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Alternative representations of visual space

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ABSTRACT

Although each retinal image is two-dimensional, binocular geometry requires complete representations of field of view to be three-dimensional: the set of visual directions from which light can impinge on *either* retina can be fully represented in no less than three dimensions. An easily interpretable means of representing environmental space as viewed by a human operator would have wide application in many areas of human factors engineering.

This paper discusses a method for delineating and testing hypotheses about the relationship between the retinal images and the three-dimensional visual space they serve, under the conditions of (a) changing eye position, (b) occlusion by structures that are part of or are mounted on the observer such as the bony facial structures, spectacles or headgear, (c) occlusion by environmental objects, (d) defects of the visual field such as the normal blind spot, areas of temporarily reduced visibility due to local adaptation and photopigment bleaching effects, and (c) variables that alter the focus of environmental imagery on the retinas.

1. INTRODUCTION

Given that we perceive in a three-dimensional world, how do we represent the set of visual directions, those directions from which light can impinge on functioning retina? The traditional representation, the *visual field*, is shown in Figure 1. It is inadequate for representing typical visual circumstances both because it is two- rather than three-dimensional, and because it represents only one eye's view of the world, whereas the typical observer uses the receptor surfaces of *both* eyes. Often, the *binocular visual field* is used to to represent the set of visual directions for the two eyes (Figure 2), but that representation is also inadequate. Its most important failure is that it can only depict a single surface of visibility. It assumes that the eyes are converged to a particular distance and is capable of representing only points *at that distance* which cast images on functional retina in either eye. It cannot depict the visibility of objects situated away from the convergence distance in depth.

In the ophthalmological domain, where scotomas (local retinal areas of blindness) often fall on disparate locations in the two eyes, such maps cannot even depict some volumes of visual space to which a patient may be totally blind (Arditi, 1988). Despite this, the currently accepted technology for assessing disability in the functional visual field uses only this type of representation (Committee on Rating of Mental and Physical Impairment, 1988; Esterman 1982). Even if we display the visual fields of both eyes, it is difficult to visualize exactly what portions of visual space an observer *can* see.

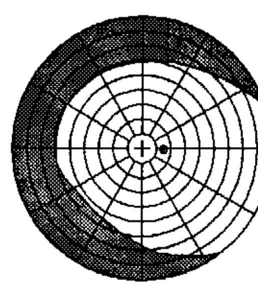


Figure 1. The normal visual field of the right eye. The origin of the field corresponds to the fovea, where visual acuity is highest. Each radius represents 10 deg of visual angle. The shaded area surrounding most of the field represents the boundary of occluding facial structure. The small egg-shaped shading about 15 deg in the temporal field is the normal blind spot, produced by the absence of light sensitive receptors in the region where the optic nerve exits the retina.

In the human factors engineering domain, methods for representing visibility of a binocular observer are also critically lacking. The problems are generally of usefully depicting on a single display 1) the two views of the environment that the binocular observer has, given that objects whose view may be occluded at one eye may in fact be visible to the other eye, and 2) the *volumes* of space that may or may not be visible to an observer given local areas of reduced sensitivity in the two eyes due to retinal bleaching or damage incurred from viewing high energy light flashes.

The solution offered here relies on two graphic constructs, each of which depicts in *two dimensions* aspects of field of view that are useful in delineating and testing hypotheses about visibility of objects in space on the basis of purely geometrical considerations. It does not address many other important factors contributing to visibility such as retinal inhomogeneity and adaptation level, though the solution may be useful in analyzing the effects of such factors.

The graphic constructs offered are currently implemented on a Commodore-Amiga 1000 microcomputer, and we have begun porting to and enhancing this system on a Silicon Graphics IRIS 4D/50G system.

2. THE VOLUME VISUAL FIELD

The first construct is called the *volume visual field*, and it is defined as the set of loci in space from which light can impinge on either of the two retinas, given fixed eye positions. Each locus has coordinates in ordinary environmental space (x, y, z), where the origin is taken to be the midpoint of the line connecting the centers of rotation of the eyes. Figure 3 shows a top view of the normal volume visual field, given eye convergence to a near distance. Our software, which allows the user to move the eyes in x and z in this view by moving a cursor located at they eyes' convergence distance, also displays a side view of the eyes (e. g. Figure 5b) permitting eye movement in y and z as well. By manipulating both these views, the user can produce any combination of naturally assumable lateral, vertical, or convergence eye positions.

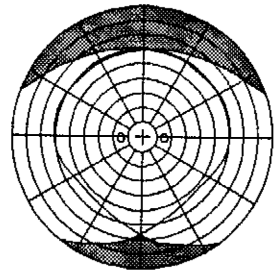


Figure 2. The binocular visual field.. Shaded areas represent field locations that are occluded or dysfunctional in both eyes, i. e. directions in which neither eye can see.

3. THE RETINOCENTRIC BINOCULAR FIELD

The second construct is the *retinocentric binocular field*, defined as the set of retinal locations which are both light sensitive, and unoccluded by facial structure or head mounted gear, such as spectacles, also given fixed eye position. The retinocentric binocular field consists of points with three values (θ,ϕ,O). θ and ϕ are horizontal and vertical visual direction, as conventionally defined for the monocular field, and $O \subseteq \{l,r\}$; that is, O identifies the eye of origin of field points. Figure 4 illustrates a graphic representation of the retinocentric binocular field of a normal binocular observer. It is important to note that there are two superimposed origins on this representation, one for each eye, and that the right side of the graph is the temporal field of the the right eye and the nasal field of the left, while the left side is the nasal field of the right eye and the temporal field of the left. The blind spots and facial structures shown are graphic objects that may be drawn with a paint program and subsequently loaded. Obviously, graphic objects representing arbitrary retinal imagery of head-mounted and environmental objects, and arbitrary patterns of retinal sensitivity, may be used with such a system.

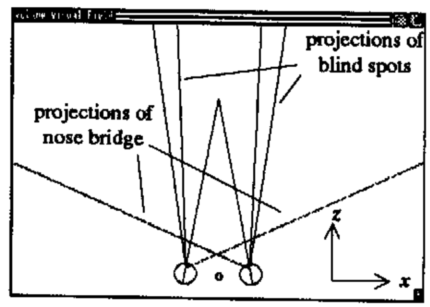


Figure 3. Top view of the normal volume visual field., with projections of the blind spots and occlusions of the nose bridge. shown. The origin of the volume visual field coordinate system is marked with an O .

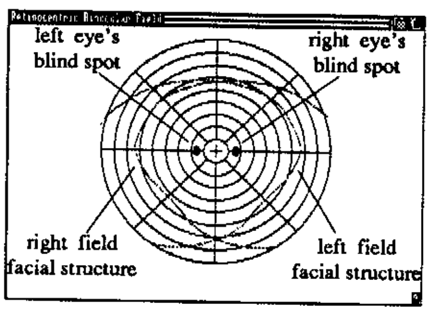
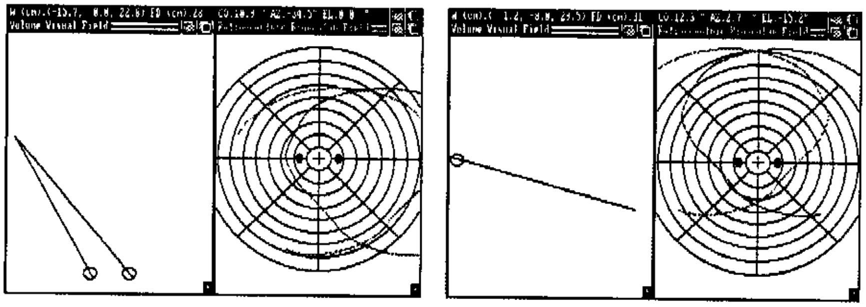


Figure 4. The normal retinocentric binocular field, constructed graphically as the superposition of the visual fields. Although not apparent in the graphics of the present article, our software codes O, the eye-of-origin, with color--elements arising from the left eye shown in green, while those from the right are shown in red.

4. APPLICATIONS

Our system, called *VP*, to stand for for volume perimetry, integrates the volume visual field and the retinocentric binocular fields, displaying each in a separate window of the computer display. The representations are yoked so that motion of the eyes in the former produces appropriate movement of certain graphic objects (e. g. the facial occlusions) in the latter. The relationship between these two representations and how their behavior covaries with eye movements is easily grasped. For example, Figure 5 shows the fact that areas of the retinas that are common to both eyes shift with eye movements. Although not illustrated here, with this kind of graphic one can also easily see the size changes of this area of binocular overlap that come about from changing viewing distance from near to far (on the order of 40% in areal terms). Functionally this is important because this is the area within which stereoscopic vision operates, and within which vision is otherwise enhanced by viewing with two eyes rather than one (Blake and Fox, 1973). One can see that such functions are not necessarily restricted to the central 120 or so deg, as is often believed, and that we need not view visual directions that fall in the shadow of the



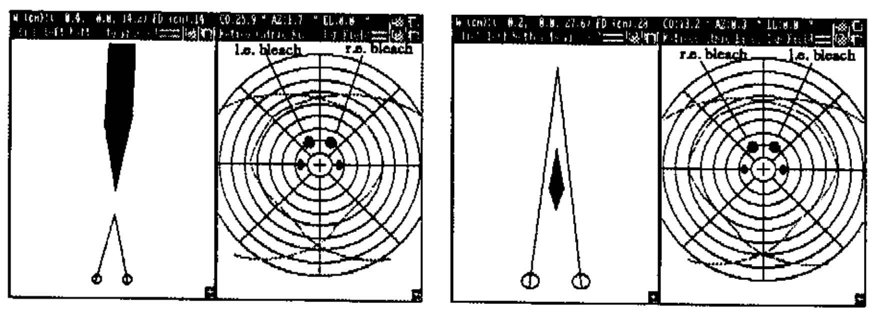
(a) (b)

Figure 5. Effects of lateral and vertical shifts of gaze on the retinocentric binocular field. (a) illustrates looking left, while (b) shows looking down.

nose as dysfunctional or unused retina. When the eyes move, these visual directions become as functional as any. Indeed, any map of retinal sensitivity and arbitrary imagery of environmental and head-mounted objects may be loaded into VP in order to assess which eye positions allow objects to be imaged on particular retinal locations in the two eyes. An expanded discussion of the theory underlying volume perimetry, from a clinical vision science perspective, can be found in Arditi (1988).

While the retinocentric binocular field representation is useful for depicting such relationships between retinal images and elements, the volume visual field is correspondingly useful in depicting visual function in the domain of environmental space.

For example, suppose that an observer has been exposed to a visual stimulus sufficiently intense to render a particular portion of each retina locally less sensitive, say a camera flash. If the photographer is more distant than the observer's fixation distance, the area of local bleaching on the retinas might look like the left panel of Figure 6a, which shows a top view of the the volume of space within which objects would be less detectable by reason of the bleaching and adaptation. Notice that both the the right and left eyes' bleaches are in the temporal fields of each eye.



(a) (b)

Figure 6. Volume visual and retinocentric binocular fields portraying volumes of visual space of reduced visibility due to bleaching, of a light flash in the,superior field. (a) shows the volume of reduceed visibility more distant and (b) closer than the fixation distance. Note that the volume field of (a) is shown at a different level of zoom than (b).

If the photographer is closer to the observer than the fixation point, of course, the volume appears in a different place and is of somewhat different shape (see Figure 6b). Here the bleaches are in in the nasal fields of the two eyes.

Actually the situation is a bit more complex than what is depicted, because since these volumes are not located equidistant to the fixation point, they are also not located at the most likely accommodation distance, and images emanating from these volumes may be somewhat defocused. The Amiga version of VP places outer bounds on the geography of these volumes of reduced sensitivity in space. The IRIS version of VP currently under development will additionally model retinal blur from objects located off the fixation plane and will display this blurred imagery on the retinocentric binocular field.

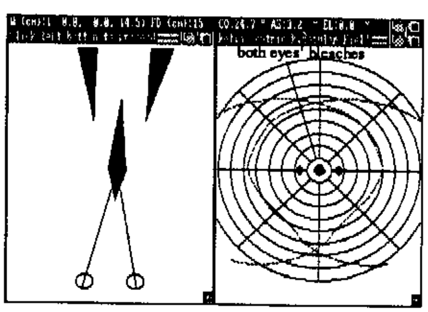


Figure 7. Volume visual and retinocentric binocular field of a normal observer with a central retinal area of reduced sensitivity caused by retinal bleaching or other factors such as night viewing.

Suppose now that the observer is fixating the flash, and that both central retinal regions are now bleached (Figure 7). In this situation there are three volumes of local insensitivity affected in space, those volumes within which an object may fall into both areas of reduced retinal sensitivity (the bleached areas), or into that area in one eye and the normal blind spot of the other eye. Figure 7, incidentally, also approximates the normal volume visual field for an observer viewing dim stimuli at night. Because there are no rods (photoreceptors of highest absolute sensitivity) in central vision, normal observers have central blind spots to dims stimuli at night.

One other interesting type of view falls out of the volume visual field analysis. Figure 8 shows a top view of an observer's eyes fixating a point in space labeled "f." Projections are drawn to indicate an arbitrary retinal region of high visual acuity, say within which 30 c/deg can be resolved on the basis of neural factors (Campbell and Green, 1965). Dashed lines are also drawn to in-

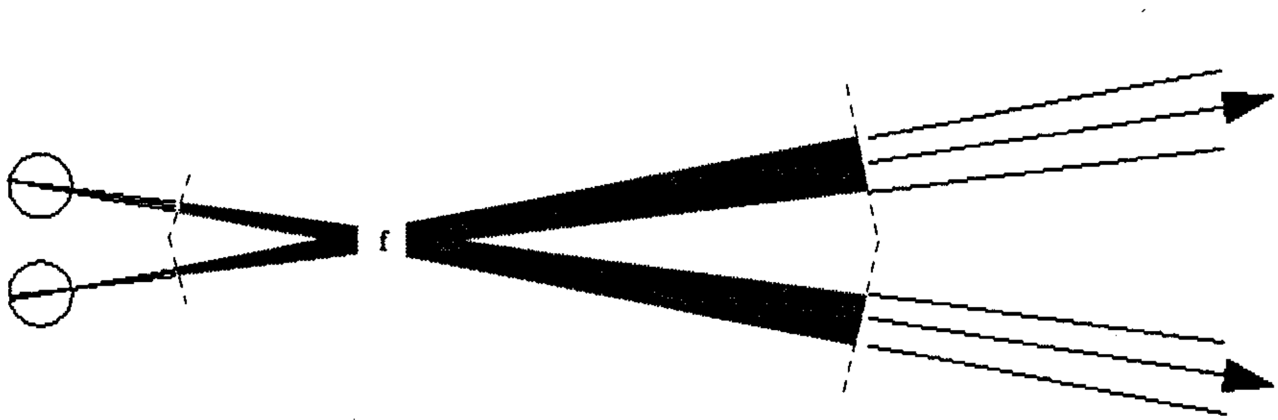


Figure 8. Theoretical region of space in which objects' images fall onto high acuity retina and are in sufficiently sharp focus to be effectively discriminated. Arrows indicate projections of the foveas. Solid lines indicate projections of retinal boundaries of high acuity region. Dashed lines show boundaries of necessary focus quality to permit high acuity discriminations. The shaded area is the intersection of these.

dicate visual acuity limits to the same 30 c/deg information, but on the basis of optical defocus rather than neural factors. Anything falling too distant from the focal point will not be discriminated because its image is simply too degraded, whereas anything that falls outside the central cones of high acuity will fail to be detected because they fall on retina with lower acuity due to neural factors. The odd shape shown as the shaded region, then is the volume of space within which an observer can discriminate this high spatial frequency information. One can apply similar analyses to other variations of visual function across the retina such as color discrimination (Baird, 1905).

When we consider strictly monocular vision, or when we permit visual stimuli to be presented only in the frontal plane, the ordinary visual field or the binocular visual field prove quite adequate. But when we become interested in typical visual function, that is, using two eyes, and with stimuli distributed in three dimensional space, the constructs presented above can be of considerable use.

5. ACKNOWLEDGEMENTS

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