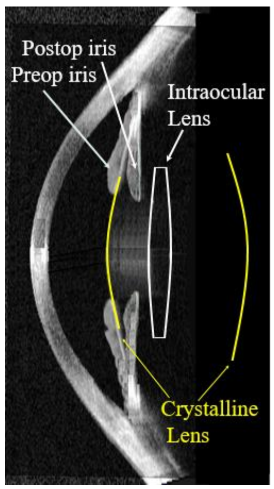


Figure 1. Superposition of preoperative and postoperative OCT images for a single eye.

The ray paths for a single light beam entering the eye at 85^0 of visual angle, are illustrated in Figure 2(a) using the Zemax raytrace software (Zemax, Kirkland, WA) (Simpson, 2016). This shows that as the visual angle increases, light gradually misses the IOL. If this was a conventional lens system, the light would be described as being vignetted at the edge of the lens, and the main image would go dark at the edge. However, light can also bypass the IOL and illuminate the peripheral retina, and this can affect the perception of a "shadow" in the periphery. These optical effects vary strongly with both visual angle and pupil diameter in this region because the light is traveling in a direction that is more across the eye than into it. By the time the visual angle reaches 90 degrees for this example, no light at all is focused by the IOL. Early papers often gave angles relative to the optical axis of the eye, but adding 5 degrees to angles on the temporal side gives the approximate visual angle, which is now preferred. Figure 2(b) illustrates focusing by a crystalline lens instead.

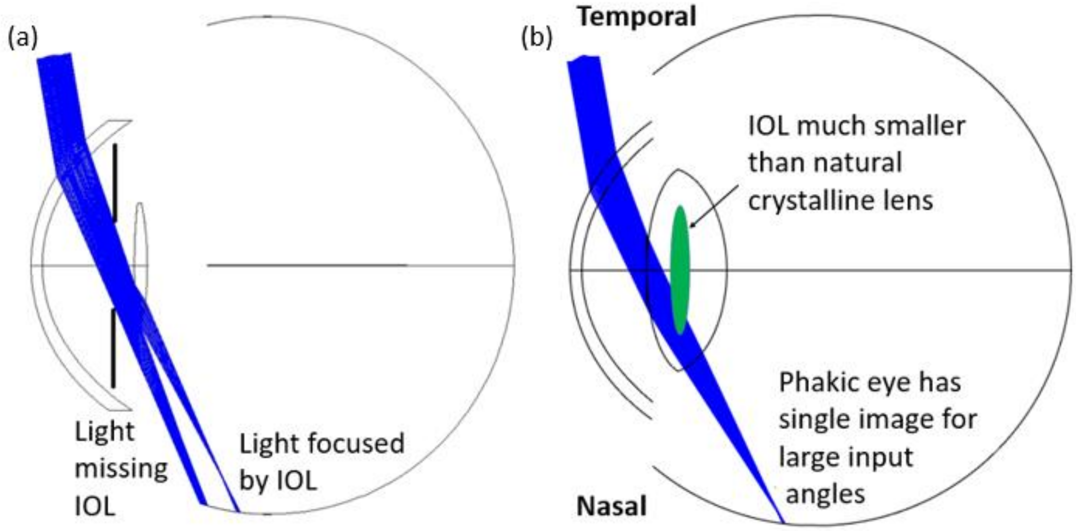


Figure 2. (a) Zemax raytrace illustration of light near the edge of a 6 mm diameter IOL. Right eye from above. 4mm pupil. (b) Zemax raytrace of gradient index crystalline lens (with overlay of approximate IOL).

Figure 3(a) provides an additional perspective on the peripheral light paths, by indicating where light from a large range of object angles will be directed, rather than just illumination from one visual angle. This shows that when the pupil is small, it is possible to have a region of the retina with no illumination at all, because the limit of the primary image occurs before the light that misses the IOL illuminates the retina. This modeling of peripheral vision is discussed in detail in Holladay et al (Holladay & Simpson, 2017), where the relationship between the pupil diameter, and the IOL location are explored. The modeling method uses a simple IOL edge, and it does not include the effects of light scattering, Fresnel reflections, or of light passing through the outer edge of the IOL.

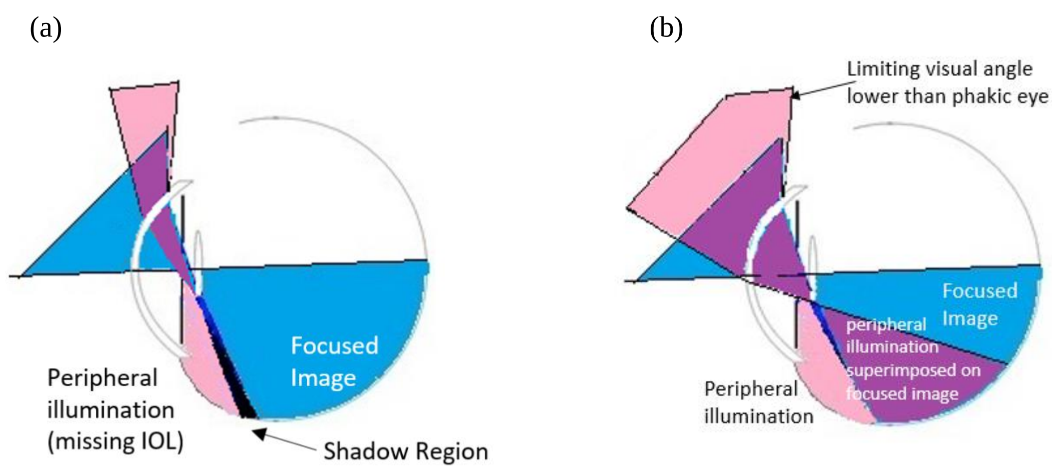


Figure 3. (a) With a small pupil, there can be a dark retinal region (a “shadow”) that receives neither light passing through the IOL, nor light missing the IOL. (b) With a larger pupil, an extensive region of the focused image is also illuminated by light missing the IOL.

The perspective about the far peripheral vision region of the pseudophakic eye that is illustrated in Figure 3(a) was not envisaged by most of the earlier publications about negative dysphotopsia. There are several references that have theoretical evaluations of the image from a point light source (Coroneo, 2007; Holladay et al., 2012; Hong et al., 2011), but these typically did not consider extended images, or conduct evaluations up to the angle at which light is no longer focused by the IOL (and errors in theoretical calculations in Holladay et al (Holladay et al., 2012) were later corrected (Holladay & Simpson, 2017)). Also, the published clinical data rarely include any information at all about the visual angle at which the shadow phenomenon is seen, which would identify the visual region of interest. There were often discussions relating to the edge of the IOL, generally based on the concept that a lens with a sharp edge might cast a stronger shadow than one with a rounded edge, but there was no evaluation of image dimming.

A recent paper by Makhotkina et al (Makhotkina et al., 2016) has now evaluated visual angles related to the shadow using a V4e target size in the Goldmann perimeter, and it was found that patients who are bothered by negative dysphotopsia have a smaller visual field extent using this target than other patients who are not bothered (Figure 4), though these were not directly matched controls. The visual angle of this difference is between about 70 and 80 degrees of visual angle, with a difference in all azimuths, but greater temporally and infero-temporally. There are no publications yet where clinical results are compared to modeled imaging for specific eyes, which should confirm the primary cause of negative dysphotopsia. There are also issues surrounding the measurement of the pseudophakic eye using standard perimetry, and these are discussed in Section 5.

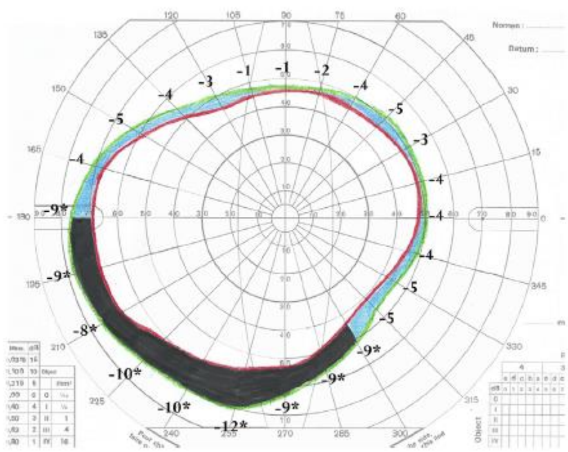


Figure 4. Mean extent of the visual field for subjects bothered by negative dysphotopsia (inner boundary, red), and other subjects not bothered (outer boundary, green). Makhotkina et al. (Reprinted with permission from Elsevier).

Negative dysphotopsia is only perceived with small pupils, which is consistent with the sketch in Figure 3(a). However, modest increases in the pupil diameter lead to the peripheral retina being rapidly flooded with light that bypasses the IOL, and Figure 3(b) illustrates how a large region of the retina can be illuminated by additional light as the pupil opens up. This is a type of double image, with the light that misses the IOL not experiencing the focusing power of the lens, leading to it being both displaced and a different size. There have never been specific reports of double images in the periphery with IOLs, though it is possible that these could be included with comments about visual phenomena at night. The optical regions illustrated in Figure 3 really raise the question about why more people don't perceive their "far" peripheral vision to be different with an IOL than it was with their natural crystalline lens. It is fortunate that only a very few patients find dark shadows to be bothersome, and additional clinical data may show this to be due solely to geometrical factors of individual eyes that make the shadows prominent. However, it may also be the case that the peripheral retina in some eyes is particularly sensitive to some aspect of the shadows that makes them bothersome. Patients often get used to visual characteristics that are always at the same location, such as spectacle frames, and it is not clear why the same type of adaptation is not always experienced for negative dysphotopsia.

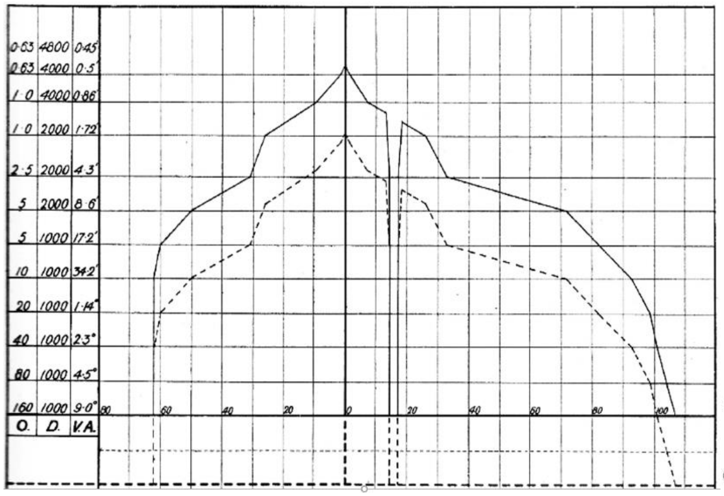
An additional characteristic of the pseudophakic eye is that the limiting visual angle may also be different from that of the phakic eye. One limit of the primary image is the vignetting limit, where light no longer passes through the IOL. Light can also miss the IOL however, and although this can illuminate the retina in the far periphery, it is not at the original limiting angle of the phakic eye, and the new limiting angle is likely to be lower.

The fact that dark shadows were not reported until this century is consistent with improvements relating to both the methods used for cataract surgery, and to IOL designs. At the time of the first reports there was a shift to phacoemulsification, small incision cataract surgery, foldable IOLs, and sutureless corneal incisions, along with a particular emphasis at the time about cleaning the capsule thoroughly. Earlier rigid IOLs had led to excessive scattering from the capsule, particularly from features like Soemmering's rings, and it was probably not possible then for light that missed the lens to create an image. Capsule polishing is not particularly emphasized any more, but sharp edges have become a routine feature of IOLs in order to inhibit cell growth and PCO. It is likely that the sharp edges to the posterior optical surface, which were newly introduced at the time, helped keep the capsule clear, and not that the edge itself was directly the cause of dark shadows. This was also a change from the rounded outer IOL edges that were common for rigid lenses, which could direct light into peripheral vision regions that might otherwise be dim. Differences between the edge characteristics of different IOL styles may still have an effect, but that is not evaluated in this review. Light may also pass through the haptic region, and a recent paper suggested that orienting a single-piece IOL at a certain angle may be beneficial (Henderson et al., 2016).

4. The limiting visual field and far peripheral vision

A paper by Roenne from 1915 is a primary reference for the limit of the visual field (Roenne, 1915), with slightly modified data for the horizontal visual field being replotted in 1927 in a book on visual fields (Traquair, 1938), and the same plot being included later in a primary reference for ophthalmology (Duke-Elder, 1962) (Figure 5(a)). Looking back at the original paper, however, the plot was for a single measurement of the author's own eye, which seems to emphasize how little importance is given to the limiting visual field. The values were recorded using a kinetic perimetry method, where an illuminated object was moved inwards from the periphery until it was first seen. Different sized objects were used for different visual regions, and the plot relates the angular size of the object on the vertical axis, to the visual angle when perceived on the horizontal axis. The horizontal extent goes from about -62 degrees nasally to +105 degrees temporally.

(a)



(b)

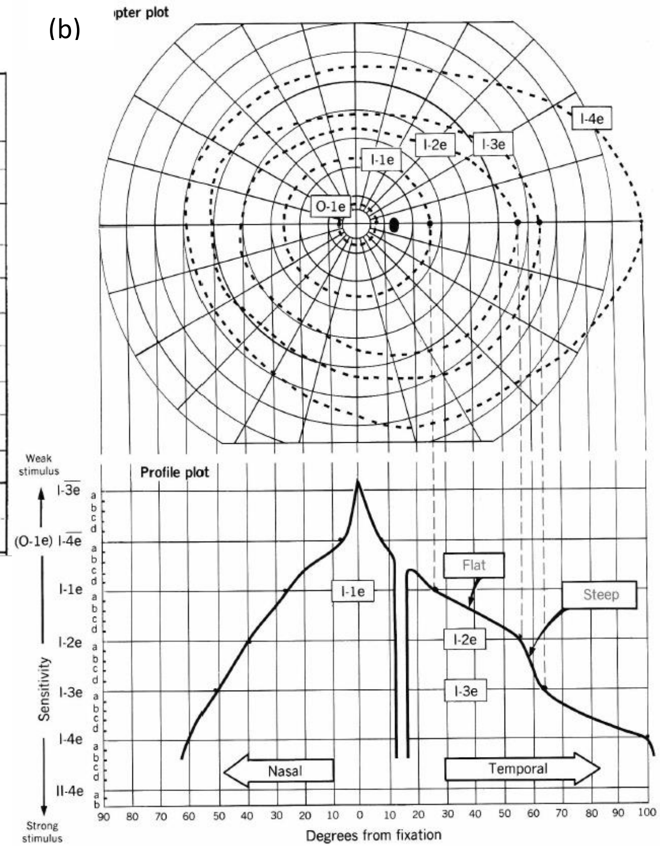


Figure 5. (a) Roenne’s data, modified by Traquair, for the sensitivity of the eye to a white object in the horizontal meridian. Abcissa=visual angle, O= diameter of the test object in mm, D=distance from the eye in mm, and V.A.= angular size subtended at the nodal point (Duke-Elder, 1962). (b) Visual field data plots for typical eye from Anderson (Anderson, 1987). Figures reprinted with permission from Elsevier.

A more complete visual field from a standard text on perimetry is given in Figure 5(b) (Anderson, 1987). This plot gives “isopters” for a range of angles where targets with different size and luminances are just seen. This is a standard plot for kinetic perimetry. The horizontal response curve is also plotted below the radial plot, and this is broadly similar in extent to the Roenne data, but with somewhat different characteristics, presumably because of differences in the measurement method. In practice, this type of data is recorded now using a Goldmann perimeter, which standardized this type of measurement, yet a standard modern Goldmann system only extends to a visual angle of 90 degrees (Schiefer et al., 2005). The plots in Figure 5(b) are perhaps typical of reference texts, where they are representative of a typical eye, but no information is given about how the plots might vary across a range of normal healthy eyes, or whether the plot might vary with the parameters that are normally monitored during a modern clinical study, such as age, gender, race, and refractive error.

More recently, there are indications in the literature about the magnitude of some of these parameters. A study using semi-automated kinetic perimetry (Niederhauser & Mojon, 2002) indicated that 2 standard deviations for the variation in isopter location at large angles is approximately 10 degrees for these types of measurements (estimating the value from plots in the publication). This was for a range of subjects with refractive errors from -8 D to + 8D, and ages from 19 to 42, with no evaluation by age or refractive error. This standard deviation is also broadly similar for data that includes older subjects with clear media (Vonthein et al., 2007), where isopter locations were found to reduce with age. In another publication (Grobbel et al., 2016), a group aged 70 and older included both phakic and pseudophakic patients, which may lead to a complication since pseudophakic eye measurements may be different to phakic eye measurements (see below). Visual field limits for children have also been recorded (Patel et al., 2015).

With all these measurements, the 90^0 field limitation of the Goldmann perimeter may affect the upper temporal limits from being recorded when the instrument is used conventionally. Limiting the target so that visibility is always within the 90^0 field is one method for suggested routine measurements at large angles (Monter, Crabb, & Artes, 2017). Static perimetry is an alternative to kinetic perimetry, and there are papers that contain data covering a large field up to 85 degrees (Weleber et al., 2015), though these measurements also do not go out to the limit of the visual field.

A detailed evaluation of the limiting visual field with age was also conducted by Fisher 50 years ago Fisher, 1968), where care was taken to ensure that the ocular media were clear at all ages, and none of the subjects had an IOL. A Goldman perimeter was used, and because there was a lot of variability, the mean of centrally and peripherally moving target visibility was used (Figure 6, mean pupil diameters also plotted). There were 105 patients divided between the different age groupings, all with refractive errors within $\pm$2D. The text indicates that the target brightness was sufficient for readings of just over 100^0 to be made on some younger subjects, but the mean value with the double direction average is much lower in Figure 6. The plot shows a general reduction in the limiting field with age, with a standard deviation in the range of 3^0 to 4^0. This paper, and another paper by Fisher (Fisher, 1967), also discuss limits on the visual field due to the orbit and the eyelid.

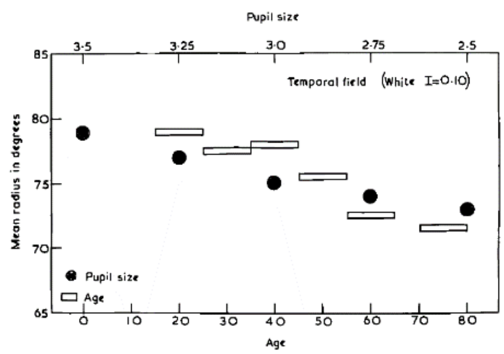


Figure 6. Variation with age of mean visual angle for visibility of radial and central motion of a 4mm^2 135 apostilb target at 300mm (Fisher, 1968). Mean pupil diameters are also plotted. Figure reprinted with permission of Springer

A new specific test for the limiting temporal visual field is the tangent corner test (Johnson et al., 2016), where a test subject faces the corner of a room, and a black tennis ball is moved along the wall until it is visible. This test uses very simple equipment, has shown good repeatability, and found a mean limit for the temporal visual field of about 95^0 for 76 patients with a range of ages.

An alternative characterization related to the horizontal limiting visual field is depicted in Figure 7, where the iris is viewed from outside the eye (Mathur, Gehrmann, & Atchison, 2013). At large visual angles very little light goes through the pupil, because the light is traveling almost parallel to the iris, and eventually nothing goes through the iris at all. This is not a plot of the limiting visual field, but it provides an upper limit. The plot itself is the ratio of the minor to the major axis of the apparent ellipse that represents the iris when viewed obliquely, but it captures the angle at which the light no longer passes through the iris in the horizontal direction. The limiting angle of 105^0 is broadly similar to the limiting value found by Roenne.

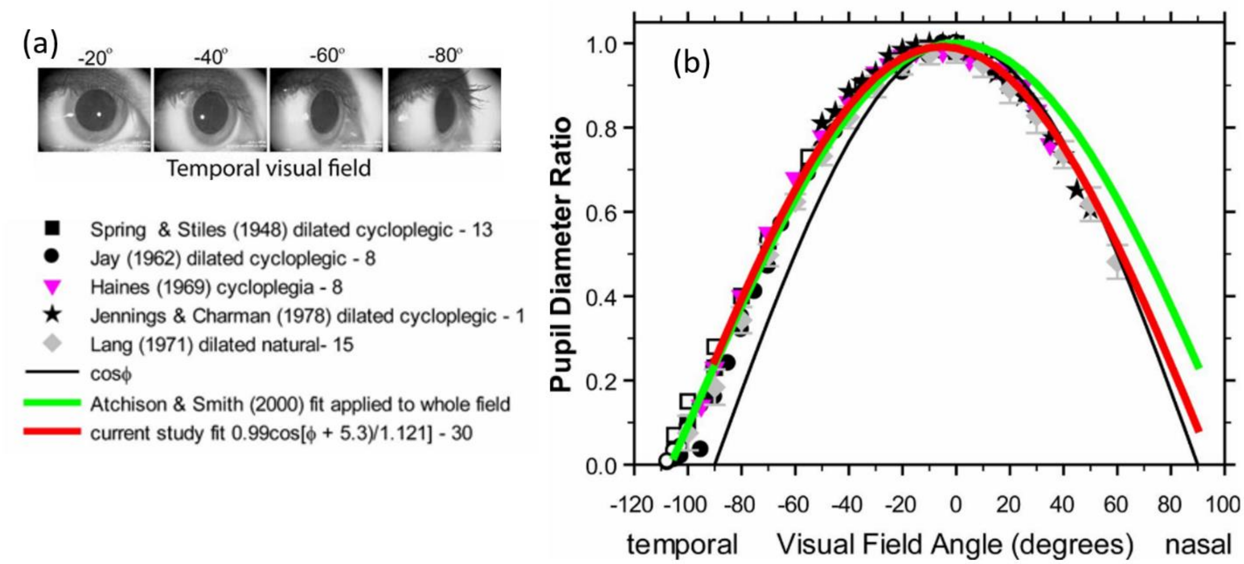


Figure 7. (a) Images of iris with increasing angle. (b) Ratio of minor to major axis of pupil visible in images (Mathur, Gehrmann, & Atchison, 2013). Figure reprinted with permission of ARVO.

The photographic method depicted in Figure 7 was for young subjects with dilated pupils, though the results in Figure 7(b) include earlier published results that have a range of normal pupil diameters. A change in the peak visual field angle (reducing with myopia), and in the overall period of the fit of the data to a cosine function (also decreasing with myopia), were found with respect to refractive error. Patient age was not tracked. Earlier measurements using a similar method were reviewed by Weale (Weale, 1956), who also discussed other characteristics of limiting vision, including a comment that trans-illuminating the sclera of a fair person in the dark would cause the pupil to glow red, and this would disappear at about a visual angle of 104^0. An early paper by Hartridge also gave a limit of peripheral vision as 104 degrees, though without including any detail (Hartridge, 1919).

As the eye ages, the iris is pushed forward by the natural crystalline lens, which can change the potential limiting visual angle. This is tracked by the change in the anterior chamber depth (Atchison et al., 2008). The theoretical effect of this is illustrated in Figure 8(a) using calculations for when the chief ray ceases to go through the iris, for a model eye with an average cornea and a thin iris (Simpson, 2016). This indicates that the iris motion places no additional limits on the limiting visual field. Conversely, with the pseudophakic eye, even though the iris moves to the posterior, there is little reduction in the potential limiting angle.

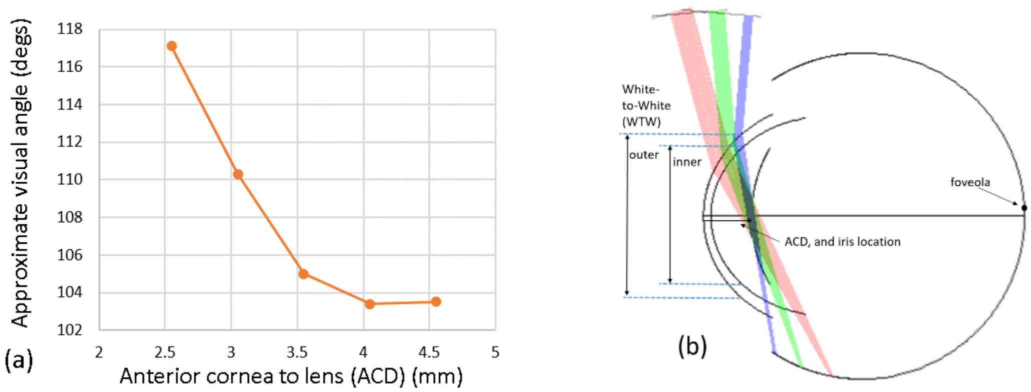


Figure 8.
(a) Maximum chief ray angle for average eye. (b) Ray paths with no lens for visual angles of 80^0, 90^0, and 100^0(visual angle =angle to optical axis + 5^0 (to place image on foveola)).

A related parameter, for which there are also no published data, is the clarity of the cornea for light traveling across the eye. This is illustrated in Figure 8(b) for an average eye, where rays that can pass through a thin 2.5 mm diameter pupil are shown entering the eye from visual angles of 80, 90, and 100 degrees. As the visual angle increases, the rays enter the cornea increasingly to the posterior, and they would be obstructed if this was a scleral region. Any limitation here would be related to the “white to white” images that are routinely recorded and evaluated from the front for IOL power calculation, but the clarity from the side is not known. It is possible for the sclera to cut into the clear pupil region, particularly for large pupil diameters. Overall, there is relationship between the clear cornea, the pupil location and diameter, and the limiting retinal location, and these may collectively determine the limit of peripheral vision. These relationships do not appear to be clearly discussed in the literature.

The location of the most peripheral active retina is also not normally measured in the living eye, and even in postmortem eyes, the physical extent may not be measured accurately in relation to other parameters of the eye. Two methods for characterizing the physical limit of the retina in vivo are described in a book chapter by Moses (Moses, 1975). One method is to trans-illuminate the eye to cast a shadow of the ciliary body and ora serrata onto the opposite sclera. A second method is the use of a bright point source to illuminate the sclera, with the subject responding when the light is visible (Figure 9). Moses says that the shadow of the first method can be easily seen, and that it agrees with the second method, though the latter is very noisy. These methods, and results, do not seem to be published in the general literature. The measurements also showed that the ora serrata moved forwards slightly with the force of accommodation in a younger eye.

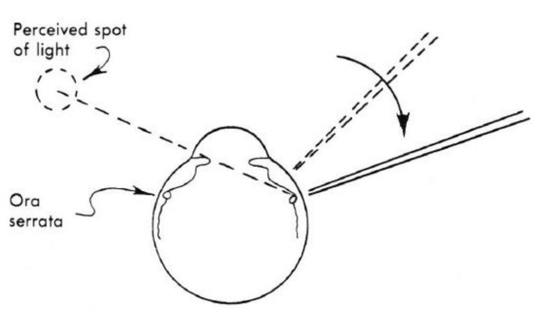


Figure 9. Method from Moses for measuring the location of the limiting retina (Moses, 1975). Reprinetd with permission from Elsevier.

Moses also states that there are retinal sensors that are not activated; where the retina looks normal, but it does not behave normally. No references are given for this suggestion, but it introduces a concept somewhat like amblyopia, where if the retina does not receive an appropriate image during development, then the visual pathways do not develop in an eye. This might happen at all visual angles, but the eye can rotate, so if a retinal region is occluded by the nose, for example, a rotation of the eye will provide an image temporarily. The outline of the limiting visual field, measured straight on, may include the shape of the orbit, and characteristics of the eyebrows. As a person ages, this may change, as facial characteristics change. If the eye is rotated in different directions, there may also be another limit that represents the limit of the retina, independently of the surrounding obstructions. There does not appear to be a reference where these types of parameters are evaluated by age, or race, or other characteristics (though Traquair makes a comment in a footnote that a flat nose does not lead to an extension of the nasal margin of the visual field (Traquair, 1938)).

This discussion also raises an additional fundamental question about the periphery, since with a normal eye the image is not perceived to be dim in the periphery. The intensity change is illustrated approximately by the plot in Figure 7(b) which gives the change in the effective pupil area. There must be a mechanism of some sort in the visual system that compensates for the intensity falloff, but it is not clear if this has been evaluated anywhere. One possibility might be that IOL patients who are persistently bothered by dark shadows might have a characteristic of this mechanism that was not problematic for the phakic eye, but which causes shadows to be bothersome.

Other types of visual testing have also been conducted for the far peripheral vision region at visual angles that are lower than the limit. These are not reviewed here in detail, but a discussion of general peripheral vision is given by Strasburger et al (Strasburger & Jüttner, 2015), and other papers explore the ability to recognize the characteristics of images presented in the periphery (Thorpe et al., 2001; Fortenbaugh & Sanghvi, 2012; Boucart et al., 2013; Boucart et al., 2016). It was found that features of images that contain natural scenes could be identified at a much greater level than chance when images were suddenly presented at large visual angles.

Work has also been done to explore the effect of motion, and in the paper by To et al (To et al., 2011) it was found that contrast sensitivity beyond 70^0 is higher for moving stimuli than for stationary, and in the outermost region, only moving stimuli are visible. This involved very sophisticated testing on few patients. Motion detection thresholds have also been determined for very large angles (Monaco, Kalb, & Johnson, 2007). This type of work does not appear to have led yet to simple tests for motion sensitivity or object detection in the far periphery.

5. Eye Parameters and Modeling Methods for the far periphery

There are many publications on the optical modeling of the eye (Liou & Brennan, 1997; Navarro, 2009), but these models were primarily created for use with modest visual angles, and even when large visual angles are envisaged, they are not expected to work up to the visual limit (Goncharov & Dainty, 2007). One difficulty with the phakic eye is the modeling of the crystalline lens, where although there are models for the gradient index, the outer shape is not specifically characterized, and it often looks uneven when it is visible in images. A simplified approximation is depicted in Figure 10(a) using the Zemax raytrace software (Radiant Zemax, Redmond, WA), where the gradient index model from Liou and Brennan was used, but the outer surface asphericity was adjusted until it corresponded more closely to a normal crystalline lens shape (Simpson, 2014). The changes for the pseudophakic eye are also depicted in Figure 10(a), where the iris moves to the posterior, and the IOL is much smaller than the natural lens. The eye has an unusual optical system at large angles because the input angle is greater than 90 degrees, and the output angle relative to the center of a spherical retina is also greater than 90 degrees. To model it in Zemax, the eye was rotated, and a macro was used to evaluate image ray intersections with the retina.

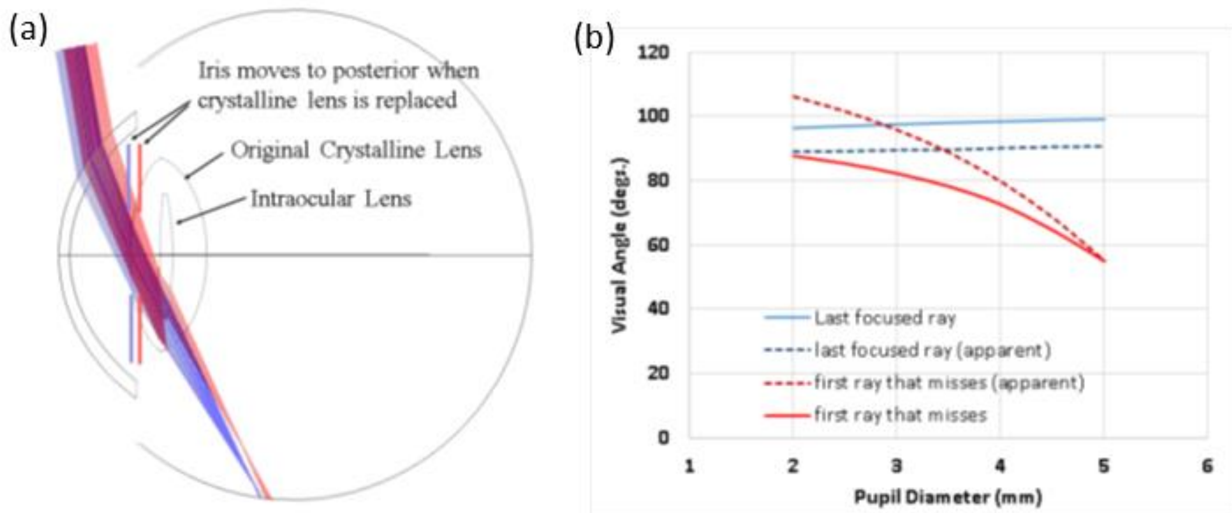


Figure 10. (a) Phakic eye model with gradient index crystalline lens, overlaid with pseudophakic iris and IOL. (b) Real and apparent visual field angles for pseudophakic limiting rays, where the first ray that misses the IOL appears to come from a larger visual angle because it has not been focused by the IOL, and the last focused ray appears to come from a lower visual angle because of aberrations.

The iris location is important for modeling peripheral rays, and the traditional method for optical modeling has been to put a thin iris at 3.6 mm from the anterior cornea for an average phakic eye, even though the iris moves forwards as the eye ages, and moves backwards if an IOL is used. The iris can also obstruct peripheral rays due to its thickness, and although there has recently been a lot of work on the change in the iris angle following cataract surgery, the papers do not typically give values for the iris location at its inner boundary, or values for the thickness of the iris. An estimate from the limited data available is to place a thin iris at 4 mm from the anterior cornea in the pseudophakic eye, with a modern IOL anterior surface at about 4.5 mm. This leaves about a 0.5 mm gap between the iris and the IOL, but eyes can have a large variation in values. An initial evaluation of iris thickness from OCT images indicates that it can be modeled as a triangular region near the center, with a thickness of about 0.5 mm at a distance from the pupil margin of about 1 mm (Simpson & Muzyka-Wozniak, 2017).

Even if the eye is modeled correctly, a method is still needed to represent images in the far peripheral visual field. The standard method for creating a simulated image is to convolve the image of a point source (the point spread function (PSF)), with an image, but this is not correct when the PSF changes significantly from point to point, which it does in this visual region (though the method can be used for sub-regions that are isoplanatic). The image is also formed on a highly curved retina, yet images are normally evaluated on a flat surface, such as a computer screen or printed page. This raises particular questions for IOLs since both bright photic phenomena, such as reflections from IOL edges, and dark shadows, are often described as being arclike, or curved, and the image needs to be converted to how it is perceived. One image representation method that was described for the central horizontal visual region for a square object (Simpson, 2014), was to assume that if the brain knew that something was straight, by glancing at it straight on, then that could be used to scale a peripheral image so that it looked straight (a type of distortion adjustment). It turned out that the scale adjustments were relatively modest for an image specified by visual angle subtended at the center of a retinal sphere.

Another image representation is to use the radial charts used for visual fields, where object locations are given in terms of visual angle. These do not normally represent an image, however, since they are plots of object space visual angle, and the actual locations of points in image space are not known. The retinal image locations need to be converted back to object space visual angles in order to use this to represent an image. One approach to this has been to use a simple model of the eye with a gradient index crystalline lens (Holladay & Simpson, 2017; Simpson, 2014) and a spherical retina, and to trace chief rays through the center of the pupil. The relationship between input visual angle and retinal image location was found to be very linear up to about 90 degrees for both angles subtended at the center of the retinal sphere, and at the second nodal point. This creates scaling relationships between an image location on the retina and input visual angle. There are also several papers discussing the scaling of the peripheral retina in comparison to visual angle, which are reviewed in Suheimat et al (Suheimat et al., 2016). These give a broadly similar linear scaling to the discussion above, though with less linearity for large angles than the relationship found using the gradient index crystalline lens, and the use of the phakic second nodal point as a reference (instead of the pupil plane that defines the chief ray). In practice, there is no independent method to confirm the values, but this provides a framework to display conventional images.

When converting retinal images back to object space, any actual rays that were defocused or misdirected would be represented at their "apparent" input visual angles. For a pseudophakic eye, rays may end up at locations that are very different from conventional imaging, such as when they miss the IOL completely, or if they are refracted through the edge of the IOL. Light that reaches a particular retinal location may have come from more than one source, and this is not specifically captured in the image representation, and it needs to be tracked separately. Figure 10(b) illustrates this in a simplified form, where it compares the actual visual angles for two limiting rays, and the "apparent" visual angles based on the retinal intersection, for the average eye in Holladay et al (Holladay & Simpson, 2017). This indicates that for a 5mm diameter pupil, all visual angles above about 55^0 have additional illumination from light bypassing the IOL This type of characteristic was also sketched in Figure 3(b).

This modeling also raises questions about the use of standard perimetry for the pseudophakic eye, since perimetry expects light from a single object point to reach only a single image location, and this is not necessarily the case. The subject only responds that they have seen light of some sort, and there is no measurement of where the light was seen. For large regions of the visual field this would not create a problem, but at very large visual angles there may be a double image, and there may be ambiguity. This is illustrated in Figure 10(b) in a comparison of the two curves. Different retinal sensitivities at different locations could also affect visibility. Interpretation of standard perimetry measurements of pseudophakic eyes should bear this in mind. This might also be an issue if a complex implant created unexpected reflections for certain visual angles.

6. Far peripheral vision and Myopia

The work on dark shadows described above, and the paucity of data relating to the limiting visual field, led to a question about whether the growth of the eye might be affected somehow by far peripheral vision, and whether this might affect the development of myopia or other refractive errors. It is certainly important for animals to be alert for predators at all times in their peripheral visual fields, and perhaps awareness of peripheral predators may have been as important as foveal vision for the early human eye. If there happens to be some aspect of "far" peripheral vision that is linked to axial eye growth, there may not be enough data for any correlation to have been observed. There has recently been a great deal of interest in whether defocus in the mid-periphery affects axial myopia (Mutti et al., 2000; Smith, 2011) , but although there seem to be trends, that only seems to be a partial explanation (Atchison et al., 2015). Visual characteristics of the far periphery are not even measured and evaluated in myopia studies, which is consistent with the limiting visual angle, and the physical limit of the retina, not being considered to be important in vision analysis, despite their widespread use in everyday life. Two additional characteristics that might also be considered are a cone-rich rim around the periphery of the retina whose purpose is unknown, (Mollon, Regan, & Bowmaker, 1998), and the fact that the retinal periphery is physically very close to the ciliary body that causes the accommodative effect.

One set of data that might explore this topic is any relationship between the limiting visual field and refractive error, but this information does not appear to be available. The emphasis of visual field testing has been to mitigate the effect of refractive error in order to test the underlying visual mechanisms, rather than to evaluate and characterize the overall visual effect. Spectacles do not correct the far peripheral vision region anyway. An evaluation of uncorrected far peripheral vision would really be asking a different question, about the quality of the image in the far periphery, where the detection and rapid analysis of a moving object is the primary concern. Standard visual field measurements also do not even measure the limiting visual field angle, though this would be possible with an adjustment to the gaze direction (Monter, Crabb, & Artes, 2017).

7. Discussion

This review has explored various characteristics of a visual region that appears to be under-researched, which is probably because people rarely complain about their far peripheral vision, and they usually do not even notice when they lose capabilities. In addition, visual field testing is presumed to be a measurement that captures everything that is important about this visual region, though the use of these tests is rarely to characterize far peripheral vision itself, they are rarely performed out to large visual angles, and they do not measure the limiting visual field.

Interest in the topics discussed here has arisen because some patients with intraocular lenses see dark shadows in the periphery. The use of intraocular lenses is now quite common, particularly in the older cataract age group, centered on about 70 years of age. There does not appear to be an ongoing measure for IOL usage, but data from about 2000 indicated that 5% of the US population had at least one IOL (The Eye Diseases Prevalence Research Group, 2004), which indicates that vision with an IOL is actually "normal" vision for many people, particularly in older age groups (>18% over age 70). There is no consensus yet about the cause of "negative dysphotopsia", but it was not initially recognized how little research had been done into "vision" in the far periphery, or that even the most basic calculations about light paths to the peripheral retina had not been carried out with enough thoroughness. Initial calculations have been summarized here, using simplified model eyes and simple IOL edges. This modeling could be enhanced to use such things as different edge types, light passing through the lens edges, Fresnel reflection coefficients, and the effects of capsular scattering. It should be possible to obtain objective visual angle measurements for patients bothered by persistent dark shadows, and to compare clinical observations to optical modeling for the same eyes to confirm the cause.

Broader questions about far peripheral vision have also been raised: What is the mechanism that prevents the edge of the visual field from appearing dark (and might that affect whether a peripheral shadow region is "bothersome")? What measurement is there that might characterize the value of far peripheral vision for everyday life? What is actually known about the detection of motion in the periphery, and how rapidly signals are processed in the brain and compared to known signals? How does the limit of the visual field vary with age, refractive error, and race? How do the diameter of clear cornea, the location and characteristics of the iris, and the extent of the active retina affect the visual limit? And although there is no known link between far peripheral vision and myopia, is it possible that signals from the periphery are somehow involved in eye growth, and are affected by excessive accommodation to the extent that they influence the creation of axial myopia?

One additional outcome of this evaluation is to raise questions about the testing of the pseudophakic eye using perimetry. At large visual angles, there is not necessarily a single image from each target presentation, because light can miss the IOL, or it might be scattered or redirected. This is a situation that is not envisaged by the test, and it may need to be considered when interpreting the results.

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