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VISUALIZATION OF 2-D AND 3-D ASPECTS OF HUMAN BINOCULAR VISION

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Abstract

We have developed a computer graphic environment for modeling geometric relationships among visual imagery, retinotopic maps describing visual capabilities and visual space. Incorporating a simple model of visual optics, this interactive tool enhances exploration of linkages between 2-D and 3-D aspects of vision.

	Direction in *RETINA* window			
	⇐		⇒	
	Eye		Eye	
	Left	Right	Left	Right
Visual Field	Temporal	Nasal	Nasal	Temporal
Retinal	Nasal	Temporal	Temporal	Nasal

Table 1: Horizontal coordinate conventions used in *RETINA* windows. The table shows, for each direction and eye represented in a window, the direction in conventional visual field or retinal coordinates.

Introduction

We have developed a computer graphic tool for modeling geometric relationships among visual imagery, retinotopic maps describing visual capabilities and visual space. This approach grew out of an analysis of how visual field defects in the two eyes that occur as a result of ocular disease affect visual functioning in three-dimensional space[1], but has found additional application in analyses of normal vision[2], and in crewstation design[3, 4].

The main function of the tool, which is called *VP* and is implemented on a Silicon Graphics 4D workstation, is to elucidate geometric aspects of visual perception of a hypothetical observer. *VP* maintains two types of windows on the screen, one associated with the environment of this observer, the other associated with the observer's retinal imagery and retinal function. The former, which we call *WORLD* windows, describe the distal, while the latter *RETINA* windows describe the proximal, stimulus to vision. As the geometry of eye movements and of image formation in the eye are complex, *VP* uses a simplified model of visual optics. Figure 1 shows a half-tone rendition of one of *VP*'s screens containing one *WORLD* and one *RETINA* window.

WORLD Windows

WORLD windows are perspective renditions of the observer's environment. Under default conditions, they contain only a rendition of a ground plane to aid the user in interpreting the perspective view, and a model of the observer's eyes with the lines of sight drawn to indicate the fixation position in the environment. A user typically adds graphic object models to the *WORLD* window to represent objects that are in the view, or potential view of the observer's eyes. A parser reads model descriptions from files conforming to *VP*'s model description grammar. Model descriptions may be hierarchically defined, allowing the construction of arbitrarily complex models from more basic forms such as cubes, spheres, *etc.* In addition to the eyes, ground plane, and models representing objects in the visual environment, a *WORLD* window also has the capability to display what we term *retrojections* (see below).

When a *WORLD* window is active, the three-button mouse is used to change the location of the fixation point in space, and hence the positions of the eyes. Each button is associated with movement of the fixation point along one of the (x, y, or z) axes of the environment. In addition, the mouse can be used for changing the position of the center of projection and hence the viewpoint of the user in the *WORLD* environment.

RETINA Windows

RETINA windows map graphic retinal objects either arising from retinal imagery or from two-dimensional retinal models of the user's creation, onto coordinate axes whose origin represents the fovea. Generally, both retinas are represented superimposed on a single window, with directions indicated as shown in Table 1. Image objects are referred to as *projections*. Additionally, *VP* allows the

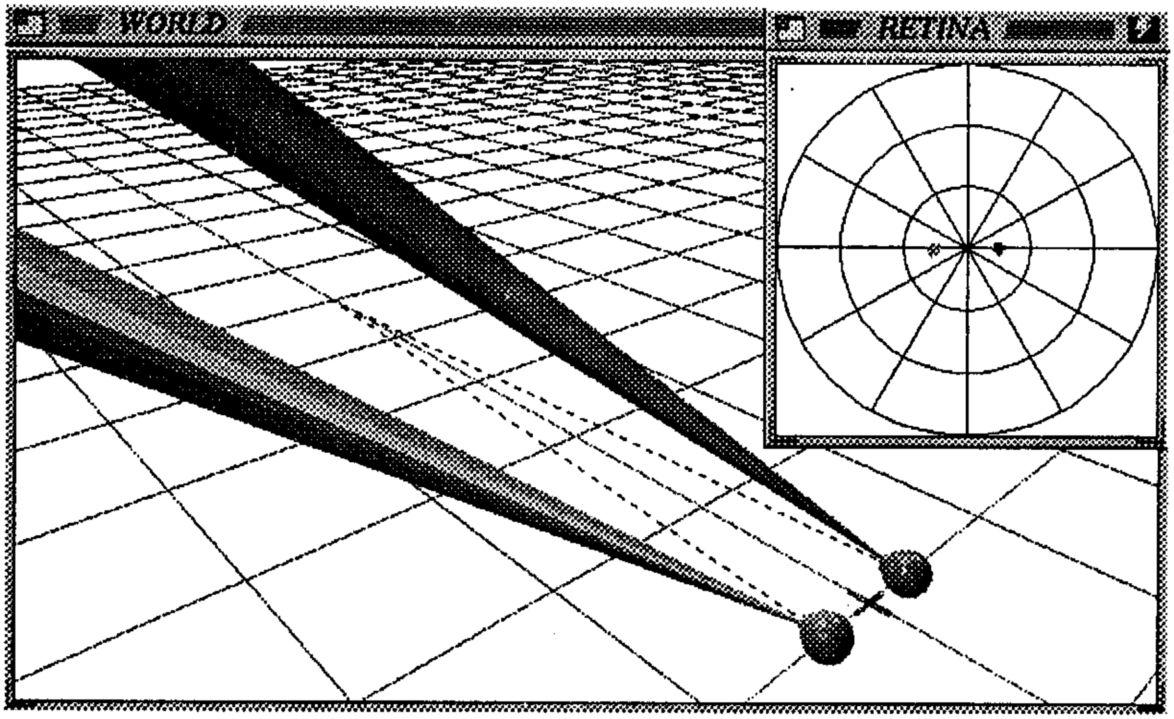

Figure 1: A screen of *VP* showing *WORLD* and *RETINA* windows. Shown here only in half-tones, color is used to code certain screen elements. Red and green code retinal objects and retrojections imaged in or arising from the right and left eyes, respectively. Dashed lines indicate the visual axes; the long cones are retrojections of the normal blind spots.

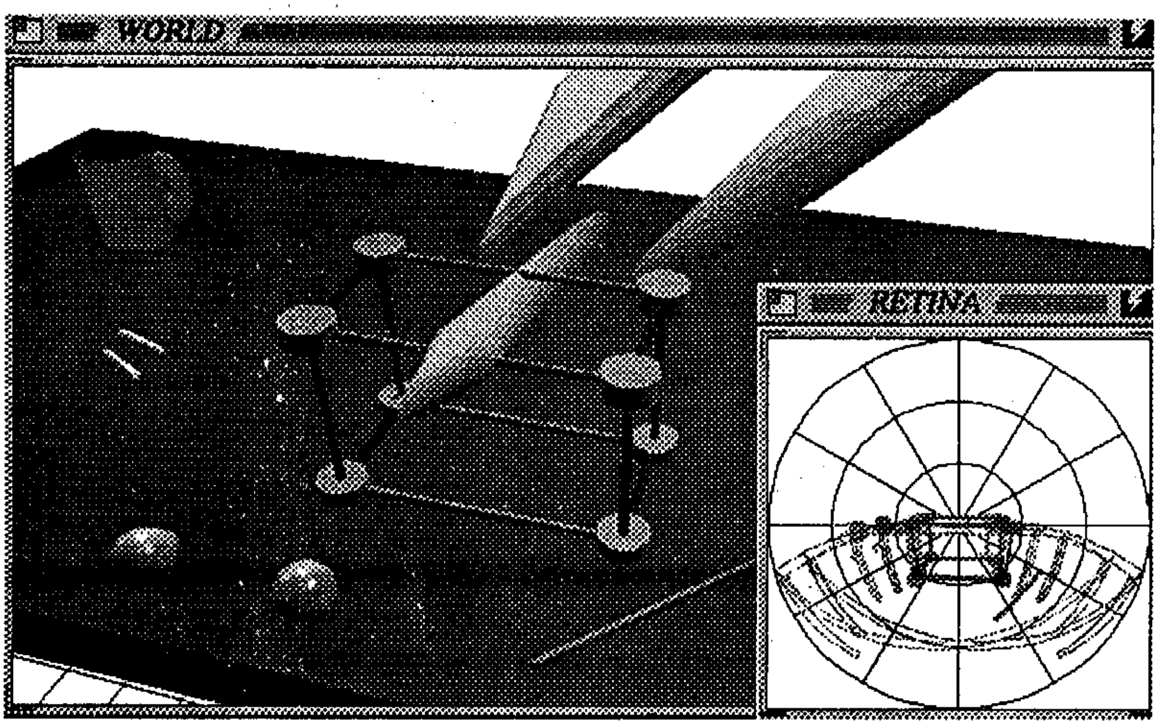

Figure 2: In this *VP* screen, the *WORLD* window depicts the eyes converged to the midpoint of the near top limb of the Tinker Toy model. The three oblong structures are volume reconstructions of all possible intersections of retrojections at this viewing distance corresponding to the normal blind spots and a central circular region of 10 deg diameter. The *RETINA* window contains these retinal elements in addition to retinal imagery of *WORLD* objects.

construction of two-dimensional *RETINA* models, which generally indicate aspects of visual function. For example, a *RETINA* model might bound a central retinal region within which visual acuity exceeds some value. Or it might indicate a region of complete visual dysfunction (scotoma).

The major functions of *RETINA* windows are 1) to represent image motion on the retinas as the eyes move, and 2) to display shapes of *WORLD* object models as they would appear on the retina in the perimetric coordinates that are familiar to most users

As in human vision, if the eye moves to foveate an image point falling on eccentric retina on the map, the coordinates of that point must completely specify the direction and magnitude of the eye movement required to fixate the point. In *VP* the Listing eye movement system of coordinates is adopted, where an eye movement from the primary position (eye straight ahead, head fixed and erect) is assumed to be accomplished by selection of a meridian ϕ (direction of rotation), rotation along that meridian to a parallel that corresponds to the magnitude of the eye movement θ, and rolling about the line of sight ω (see Figure 3). Good treatments of eye movement coordinate systems can be found in Alpern[5], Southall[6], or Hallett[7]. This system of axes is particularly convenient when Listing's law, which states that $\omega = 0$, is assumed, since, with the further assumption of a constant center of eye rotation, eye movements are completely determined with two degrees of freedom. Listing's law is generally found to hold approximately for normal observers, and especially for movements of less than about 25 deg (see Hallett [7], and is assumed in *VP*.

The particular projection chosen to represent the retina and associated eye in the default *RETINA* window is a zenithal equidistant projection of the Listing coordinate representation. Figure 3 is is an example of such a projection. Generally, the maps of both eyes are superimposed, to elucidate important features of the binocular field of view (see below). This projection is commonly used in visual perimetry and vision science, and is easy to comprehend, since the parallels are equidistant and denote visual angular distances from the fovea, or retinal eccentricity. Meridians of the map also faithfully indicate directions from the fovea. A further advantage of this projection is that its coordinates are linearly related to pixel and mouse position.

Several important aspects of vision are especially easy to appreciate in a *RETINA* window that displays the retinas of both eyes superimposed. First, where areas of permanent or transient retinal dysfunction are displayed, areas that are functional in at least one eye are displayed in red or green, or white. Where dysfunctional areas fall on corresponding locations in the two eyes, the intersection of those areas is displayed in yellow, indicating that the yellow region of the binocular visual f

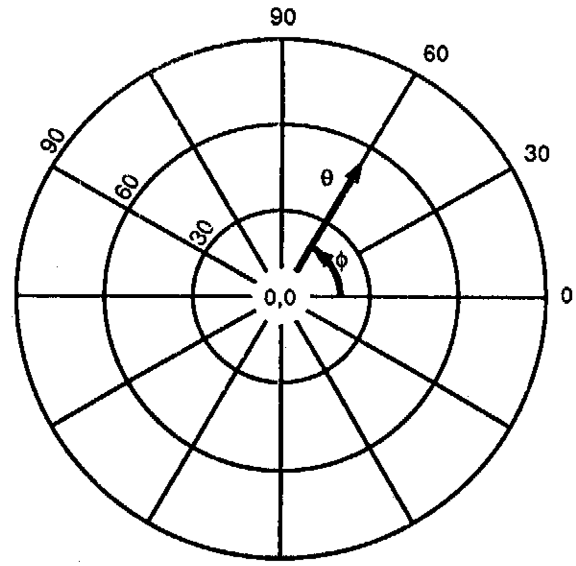

Figure 3: Zenithal equidistant projection of Listing coordinate system used in *VP*'s *RETINA* windows.

tional. Second, when retinal eccentricity of object imagery is different in the two eyes, one can visually compare eccentricity of the eye's images on the same coordinate map by comparing the red and green representations of the object. Third, since objects lying at distances removed from the fixation plane cast images on disparate retinal locations, the retinal disparity can be easily comprehended and computed directly from the map.

Linking *WORLD* and *RETINA* windows

Much of the power of *VP* lies in its ability to elucidate relationships between the proximal retinal visual stimulus, and the distal environmental stimulus. Figure 2 is an example of a screen that depicts such relationships, showing both retinal elements such as the blind spots and a central 10 deg dysfunctional region, in addition to retinal imagery of the world, viewed in wireframe.

Projection of retinal images. In *VP* *WORLD* object models can be rendered not only in *WORLD* windows, but in *RETINA* windows as well, to represent the optical image projections that take place in human vision. At present, projections are rendered only in wire-frame. Given a vertex $P = (x_p, y_p, z_p)$ of an object in space, and assuming that the optical node of the eye is at the origin, with the eye aligned with the positive z-axis, the coordinates (θ_p, ϕ_p) (see Figure 3) of P on the retina map in the *RETINA* window are:

$$\theta_p = \sqrt{\lambda^2 + \mu^2}$$

$$\phi_p = \arctan\left(\frac{\mu}{\lambda}\right),$$

where $\lambda = arcsin\left(\frac{x_p}{\sqrt{x_p^2+z_p^2}}\right)$ and $\mu = arcsin\left(\frac{y_p}{\sqrt{y_p^2+z_p^2}}\right)$.

When the nodal point is not at the origin and the eye is rotated in an an arbitrary direction of fixation, retinal image vertices must be calculated with respect to the current location and orientation of the eye. *VP* maintains global coordinate transformations for each eye and computes retinal imagery with respect to these transformations.

Points between vertices undergo linear interpolation prior to projection so that shape on the retina map appropriately reflects shape on the retina, within the constraints of the zenithal equidistant projection.

Retrojections. While retinal images are projections of visual world objects onto the retinas, *VP* additionally performs a kind of converse operation that we call here *retrojection*. In retrojection, we begin with a retinal object point on the two dimensional retina map, and construct the locus of possible points in the visual world which may give rise, through projection, to that point on the retina. For a point on the retina, this point is always a line passing through the node of the eye. Given a point (ϕ_r, θ_r) on a retina map, define (λ_r, μ_r) as

$$\lambda_r = \theta_r \cos\phi_r$$

$$\mu_r = \theta_r \sin\phi.$$

The retrojection vector has arbitrary length $\rho = \sqrt{x_r^2+y_r^2+z_r^2}$, and a direction in space given by components

$$\begin{aligned} x_r &= \psi \tan\lambda \\ y_r &= \psi \tan\mu \\ z_r &= \psi, \end{aligned}$$

where $\psi = \sqrt{\frac{\rho^2}{\tan^2\lambda_r+\tan^2\mu_r+1}}$. Analogously to projection, retrojections in other than the primary position are transformed by the global coordinate transformation of the eye.

Retrojections are displayed in *VP* in several ways. First, they may be displayed simply as lines of a constant radius selected by the user. Retrojected lines in this case fall on the inner surface of two hemispheres whose centers are the optic nodes of the eyes. Second, their intersections with any face of a *WORLD* object model polygon may be computed and displayed. This feature permits viewing retinal features directly on a surface being designed. For example, a designer wishing to view the locus of points within which either eye has sufficient visual acuity to read text on an indicator, may do so by using this feature. Third, the volume intersection of retrojections between the two eyes may be constructed and displayed. This permits the display, for example, of the volumes of space to which both eyes have reduced visibility as a result of disease, or temporary local retinal dysfunction.

In vision science, human factors, and vision care, retinal information and information about the visual world are rarely viewed concurrently. Since most displays are two-dimensional, distortions that arise from projections of the retina are difficult to appreciate since they are usually viewed in isolation. But in *VP*, the impact of transformations in either the retinal or the environmental domain can be appreciated in the other domain. Motion of world objects, for example, will result in retinal image motion, but often in nonintuitive directions and speeds—viewing *VP*'s yoked display of visual space and retinal space side by side is a conceptually simple but powerful aid to the understanding of such motion.

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