Analysis of eyepoint locations and accuracy of rendered depth in binocular head-mounted displays

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ABSTRACT

Accuracy of rendered depth in virtual environments includes the correct specification of the *eyepoints* from which a stereoscopic pair of images is rendered. Rendered depth errors should be minimized for any virtual environment. It is however critical if perception is the object of study in such environments, or *augmented reality* environments are created where virtual objects must be registered with their real counterparts. Based on fundamental optical principles, the center of the entrance pupil is the eyepoint location that minimizes rendered depth errors over the entire field of view if eyetracking is enable. Because binocular head mounted displays (HMDs) have typically no eyetracking capability, the change in eyepoints location associated with eye vergence in HMDs is not accounted for. To predict the types and the magnitude of rendered depth errors that thus result, we conducted a theoretical investigation of rendered depth errors linked to natural eye movements in virtual environments for three possible eyepoint locations: the center of the entrance pupil, the nodal point, and the center of rotation of the eye. Results show that, while the center of rotation yields minimal rendered depth errors at the gaze point, it also yields rendered angular errors around the gaze point, not previously reported.

Key words: head-mounted displays, rendered depth error, accuracy of rendered depth.

1. INTRODUCTION

In today's information intensive environment, it is necessary to collect, process, and display accurate data from a variety of external sources so that today's experts across many disciplines can make critical decisions in real-time. While rendered depth errors should be minimized in virtual environments, the knowledge of remaining errors is important in most cases and specifically if perception is studied in such environments, or *augmented reality* environments are created where virtual objects must be registered with their real counterparts. The military, for example, is interested in the development of Helmet Mounted Displays (HMD) that can accurately display information to increase visual awareness for detection, identification, and tracking of objects of interest, as well as reduce cognitive demand, improve navigation maneuvers, and increase acceptability for closed-hatch operations. The medical profession faces similar challenges related to medical visualization and would benefit from similar technology for example for guided surgery and medical training. It is thus important to gain a comprehensive understanding of the various factors causing errors in rendered depth in HMDs.[1-2]

In this paper, we have investigated the types and the magnitude of rendered depth errors occurring in HMDs as a result of incorrect specification of the *eyepoints* location for the generation of the stereoscopic pairs of images. Given no eyetracking capability in HMDs, it has been established that the center of rotation of the eye can be chosen to minimize rendered depth errors at the gaze point.[2-3] This paper extends previous investigations on viewing errors in HMDs to include the investigation of errors surrounding the gaze point, as well as to yield insight into the types of errors by illustrating how simple objects such as lines and spheres are deformed under various viewing conditions.

If eyetracking is enabled, fundamental optical principles lead to the entrance pupil of the eye as the correct eyepoint location in the projective model for the stereoscopic pair generation as discussed in Section 2.[4-5] Any other location shall necessarily yield some rendered depth errors. If eyetracking is disabled, HMDs are necessarily prone to

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rendered depths errors. While the center of rotation eliminates rendered depth errors at the gaze point, it is of interest to understand rendered depth errors around the gaze point, and to know how errors compare according to other choices of the eyepoint location. To this end, three locations have been considered: the entrance pupil, the nodal point, and the center of rotation of the eye.

The investigation of rendered depth errors presented in this paper assumes that under no eyetracking, the graphical eyepoints are fixed in the computer graphics software and are used to render the pairs of stereoscopic images. We shall first review some basic anatomical properties of the eye as well as some of its functions related to eye motion in HMDs. The formation of the stereoscopic image is then briefly discussed. We shall then describe how lines are distorted according to eyepoints' location given on- or off-axis viewing. Finally we examine the deformations and displacement of spheres. Results show significant angular errrors surrounding the gaze point when using the center of rotation instead of the center of the pupil as the eyepoint. Such errors were neither reported nor investigated previously. Conclusions drawn from this analysis provide a framework for discussing the value of eyetracking capability in head-mounted displays.

2. MODEL OF THE EYE

The investigation of accuracy of rendered depth presented in this paper is based on an optical model of the eye proposed in *Physiological Optics by* Sheard and shown in Fig.1.[6] Using the imaging equation recursively, the radius of the equivalent spherical lens for the cornea is found to be 8 mm and the entrance pupil is computed to be located 3.03 mm behind the front surface of the cornea.

We further consider the eye as a sphere whose radius of curvature is imposed by the curvature of the retinal surface. Thus, the relative position of the center of rotation of the eye, the nodal point, and the center of the entrance pupil are determined and shown in Fig.1. These are labeled C, N, and EP, respectively. The model considered specified the location of the nodal point. [6]

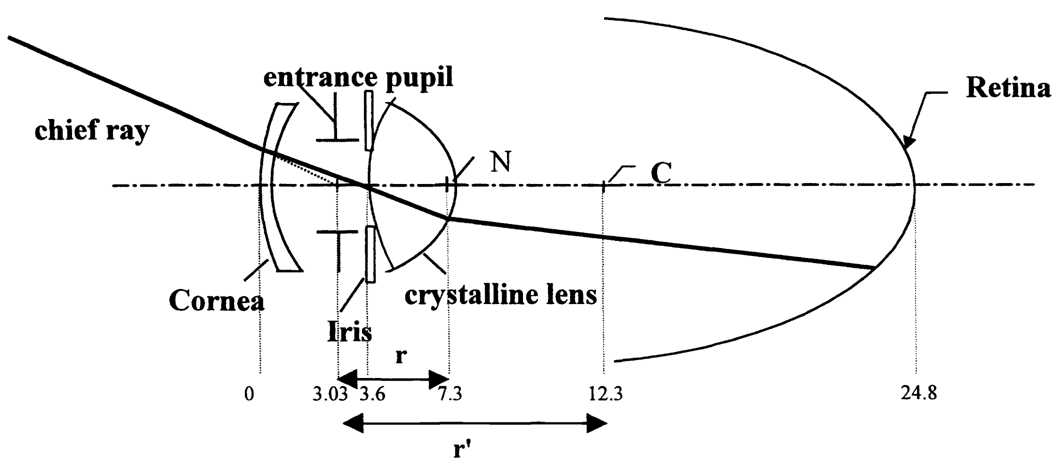

Fig.1 Schematic optical system of the eye. Distances are measured from the front of the cornea in mm.

To compute the rendered depth of a point in 3D space as the eyes rotate, the location of the entrance pupil and the center of rotation, as well as the choice of the graphical eyepoint with respect to the eye geometry must be specified.

Given eyetracking capability in HMDs, the entrance pupil of the eye is the correct eyepoint location in the projective model for the stereoscopic pair generation. This can be best understood by considering that for any state of accommodation of the eyes, the retina can be modeled as a surface detector that is optically conjugated to one surface in 3D space within a depth of focus tolerance.[7] Studies of the human visual system show that a change in fixation from far to near field involves vergence eye movements that cause the eyes' lines of sight to intersect at the new target distance. Vergence eye movements are accompanied by a change in accommodation to focus on the new target to facilitate sharp binocular vision at close range.[8] However, accommodation must be kept within the depth of focus of the optical images of the miniature displays formed through the HMD optics to prevent seing blurred images. Vergence eye movements at the location of the 3D virtual objects prevents seing diplopic images.[9] Thus, accommodation and vergence are best decoupled in HMDs for correct vergence and accommodation across all depth locations. However, because these settings are not natural to the human eye, we expect that the eyes will either tolerate blurred images or try to decouple both functions at the expense of possible side effects.[10] If we assume that the tasks performed by the users do not require decoupling of accommodation and vergence, blurry images necessarily results.[11] It is then important to note that the centroid of energy of a point of light on the retina is given by the intersection of the chief ray with the retina. A chief ray is defined as the ray joining a point on a 3D object to the center of the entrance pupil. So an accurate model of rendered depth will impose the entrance pupil as the eyepoint location for rendering the images. This requires however eyetracking capability.

3. FORMATION OF THE STEREOSCOPIC IMAGE

In binocular HMDs, a 2D virtual image is displayed to each eye. The two images constitute a stereoscopic pair. The perception of 3D virtual objects is achieved in the brain neuronal system. The location of a 3D virtual point is considered to be the crossing of two rays linking the eyepoints to the relevant mapping points of the 2D virtual images as shown in Fig. 2. The gaze point location will be represented as Ig. This model is consistent with the notion of vergence linked to the perception of an object in 3D space.

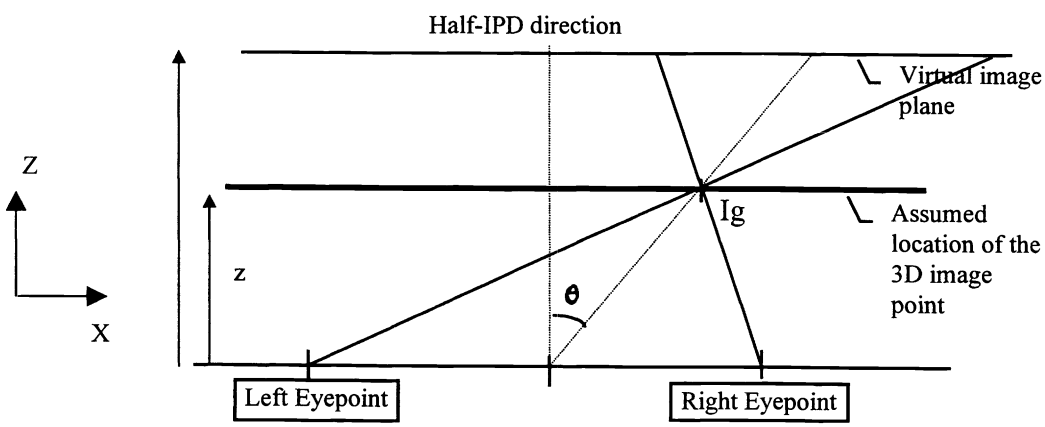

Fig 2. Model of stereoscopic vision and representation of the mid-point angle θ.

In most current graphics software environments, it is assumed that the graphical eyepoints remain fixed during visualization in the virtual environment. This assumption is in fact valid only if the graphical eyepoints are placed at the center of rotation of the eye. Considering Fig. 3, the location of the mapping points of a point Ip in 3D space is computed by considering the two rays going through Ip and the eyepoints assumed motionless. The intersection of these rays with the plane of the 2D virtual images leads to locating the mapping points V_r and V_l. It is important to note that the light emitted from a 2D virtual point image must pass through the entrance pupil of the eye for the 3D virtual image point to be perceived. The rotation of the eyes towards the gaze point leads to a rotation of the entrance pupils. Thus the chief rays coming from the mapping points into the entrance pupils have their direction modified. Consequently, the apparent rendered point located in 3D space is displaced from Ip to I'p. The error to be computed can be calculated as the distance between the assumed location of a 3D image point Ip and its apparent rendered location I'p. If the center of rotation was taken to be the eyepoint, I'g would be located at Ig. I'p is generally not located at Ip.

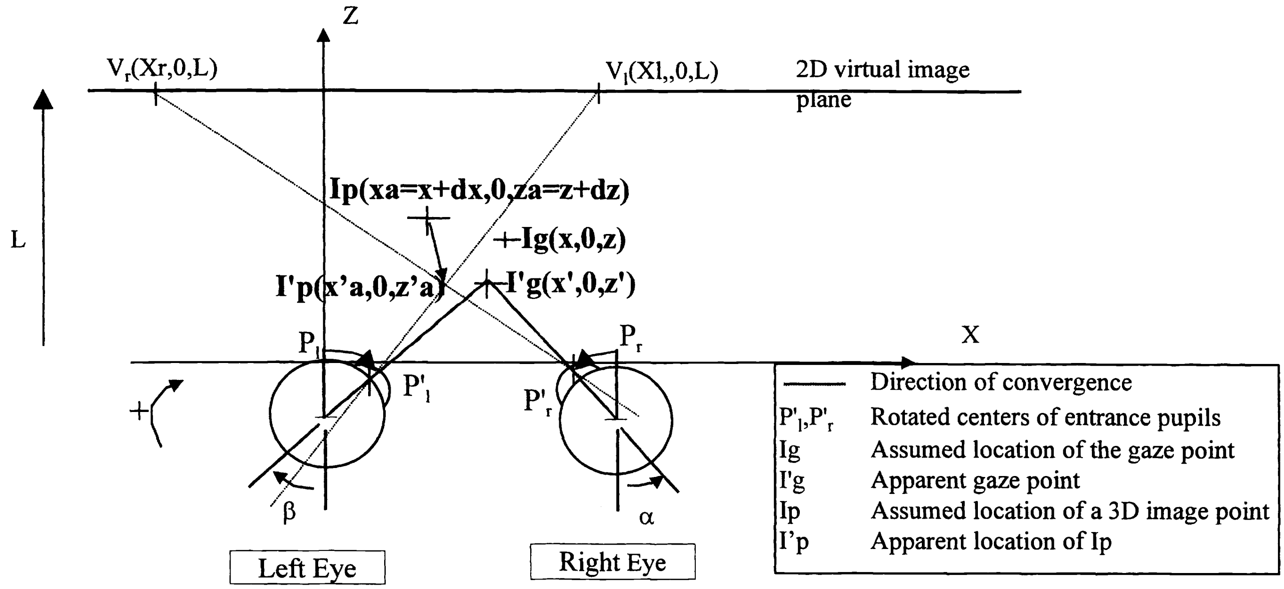

Fig. 3 Error on the rendered location of the 3D image point Ip when the eyes gaze at I'g, which is the rendered location of the gaze point Ig, and the eyepoint is the center of the entrance pupil. The 3D points are mapped with respect to the locations of the centers of the entrance pupils for infinite viewing, Pr and Pl. Because the eyes gaze at I'g(x,0,z), the chief rays coming from the mapping points actually go through P'l and P'r that are set by the direction of vergence. This results in the appearance of Ip at I'p.

4. APPARENT DISTORTION OF A LINE IMAGE CENTERED AT HALF-IPD (θ=0)

We investigated the rendering of a horizontal line image in two common HMD configurations. A line image was chosen because rendering transformations can be more easily determined than for a complex 3D object and insight can be gained into understanding the deformations of simple objects. This investigation allowed us to establish whether the line was scaled, deformed, and displaced. We assume in the simulations that the user is gazing at the center of the line image located at half-IPD.

Two common extreme settings for HMDs were selected to define the range of errors that may be encountered in HMDs without eyetracking capability. The first case assumes that the optical images are located at L equal 10m (i.e. optically collimated) and that the line object is located at Z equal 0.5m. In the second case, the optical images are located at arms length (i.e. L equal 0.5m), while the line is located at Z equal 10m. The center of the entrance pupil, the nodal point,[12-13] and center of rotation are now investigated as possible eyepoints' locations.

4.1 Center of the entrance pupil taken as the eyepoint

Let a point of the line image be called Ip(xa=x+dx,0,za=z+dz) where x and z are the coordinates of the center of the line image. As shown in Fig. 3, the rotation of the eyes will lead to render Ip in I'p(x'a,0,z'a). The center of the image, also the gaze point, is defined by Ig(IPD/2,0,z) where IPD is the interpupillary distance. Regardless of the *z* value, it can be shown that z'_a is constant and equal to z', where z' is the z-coordinate of the apparent gaze point. It means that a horizontal line image is shifted but not distorted.

However, I can be shown that the error on the x-coordinate of the apparent image point I'p is a linear function of dx. Thus a 3D object will be distorted because the shift in z and x coordinates depends on dz and dx, respectively.

4.2 Nodal point taken as the eyepoint

If we consider the nodal point as the eyepoint, the expressions for X_r and X_l as well as X'_r and X'_l have to be adjusted considering the distance **r** shown in Fig.1 between the center of the entrance pupil and the nodal point of the eye. The line image is also transformed into another line image shifted and scaled. The amount of scaling has been found to be similar to that of the entrance pupil case but the amount of shift is less important as reported in Table 1.

Table 1. Summary of transformations of a horizontal line image

1. The 2D virtual images are optically collimated (L=10 m), the line image is displayed at Z=0.5m.

	Shift of gaze point	Scaling	Tilt (gaze point off axis)
Center of rotation	no	yes (0.983)	yes (0.163 degrees)
Center of the entrance pupil	yes (8.81mm)	yes (0.983)	yes (0.17 degrees)
Nodal point	yes (4.75 mm)	yes (0.983)	yes (0.168 degrees)

2. The 2D virtual images are at arm length (L=0.5 m), the line image is displayed at Z=10 m.

	Shift of gaze point	Scaling	Tilt (gaze point off axis)
Center of rotation	no	yes (1.018)	negligible (<0.01°)
Center of the entrance pupil	yes (17.6mm)	yes (1.018)	negligible (<0.01°)
Nodal point	yes (9.42 mm)	yes (1.018)	negligible (<0.01°)

4.3 Center of rotation taken as the eyepoint

If the center of rotation is chosen as the eyepoint, an horizontal line image is transformed into another line image. The coordinate z'_a does not depend on x_a, thus the line is not shifted. The error $(x'_a - x_a)$ is a linear function of the mid-point angle defined in Fig. 2. Thus, it is a linear function of dx since x, z and dz do not vary. This can be shown simply using Thales theorem. The image is thus scaled but not shifted.

In the particular case where θ equal 0 for the gaze point (see Fig.2), the error can be computed and is given by:

$$x'_a - x_a = \frac{(R-d)(L-z')}{(L+d)(z+R)} dx \qquad (1)$$

where $d = R(1-\cos\alpha)$, R is the distance between the center of the entrance pupil and the center of rotation, and α equal β (see Fig. 3).

The expression of the scalar factor is the same for the three eyepoints, however the variables take slightly different values. The error on the Z-coordinate for a Z-line image centered on Ig (IPD/2,0,z) can also be computed as a function of dz. The relation is not linear. The expression is given by:

$$z'_a - z_a = \frac{(L-z-dz)(R\sin\alpha)}{(L+R)(x-R\sin\alpha)-(z+dz-L)\times R\sin\alpha} \cdot dz \qquad (2)$$

Since the scalar factor of the X-coordinate is not the same as the scalar factor of the Z-coordinate, a 3D image will be distorted during stereoscopic vision. It is important to note that this distortion can not be corrected without eyetracking.

5. DISTORTION FOR AN OFF-AXIS GAZE POINT ($\theta \neq 0$)

In the case of a horizontal line image centered at 10 degrees away from the half-IPD direction, the line is no longer transformed into another horizontal line image. The line image is shifted and tilted around the apparent gaze point for the three possible eyepoints. The tilt angle is almost the same for any eyepoint. The error in the X-coordinate can still be considered to be a linear function of dx. Thus the transformation of a horizontal line is, in the general case, a combination of rotation, shift, and scaling. The shift can be cancelled by taking the eyepoint to be the center of rotation of the eye. Nevertheless the tilt and the scaling of the image, which give rise to distortion, cannot be corrected without eyetracking.

6. EXTENSION OF THE ANALYSIS TO THE APPARENT LOCATION OF A SPHERE

We extended the methodology to the 3D case where the 3D object is a sphere. We considered the center of the entrance pupil and the center of rotation to be the primary choices for investigation of the location of the eyepoint. These parameters were considered because errors for the nodal point appear to be the average of those computed for the center of rotation and the center of the entrance pupil. We considered the plane formed by the eyepoints and the gaze point to be the X-Z plane. The location and size of the apparent sphere in 3D space is investigated where the user is gazing away from the sphere along the half-IPD direction (θ=0).

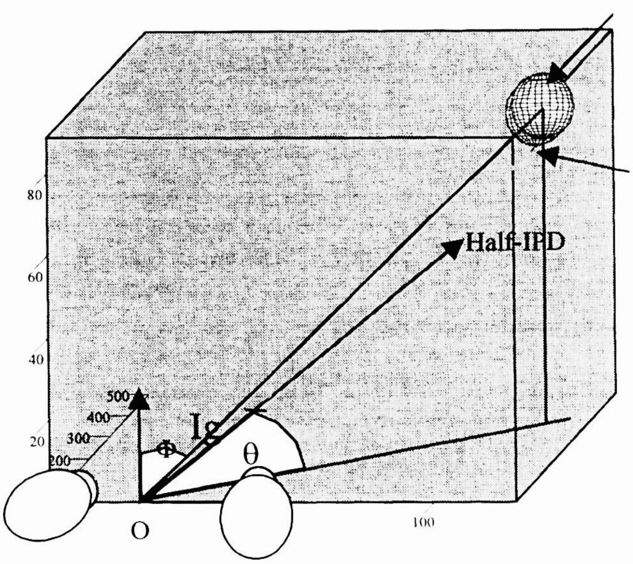

Fig. 4 : Location of the apparent sphere with respect to the position of the assumed sphere if the center of rotation is the eyepoint. The elevation angle (90°-Φ)=15° and the azimuth angle θ=15° for the center of the assumed sphere (center of the set of axis at O(IPD/2,0,0)). The radius of sphere equal 10 mm. The 2D virtual images are collimated (L=10m) and the z coordinate of the gaze point equal 200mm.

The computation of the apparent location of the sphere with respect to the assumed location of the sphere follows the identical process as the 2D approach. Nevertheless, it must be noted that the model used in this investigation considers the crossing of the two chief rays as the apparent location of a 3D image point. This model can only handle the case when the eyes gaze along the half IPD direction. For a gaze point away from that direction, the centers of the entrance pupil of the eyes and the mapping points are no longer coplanar and the chief rays do not cross in this case.

The apparent location, size, shape, and the angular rendering of an apparent 3D object with respect to an assumed object must be taken into account to determine the best eyepoint. Fig. 4 shows the displacement of a 10mm radius sphere centered at Ip (z=200mm, θ=15°, and ϕ=75°) where θ and (90°-ϕ) are the azimuth and elevation angles, respectively, measured from the center O located at half-IPD. In this case, the 2D virtual images are collimated (L=10m) and the eyes gaze at z equal 200 mm. Taking the center of rotation as the eyepoint leads to a smaller shift of the apparent image than the center of the entrance pupil. The apparent sphere is scaled by a factor of 0.98. However results show that the center of rotation leads to large rendered angular errors represented in Fig. 5. For the HMD settings considered, the maximum angular error magnitude was 1 degree.

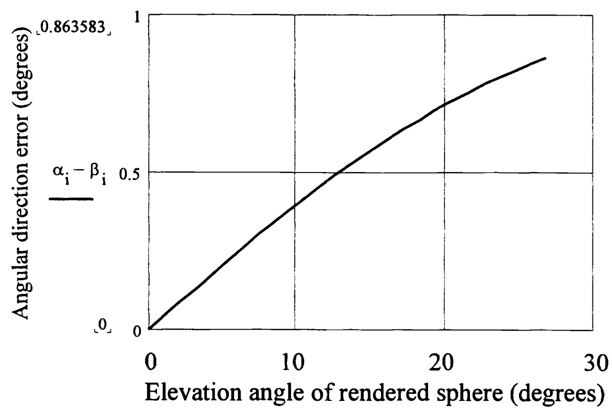

Fig.5 Rendered angular error when the eyepoint is the center of rotation. The gaze point is at Z=250mm and X=IPD/2. The 2D virtual images are optically collimated (L=10m).

7. DISCUSSION

This study demonstrated that there is no ideal eyepoint location without eyetracking since any eyepoint leads to rendered localization or angular errors in virtual environments. When considering the magnitude of the errors and the fact that the gaze point is not shifted if the center of rotation is chosen as the eyepoint, it can be concluded that the center of rotation appears to be the optimal eyepoint for a vast range of applications. It was found that the distortion of 3D objects is small and can be neglected. A line can be transformed into a line and a sphere into a sphere as the scaling factors remain close to 1.

The rendered angular errors established for the center of rotation may be important for some applications since it can be as great as 1° for objects only 15° away from the gaze point. Thus, in the case where depth error matters less than angular errors, the center of the entrance pupil should be taken as the eyepoint. Another point to be stressed is that this model cannot be applied to a gaze point away from the half-IPD direction in three dimensions. This prevents us from studying 3D object distortion when the symmetry of the half-IPD direction is broken. However, given the results computed in 2D, the distortion in 3D should be negligible as well.

8. CONCLUSION

The generation of stereoscopic images with respect to fixed eyepoint locations leads to the displacement and slight distortion of 3D virtual objects in HMDs. By comparing the rendered depth errors for the three eyepoints' locations considered in this study, the center of rotation benefits from not shifting the gaze point. It leads to the smallest error magnitude in the location of 3D virtual image with respect to the nominal value. However, regarding rendered angular errors of objects around the gaze point, the center of rotation leads to the greatest error magnitude while the center of the entrance pupil does not yield tangible error. Thus, if there is no eyetracking, there is no ideal eyepoint in HMDs. The choice of eyepoint should then be decided based on specific tasks to be performed if the HMD has no eyetracking capability. For specific tasks where angular perception is more important than exact 3D location, the center of the entrance pupil should be chosen. In contrast, if absolute depth perception is critical, then the center of rotation should be taken as the eyepoint location instead.

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