Clin. Vision Sci. Vol. 3, No. 3, pp. 173–183, 1988
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0887-6169/88 $3.00 + 0.00

THE VOLUME VISUAL FIELD: A BASIS FOR FUNCTIONAL PERIMETRY

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(*Received* 29 *March* 1988)

Summary—1. This paper introduces the concept of the *volume visual field* (VVF) map in the linear horizontal, vertical, and distance coordinates of environmental space, as a basic construct on which to build a theory of the functional visual field.

2. A number of conditions under which both finite and infinite *volume scotomas*, or volumes of space within which objects cast their images onto scotomatous or occluded retina, are identified for both normal and diseased eyes.

3. Convergence position and direction of gaze have marked effects on the VVFs of normal individuals, and on those with visual field defects. The functional impact of such effects is discussed.

4. Methods for construction of the VVF from two conventional monocular field maps are outlined.

Key words—Visual field; perimetry; binocular vision; functional vision; functional visual field; low vision.

INTRODUCTION

The traditional clinical role of perimetry is to diagnose or monitor the integrity of the retina and higher visual pathways. In recent years, considerable interest has been directed towards establishing a functional perimetry, one that predicts visual function from perimetrically obtained field maps. Functional perimetry has relevance in many realms of vision science, from general theories of visual performance that attach a functional significance to anatomically distinct neural pathways whose fibers originate in different visual field locations (e.g. Trevarthen, 1968; Held, 1970), to a wide variety of vision care applications (reviewed by Verriest *et al.*, 1985a, b) such as occupational vision screening, low vision rehabilitation and assessment of visual disability. Its main goals are to understand (a) which visual field areas are critical in visual task performance, and (b) the relationship between task performance and eye/head position. A central theme of functional perimetry is that visual tasks make particular demands on different locations of the visual field. For example, reading seems to use the central few degrees of visual field, but requires little if anything, of peripheral retina (Legge *et al.*, 1985), while locomotion would seem to ask more of the peripheral fields than it does of the central (Post and Leibowitz, 1986; see Marron and Bailey, 1984). Similarly, saccadic eye movements seem to require control systems associated with peripheral rather than central vision, while pattern discrimination is generally associated with central visual field function (Mishkin and Ungerleider, 1982).

Although many of the concepts of functional perimetry are used in basic visual science, the few attempts to provide quantitative methods have come from clinical vision science. These have been in the form of scoring procedures to predict overall, rather than task-specific visual function. The widely used methods of Esterman (1967, 1968, 1982) condense the information in the field map to a single "functional" score by first (effectively) multiplying the map by a spatial weighting function whose magnitude is proportional to the importance of the field location in visual function, and subsequently computing the percentage of intact (weighted) field remaining. Others have developed related methods (Crick *et al.*, 1983; Dannheim, 1983; Gandolfo, 1986; see Verriest, 1986 for a review). The only binocular method in existence to data (Esterman, 1982) measures the field available to the two eyes at once, at the single surface of the perimeter bowl. This is usually referred to as the binocular field map. As will be shown below, the binocular field map effectively ignores the third dimension of space, and is not a complete representation of what is visible to an observer.

This paper provides a rational geometrical basis for functional perimetric methods, that uses established principles of binocular geometry to map visual fields to the visual environmental space of normal observers and those with field defects. It attempts to clarify the issue of what is visible to an observer solely on the basis of environmental location, given eye position, and the presence of anatomical and other obstructions. It does not address other factors determining visibility such as contrast, color, glare, or ambient light level; nor does it provide either overall or task-specific weightings as do other functional perimetry scoring methods. It does provide a method for computing the set of environmental loci that are unobstructed to an observer's healthy retinal areas. This set is the appropriate input to any subsequent weighting of the visual field for functional purposes, unless one is certain to be dealing only with monocular vision.

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What is visible to a single eye can be described completely in the two dimensions of a visual field map, because the retinal image is itself a two-dimensional projection of space. What is visible to a binocular visual system, however, requires a full three dimensional representation. Such a map is termed here the *volume visual field* (VVF). It is argued that the volume visual fields are the appropriate field maps for functional perimetry. Furthermore, the process of computing the VVF yields understanding about visual behavior that cannot be obtained from single visual field maps or binocular field maps such as those suggested by Esterman (1982). Although the construction of a VVF involves simple geometrical concepts, computer graphic techniques are recommended for speed and ease of computation.

Disregarding sensitivity variation across the retinas, the volume visual field can be defined as the set of points in linear horizontal (x), vertical (y) and distance (z) coordinates that can evoke the light sensation to an observer with fixed eye position. So that we can study the effects of changing eye position on the VVF, we adopt the point bisecting the centers of rotation of the two eyes as the origin of this coordinate system, a location that is invariant with eye position changes. Armed with an observer's volume visual field map, we can in theory, establish where in space detectable and undetectable object points lie. It is not possible for a single monocular visual field map to provide all the information necessary to construct the volume field map, unless the individual being considered has but a single functioning eye.

To appreciate intuitively what the VVF is, imagine a perimeter that instead of presenting stimuli on a single hemispheric bowl, arc, or screen, presents stimuli from a representative sampling of points in three dimensions, as shown in Fig. 1, while the observer fixates a single point in space with both eyes open. The resulting three-dimensional map would show all the points in space that had been seen *by one eye or the other or both.* Although at each tested location, the suprathreshold stimulus was either (1) seen or (2) not seen, there are actually six possible outcomes: (1) Both eyes might detect the test stimulus; (2) the left eye detected it but it fell into a scotoma in the right eye; (3) the right eye detected it but it fell into a scotoma in the left; (4) the left eye alone detected it within its monocular crescent (the right eye's view of it being obstructed by the nose or nose bridge); (5) the right eye alone detected it within its monocular crescent; and (6) the test stimulus fell into scotomatous areas of both eyes. Only the sixth

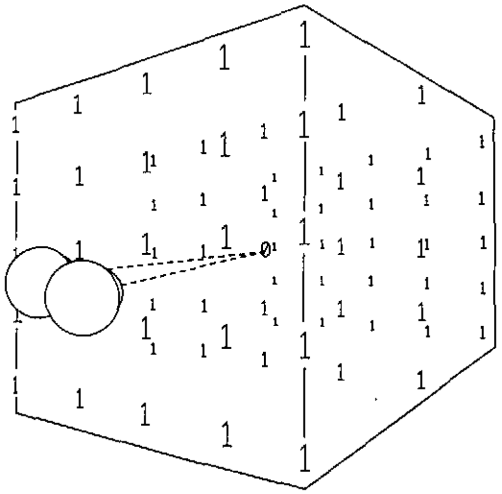

Fig. 1. Schematic ideal representation of volume perimetry. The "1"'s indicate points in (x, y, z) space that are detected by either eye. The central "0" indicates a bilateral central scotoma that destroys visibility of a volume of space enclosing the point at the intersection of the foveal projections in space. This method would assess function at test locations distributed (not necessarily uniformly) in the three dimensions of space.

outcome leads to failure to detect the stimulus, and all others would be scored as healthy field in the VVF.

It is not practical to measure the VVF directly because to do so would require either a large number of target stimuli arranged in an unwieldy three-dimensional spatial matrix, or an extremely wide-field stereoscope. Given a single assumption and the absolute position of both eyes, however, the two ordinary monocular visual field maps are sufficient to construct a VVF, much the same way one can determine the depth in a stereogram from the projections of its half-images. The assumption is that if a stimulus falls on healthy retina in either eye, it will be detected. That is, scotomatous retina is assumed not to suppress images that fall on healthy retina in the other eye.

The simplest method of computing the VVF requires both monocular field maps, obtained in the traditional fashion, that is, with the eye being tested centered in the perimeter bowl. These measurements establish the direct correspondence between field map coordinates and retinal coordinates. In contrast, the binocular viewing method of Esterman (1982), in which the *head* is centered in the perimeter bowl, disrupts this correspondence, presumably to give the measurements significance in environmental space. But Esterman's method gives the visual field only on the surface of the perimeter bowl and will fail to show points, at depths nearer or farther than that surface, that cast images into scotomas of both eyes at once (see below). In fact, all information about the z axis is lost in this representation. The present method, on the other hand, will retain monocular retinal field information so that the field maps may be projected back to the environmental space that they serve, with no loss of

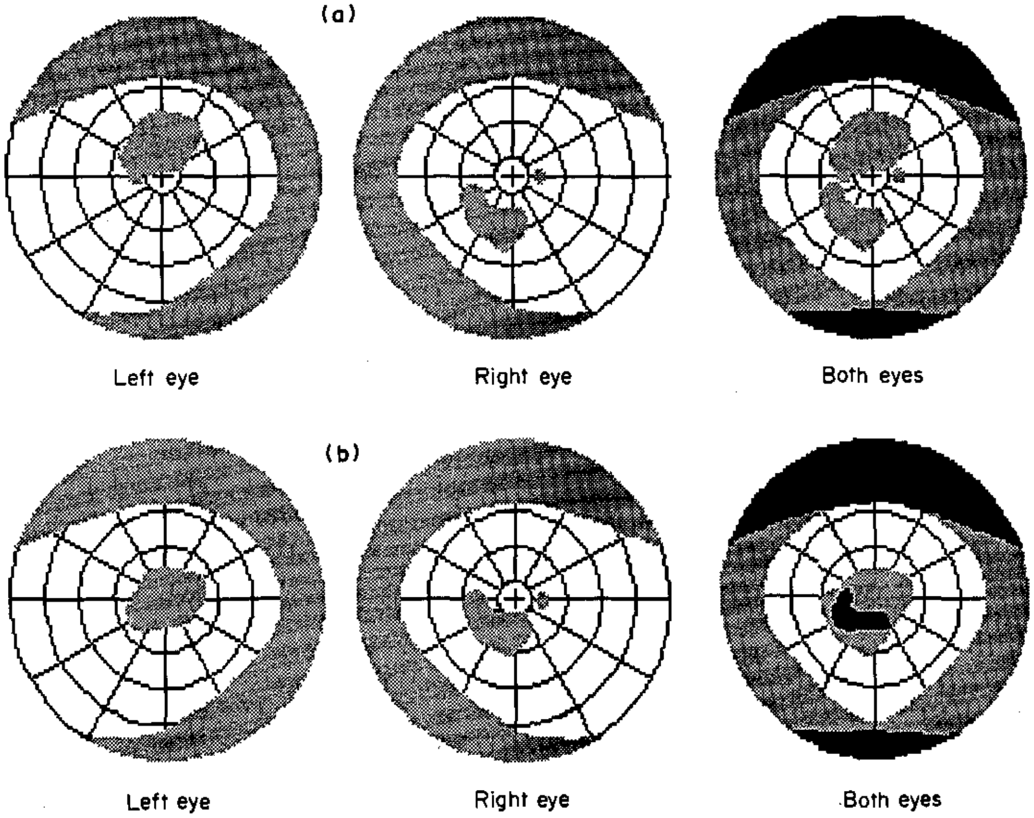

Fig. 2. (a) Scotomas that fall in the area of binocular overlap share no vertical coordinates in the two eyes, do not produce volume scotomas, and hence produce little functional loss, because one or other of the eyes can detect all points that are detectable with two normal eyes. (b) The intersecting region of overlap on the two retinas at some assumable convergence angle is where images must fall, to fall into the scotomas of both eyes at once. Since the intersecting region (shown in black) exists at corresponding points on the retinas, the fixation plane will pass through the volume scotoma that would result from the fields shown. The superimposed fields on the right side of the figure are retinocentric binocular field maps; both show the eyes viewing straight ahead, with convergence to infinite distance. The curved shaded outer regions represent areas occluded by bony structures of the face.

spatial information. Once the monocular fields have been obtained, no further testing is required; the remaining work is computational. In another paper (Arditi *et al.*, in preparation), a microcomputer-based system that performs this analysis very simply, is described.

The monocular fields thus obtained have angular coordinates relative to the nodal points and the centers of rotation of each eye (since in this case the nodal points and the rotational centers are aligned), and are appropriate to describe both retinal and environmental loci. For the present purposes we will consider these maps to refer to the *retina*, though for convenience, we continue to use visual field rather than retinal coordinate conventions. That is, for example, the right side of the right eye's field map is still referred to as the temporal, the left side nasal, and so on.

Consider the superposition of two such field maps, as on the right side of Fig. 2, labeled "both eyes". The right side of this type of map is the temporal side for the right eye's map, but the nasal side for the left eye's map. Similarly, the left side of the superimposed map is the temporal side to the left eye and the nasal side to the right eye. While at first glance, this system may seem confusing, it has the virtue of sharing its *two* dimensional topography with that of environmental space. That is, left and right on the superimposed map refer to left and right in space, respectively, for *both* eyes. I will refer to these superimposed field maps as *retinocentric binocular field maps* to distinguish them from the similarly appearing but quite different binocular field maps that are associated with perimetry obtained under binocular viewing conditions.

Since this superimposed map refers to the two *retinas*, the field positions of occlusions such as the nose, nose bridge, and brow (shown as outer shaded areas on the fields of Fig. 2, must shift as the eyes change position. In contrast, positions of scotomas of the two eyes, including the normal blind spots, are constant over all eye positions. The effect of a change of eye position is to shift only the occlusions by the amount corresponding to the shift in each eye. For example, convergence along the midline of 5 deg produces a -2.5 deg shift of the image of the right eye's bony occlusions, and a $+2.5$ deg shift of the left eye's. The significance of changing eye position is discussed below.

THE VOLUME SCOTOMA

Although we are accustomed to describing scotomas in two dimensions, it is obvious that their functional impact must depend on the *volume* of space that is not visible to the observer, rather than the area of the scotoma on the retina. For this reason we define the *volume scotoma* as a set of points in horizontal (x), vertical (y), and (z) linear distance coordinates that can be detected by neither eye as a result of falling simultaneously into scotomas or in the shadows of occlusions (such as the nose) of both eyes, or into a scotoma of one eye that falls outside the area of binocular overlap. The significance of the volume scotoma should not be confused with an inability to appreciate stereoscopic depth, despite the similarity between the geometry that defines some volume scotomas and that of stereoscopic space. Instead it signifies an actual volume of blindness in environmental space. Volume scotomas may be of *finite* volume, as when there are vertically correspondent scotomas in the two eyes, the projections of whose inner and outer boundaries intersect in front of the observer (e.g. Fig. 3a), or when the projections of the inner and outer boundaries of the scotoma in one eye intersect with the projection of a facial occlusion in the other eye such as the nose (Fig. 3b). They may also be of *infinite* volume, as is the case with all scotomas under monocular viewing conditions (Fig. 3c) and with all scotomas that fall outside the area of binocular overlap, or when the projections of the inner boundaries of vertically correspondent scotomas in the two eyes intersect in front of the observer, but the outer boundaries do not (Fig. 3d). The method for mapping a volume scotoma is simple: One simply projects the image of scotomas and occlusions to environmental space, and then computes the intersecting volumes. One cannot effectively represent the information of a VVF in a two-dimensional view of the visual field, but with successive transverse sectional views (i.e. as if from above the observer's head) one can construct an image of the VVF.

Volume scotomas are always the result of vertical coincidence between a scotoma or occlusion in one eye and a scotoma or occlusion in the other eye. (All scotomas in monocular vision are volume scotomas.) Where scotomas share no vertical coordinates in the two eyes, there is no resultant functional blindness (see Fig. 2a). That is, the VVF for an individual with widespread but vertically nonoverlapping scotomas would be the same as for normal observer, disregarding binocular summation

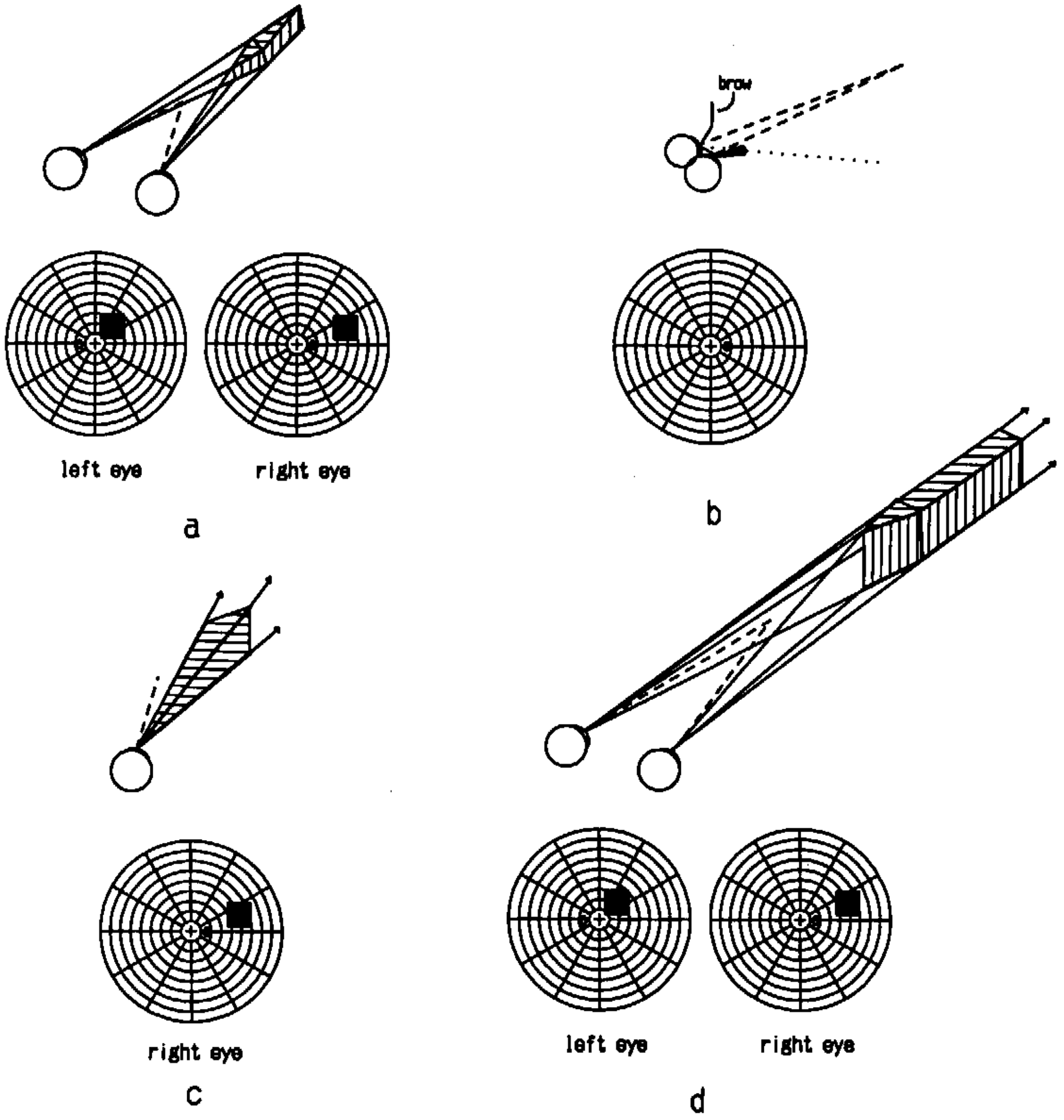

Fig. 3. Different types of volume scotomas (shown shaded), and field maps that might produce them. (a) A finite volume scotoma formed by the intersection of two vertically coincident but horizontally disparate square scotomas. This kind of volume scotoma is not represented in binocular field maps. (b) shows a finite volume scotoma (the shaded cone) formed by the intersection of the right eye's normal blind spot with the occlusion of the nose bridge (the left eye and its blind spot volume scotoma is occluded from the reader's view by the nose bridge). The connected dashed lines indicate the lines of sight, while the near horizontal dashed line represents the left eye's projection of the image of the nose bridge. This type of volume scotoma is nearly always present in normal perception, at least by individuals whose nasal field boundaries are determined by the nose or nose bridge (see Mapp and Ono, 1986). (c) With monocular vision, retinal scotomas produce volume scotomas that are infinite in extent along the depth axis. Scotomas that fall within the monocular crescents are usually infinite, but may sometimes be brought into the area of binocular overlap by a change in eye position. (d) Infinite extent scotomas also may result with binocular viewing, when specific convergence angles are assumed. The situation depicted in (d) differs from that in (a) only by a change in the observer's convergence angle.

effects (Blake and Fox, 1973; Blake *et al.*, 1981). When scotomas in the two eyes partially coincide vertically, a volume scotoma may result whose vertical extent is the extent that is shared by both scotomas (Fig. 2b). Indeed, the scotomas of most patients with field defects in both eyes, do at least partially coincide vertically, probably because the two eyes are likely to be afflicted with the same pathology. It is interesting to note, in this regard, that Johnson and

Keltner (1983) found that drivers with field loss in both eyes had accident and conviction rates twice as high as those with normal visual fields, though those with field loss in only one eye did not differ significantly from those with normal fields.

Note that scotomas need not coincide horizontally in the two eyes to produce volume scotomas. If they do fall on corresponding points in the two eyes, they will produce blindness in a volume of (x, y, z) space that contains the horopter; when scotomas are horizontally but not vertically disparate, the volume of blindness will generally be located closer or farther from the observer than the fixation plane, at the intersections of their projections.

Note also that not all vertically coincident but horizontally disparate scotomas that fall in the area of binocular overlap in the two eyes, produce volume scotomas. Generally, such volume scotomas are possible only when scotomatous points have horizontal disparity of less than about 26 deg uncrossed disparity. This is approximately the maximum convergence angle that can be assumed comfortably (for further discussion of this issue, see Arditi, 1987), and is consequently the maximum uncrossed disparity that objects in space can produce on the two retinas. One reason the normal blind spots do not produce volume scotomas is that there are 26 or more deg of uncrossed disparity between all points within them (Arditi, 1987).

Nearly any amount of *crossed* disparity of scotomas falling in the area of binocular overlap may produce a volume scotoma, however. The asymmetry between crossed and uncrossed scotoma "disparities" arises from the fact that very near objects may produce horizontal image disparities greater than those that may be resolved by convergence, whereas no physically realizable object can produce divergent disparity greater than that resolvable by zero convergence angle.

EFFECTS OF EYE POSITION ON THE VOLUME VISUAL FIELD

The VVF, then, is the set of points in egocentric space that are visible to either eye *with fixed eye position.* It should be regarded as one of a family of VVF's, each representing the visible environment for a particular position of the eyes. This section illustrates specifically how changing eye position affects retinocentric binocular field maps and the VVF.

Convergence angle

Convergence affects three aspects of visibility: (1) extent of visual panorama; (2) extent of the area of binocular overlap in the retinocentric binocular field; and (3) position and extent of volume scotomas in the VVF. Under some conditions, changes in convergence position can eliminate volume scotomas, and in other cases, produce them.

Panorama, the horizontal angular extent of the normal field binocularly viewed, increases some 26 deg at each horizontal meridian as one changes convergence from its maximum (26 deg) angle at about 14 cm viewing distance to its minimum angle (0 deg) at infinite viewing distance (see Fig. 4). This is because the temporal boundaries of the VVF are determined by eye position, rather than by occluding facial structure. Hence, when the eyes rotate inward with increased convergence, the temporal boundaries also rotate inward. The 26 deg boundary increase, of course, is far greater in the areal terms of the binocular visual field, and still greater in the volumetric terms of the VVF (see Fig. 4). While the difference in panorama may not markedly affect detectability for those with normally wide fields, those with reduced peripheral vision may, in contrast, be affected markedly. In such individuals, where the temporal boundaries of the field are less eccentric and generally of higher resolution and sensitivity, the additional flanking volumes with decreased convergence may significantly increase the probability of obstacle detection along the edges of the volume field. Indeed, to an individual with central visual fields of 10–20 deg temporal extent, a few degrees of additional flanking field make a far greater difference in ability to detect objects off to the side than they do to an individual with fields of normal temporal (90+ deg) extent. The functional difference may be further amplified by the higher spatial resolution of the central relative to the peripheral fields, and the proximity of the reclaimed field to the locus of attention.

It is important to recognize, however, that since convergence angle accelerates sharply with decreased viewing distance, much more of the decrease in panorama comes about within the range of near viewing than within an equivalent range of more distant viewing. That is, panorama changes by about 16.5 deg within convergence to 14 (approximate near point) and 40 cm (approximate reading distance), but only by about 9 deg between 40 cm and infinity.

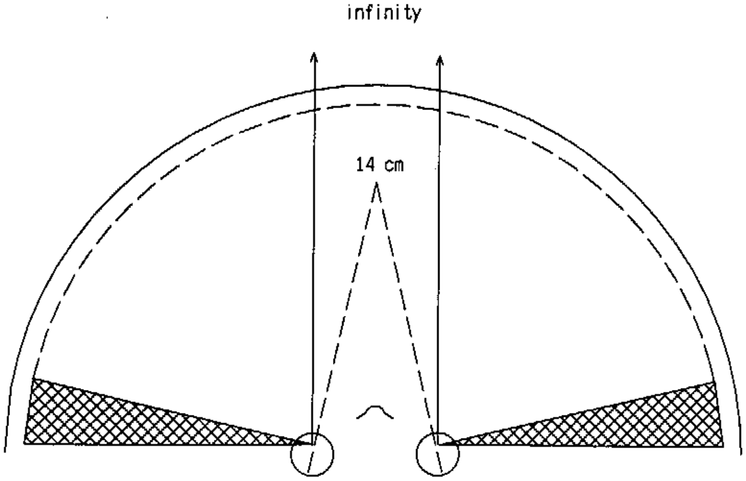

Fig. 4. The effect on panorama of changing convergence position. The solid lines show the eyes converged to infinite distance; the solid arc shows the visible panorama of the binocular field. The dashed lines and arc show the eyes converged to close distance, and the resulting panorama—reduced by an amount equal to the convergence angle. The shaded wedges show a top view of additional volumes in the VVF that are gained by convergence to great distance. Along all meridians, the horizontal extent of the binocular field is greatest with convergence to infinity, and decreases by the convergence angle. This may have the greatest consequences for individuals with restricted temporal fields.

Convergence position also determines the horizontal extent of the area of binocular overlap on the retinas. Again the horizontal extent varies about 26 deg with convergence angle, simply because with increased convergence, the images of the bony occlusions are moved closer together on the retinocentric binocular field map. Contrary to the common intuition that tells us that binocular vision seems most useful at close range, the area of binocular overlap is actually largest with convergence to infinity. This is the region over which field defects in one eye can be compensated for by healthy retina in the other eye. Figure 5 shows how the area of binocular overlap changes with convergence angle. Notice again, that in areal terms, the gain in field is quite substantial. In the example shown in Fig. 5, converging to infinity increases the area of the overlapping region by 37% relative to near (14 cm) convergence. Much of this gain (23%), again, is accomplished in the first few cm of vergence change from 14 to 40 cm (approximate reading distance), but with convergence to 40 cm, binocular overlap area is still reduced by 14% relative to convergence to infinity.

The third and final way the VVF is affected by changes in convergence eye position is in the position and extent of volume scotomas. The volume scotoma must shift in space with shifts of the eyes, because each eye's scotoma and hence the intersection of the two eyes' scotomas now receive images from different loci in environmental space. The linear extent of a (finite) volume scotoma along the z axis follows a law analogous to the familiar square law of stereoscopic depth: a *finite* volume scotoma of fixed extent in horizontal retinal disparity

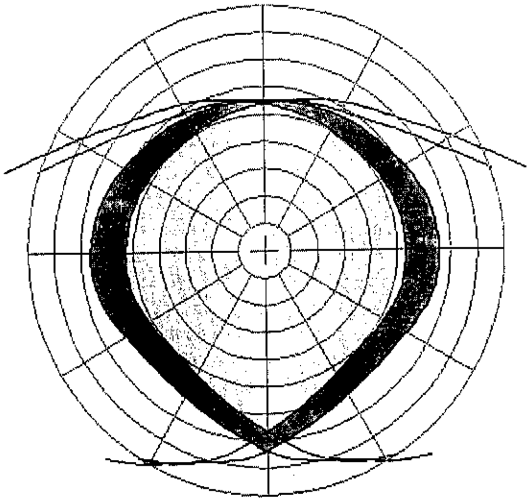

Fig. 5. Retinocentric binocular field map showing the effect of changing convergence position on area of binocular overlap. The lightly shaded area is the area of the two retinal images that receives from the same environmental loci when the eyes are converged to a distance of 14 cm. The darker shaded area is the increase in area of overlap when the eyes are converged to infinity.

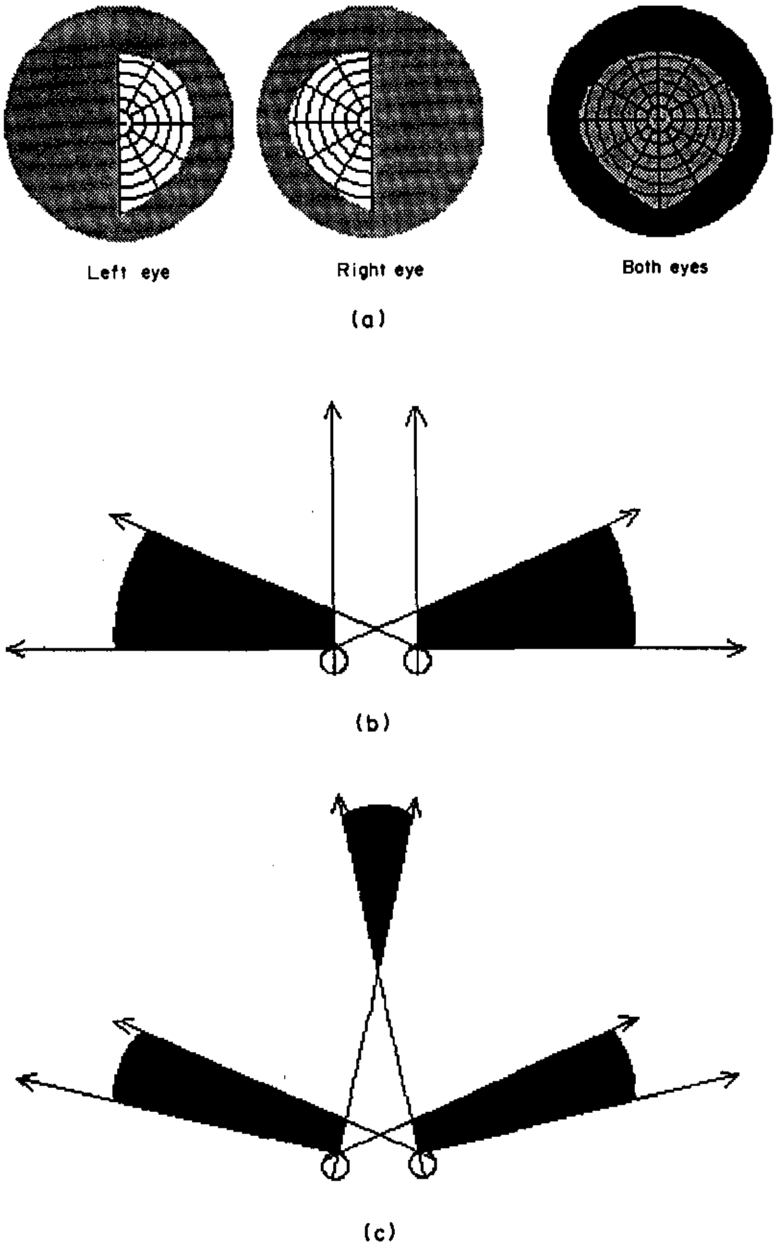

Fig. 6. The bitemporal hemianope has normal functional fields within the area of binocular overlap when converging to infinity, but has a significant volume scotoma extending from the fixation point to infinity, when converging near. (a) shows the monocular field maps with potential functional loss shown shaded. The retinocentric binocular field map on the right side of (a) shows in black all areas which neither retina serves, and in gray, those areas served by one or the other retina. (b) shows volume scotomas only in the flanking regions of the VVF, with convergence to infinity, while (c) shows the appearance of a volume scotoma at the fixation point and extending to infinity, with convergence to near distance.

units produces blindness to a volume whose extent in z is proportional to the square of the linear distance to the volume scotoma. Since some volume scotomas may change from finite to infinite and vice versa depending on eye position, however, the laws governing extent of all volume scotomas are somewhat more complex.

Less obviously, however, some vergence eye positions may give rise to large volume scotomas that are simply not present with the adoption of a different convergence position. A particularly striking example (shown in Fig. 6) is given by the classic field pattern of the bitemporal hemianope, who, within the area of binocular overlap, has a binocular field that is the same as that of a fully sighted individual when converging to infinity, but acquires an enormous volume scotoma just behind the fixation point, when converging to close distance. Thus when looking off in the distance, the bitemporal hemianope has little more problem than a fully sighted observer (within the area of binocular overlap). But when looking at the dashboard while driving, he or she may have trouble seeing the road ahead!

The functional field of greatest area, then, is that provided by convergence to infinity, both because of possible compensation of defects by the other eye, and because of the increased area along the temporal boundaries of the visual panorama.

Direction of gaze

Horizontal and vertical eye position changes affect the VVF by (1) shifting the position of the visual panorama, (2) shifting the area of binocular overlap in the retinocentric binocular field, and (3) alter the egocentric position and extent of volume scotomas. Like vergence movements, they may, under some conditions remove and under other conditions, produce volume scotomas that would otherwise be absent.

Shifts of visual panorama due to horizontal conjugate eye movements are quite simply, changes in what portion of environmental space is visible to the observer, and need not be belabored, except to note that size of the visual panorama is generally unaffected by conjugate movements.

Conjugate changes in eye position, on the other hand, do shift the position of the area of binocular overlap in the retinocentric binocular field map (see Fig. 7). In other words, the retinal areas of the two eyes that *comprise* the area of binocular overlap are shifted with shifts in eye position. Such shifts may have surprising consequences. Consider a pair of retinal scotomas, falling within the area of binocular overlap in each eye, but sharing no vertical coordinates, so that at locations where scotoma renders one field dysfunctional, the other eye compensates, and vice versa. One can see that since in the retinocentric binocular field map, the overlap area but not the scotomas will shift position, some eye positions will cause one or both scotomas to fall outside the binocular overlap area, because of occlusion of the retinas by facial structures. When this happens, the scotoma cannot be compensated for by healthy retina in the other eye, and hence the patient has a volume scotoma of infinite extent (See Fig. 8).

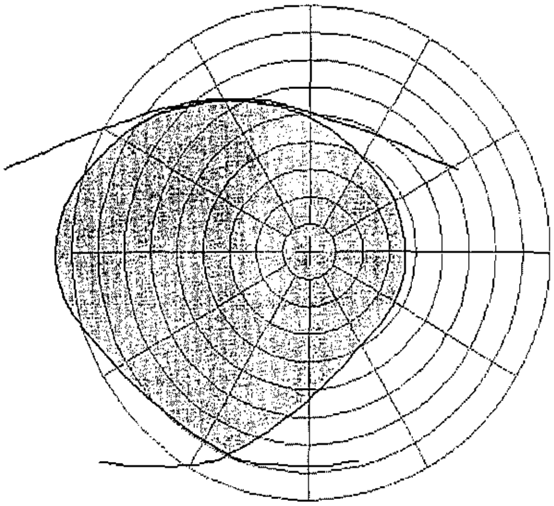

Fig. 7. Retinocentric binocular field map showing the effect of horizontal eye position on the position of area of binocular overlap on the retinas. With lateral shifts of eye position, the areas of the retinas that comprise the area of binocular overlap change.

Conversely, there may be scotomas that fall outside the area of binocular overlap with straight ahead viewing that may be brought into the area of overlap with an appropriate shift of gaze. Very possibly, some patients with visual field defects adopt the habit of asymmetric viewing positions for just this reason: to maximize the size of their VVF. Finally, for completeness, note that as the eyes shift laterally, so do the egocentric locations of volume scotomas falling within the area of binocular overlap. Practically, this means that a patient with widespread volume scotomas is faced with a highly confusing visual environment in which objects constantly appear, disappear, and reappear, in three dimensions. Most scotomas are experienced as "filled in," and with vague and undefined boundaries. Vergence and version eye movements generally may make objects in the world less constant, less predictable, and more bewildering to many low vision individuals.

CONCLUSION

The above analysis approaches visual field analysis in a rather different way than previous attempts, attempting to answer the question of what is visible to an observer on geometrical grounds before approaching the more complex issues relating to the relative importance of different field locations in performing visual

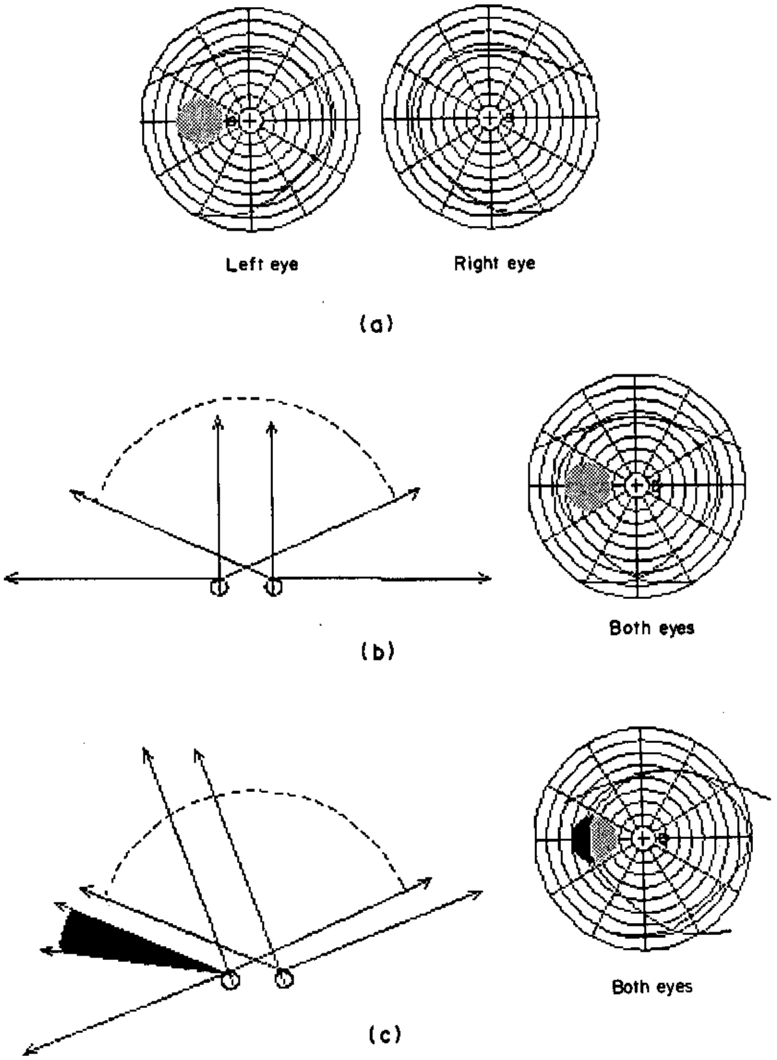

Fig. 8. A monocular scotoma becomes a volume scotoma with lateral gaze shift. (a) shows the fields of an individual with a left eye scotoma. (b) shows that the functional field is intact because the scotoma falls within the area of binocular overlap (dashed curve, left side). (c) shows a leftward versional movement of the eyes, causing the area of binocular overlap to shift rightwards on the retinocentric binocular field map. Part of the left eye's scotoma now falls in a wholly monocular area, and hence produces a volume scotoma (shown in black).

tasks. The analysis described above includes no corrections for retinal inhomogeneities nor spatial weightings of importance in visual functions, although it is certain that these play an important role in any accurate functional perimetry. Thus far the analysis does not incorporate what are surely important effects of optical defocus on the VVF. For, objects well off the focal plane (and usually the fixation plane) will cast degraded, and spatially spread images. Such images may or may not be detectable, depending on their retinal size, contrast, color, and other factors, including the refractive condition of the observer.

But volume perimetry does provide the foundation for representation of environmental visibility to an observer whose visual apparatus is distributed at two distinct locations in the head.

Acknowledgements—The author thanks Kenneth Knoblauch and Suzan Uysal for their many insightful comments and suggestions. This work was supported by National Institutes of Health Grant No. AGO6551.

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