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# Distortions of Space in Stereoscopic 3D Content

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**Abstract.** *In S3D film, many factors affect the relationship between the depth in the acquired scene and depth eventually produced by the stereoscopic display. Many are geometric including camera interaxial, camera convergence, lens properties, viewing distance and angle, screen/projector properties and anatomy (interocular). Spatial distortions follow at least in part from geometry (including the cardboard cut-out effect, miniaturization/gigantism, space-size distortion, and object-speed distortion), and can cause a poor S3D experience. However, it is naïve to expect spatial distortion to be specified only by geometry — visual experience is heavily influenced by perceptual and cognitive factors. This paper will review geometrical predictions and present the results of experiments which assess S3D distortions in the context of content, cognitive and perceptual influences, and individual differences. We will suggest ways to assess the influence of acquisition and display parameters and to mitigate unwanted perceptual phenomena.*

**Keywords.** S3D, stereoscopic depth perception, stereoscopic distortions

## Introduction

The growing box office popularity of stereoscopic 3D (S3D) content along with technological advances in acquisition and display are driving the filmmaking industry to produce increasing numbers of stereoscopic films. In addition to providing another dimension (depth), S3D can provide a greater sense of cinematic immersion. However, S3D content rarely provides a veridical representation of the 'real world' and often produces geometric distortions that can cause a variety of perceptual phenomena. The perceptual outcomes may be well tolerated or distracting and/or annoying. Understanding these distortions and their perceptual consequences at the early stages in the creation process will provide obvious advantages to content creators, allowing them to bypass time-consuming and costly attempts at correction in post-production.

## Orthostereoscopic model

The term orthostereopsis is derived from the Greek word "Ortho" meaning "equal" and refers to stereoscopic viewing conditions that are congruent with natural human binocular vision. The aim of orthostereoscopic viewing is to exactly reproduce the stereoscopic geometry of the real scene on an S3D screen.

To attain orthostereoscopic viewing, three conditions must be satisfied [1]. First, the Inter Ocular distance (IO) between the viewers' eyes has to be equal to the Interaxial Distance (IA) between cameras. Second, when fixating distant objects, the gaze direction of the two eyes must be parallel (zero binocular parallax); this can be achieved by 'shooting parallel' and shifting the images (or dual projectors) by the IA. Finally one needs to ensure that the perspective transformation is appropriate for each eye. Assuming centering of the lens, sensor, projector and viewer leads to the constraint [2] that the viewing distance V should be: $\boldsymbol{V = MF}$, where M = (screen width) / (frame width) and F is camera focal length.

Orthostereopsis is not practical, desirable or typically realized in S3D exhibition. It is not practical because of the strong interdependence of acquisition and projection and the fact that such constraints can be truly realized for only one specific seat in the theatre. It is not desirable because it unduly constrains the filmmaking process and it often results in either uncomfortable or underwhelming stereoscopic effects. As a result it is rarely attempted or achieved in practice for cinematic exhibition (many IMAX films are approximately orthostereoscopic at least for viewers in the best seats in the house). However, consideration of the orthostereoscopic viewing condition is useful as a benchmark for natural stereoscopic viewing and for understanding geometric distortion. Further, the geometry of stereopsis can be used to make predictions concerning the effects of deviations from orthostereopsis.

## Stereoscopic depth perception

### *Absolute and relative disparity*

Figure 1 depicts the geometry of stereopsis for an observer fixating point *F* (screen plane), and an object positioned beyond the screen at location *P*. Human stereoscopic vision is best expressed in angular terms. The absolute binocular parallax of an object is the angle subtended (binocular subtense) by the nodal points of the two eyes at the object. In Figure 1, angles $\theta$ and $\omega$ are the binocular parallax of *P* and *F*, respectively. Absolute binocular disparity is the retinal disparity of an object with respect to fixation and is the binocular parallax minus the convergence angle (making the typical assumption that the center of rotation of the eye is coincident with its optical center). Absolute binocular parallax provides information about the distance of the object from the observer, as does absolute retinal disparity if the convergence of the eyes is known. Relative binocular disparity is the retinal disparity of one object relative to another (or equivalently the difference in binocular parallax $\theta$ - $\omega$ in Figure 1).

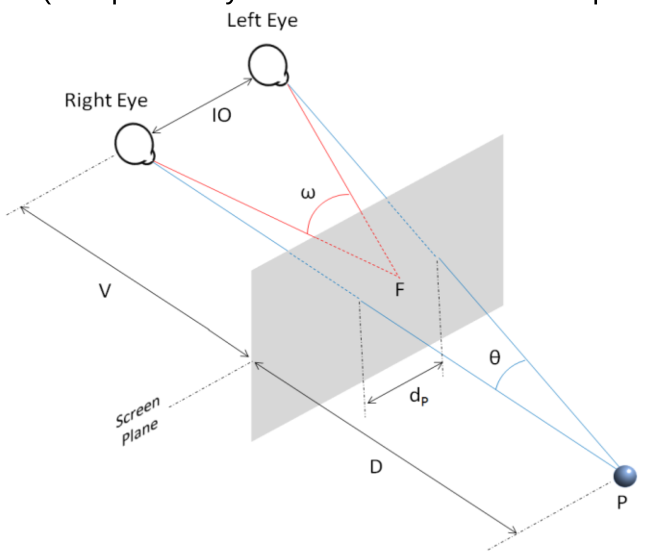


**Figure 1.** Here we illustrate the geometry of stereopsis, where: *V* is the viewing distance, *D* is the relative distance between an object *F* and the fixation point *P*. *IO* is the interocular distance, $\omega$ is the angle between eyes and the fixation point (screen plane), $\theta$ is the angle between eyes and the object. The relative angular retinal disparity $\eta$ *is defined as* $\eta = \theta - \omega$. If *V* is large compared to *D* and *IO*, then, $\eta$ varies with the inverse of distance squared. $\eta \approx \frac{IO \cdot D}{V^2}$

People are exquisitely sensitive to relative disparities [3] and the most sensitive observers can discriminate depths ('stereoacuity') corresponding to the width of a human hair at 50 cm and less than a centimeter at 4 meters. This relative disparity information is constant in spite of eye movements because the images of two objects move together on the retina as the eye moves [4]. Thus, reliance on relative disparity lessens the dependence of precise depth discrimination on eye movements. Indeed research has shown that while stereopsis is most precise when absolute retinal disparities are minimized, stereopsis appears to be relatively immune to eye movement instability [5, 6].

However, relative disparities retain some ambiguity because the amount of disparity corresponding to a given depth varies with approximately the inverse of distance squared [3]. Thus, relative depth (bas-relief) can be extracted from relative disparity but needs to be scaled or calibrated to obtain metric depth. In the context of S3D media, we are rarely concerned with accurate depth perception per se but more that the objects look proportionate in depth (i.e. not stretched or compressed) and of a natural scale. Scaling of disparity for distance controls the amount of stretching in perceived depth relative to perceived size and hence the 'three-dimensionality', 'roundness' or volume of objects. In subsequent sections we will discuss some aspects of S3D that can cause such distortions in perceived object shape.

## *Stereoscopic depth constancy*

The ability to account for viewing distance in judgments of depth is known as depth constancy. With perfect depth constancy, a fixed or constant depth interval appears to have the same depth independent of the distance at which it is viewed. Wallach & Zuckerman [7] found that depth constancy was quite good for depth intervals viewed at close distances (i.e. less than 1 m). For longer distances typical of television or cinema, constancy is partial when both monocular and stereoscopic information are available [8, 9].

How is the distance estimate obtained? Theoretically we could obtain the distance estimates to perform this perceptual calibration from binocular parallax, specifically vergence eye movements. Although precise distance estimates have been reported for near objects [10], in general estimates of target distance based on vergence and accommodation alone are very poor beyond about 1-2 m. However in a richer environment, with more monocular depth cues, distance perception is found to be good at least up to around 20 m [11]. Allison et al [9, 12] showed that monocular visual cues can significantly influence depth from stereopsis at moderate to large distances. We found that presence of monocular and binocular cues to distance such as a ground plane promoted stereoscopic depth constancy at distances of 4.5 to 40 m. It appears that ground plane information and other long range monocular distance cues can be used for scaling depth from stereopsis. Similarly Durgin et al [13] found depth constancy under binocular but not monocular conditions when judging the depth to base ratio of real cones placed at 1-3 m in a structured environment. Thus, in normal environments, interaction between stereopsis and other depth cues can be effective in scaling depth from disparity. While viewing distances in the typical cinema rule out the use of vergence to achieve depth constancy, the availability of multiple rich depth cues from monocular cues such as shading, perspective and occlusion help achieve a degree of depth constancy in S3D film.

### *Size constancy*

The size of the image that a target projects on the retina is related to its objective size scaled by distance [14]. Size constancy refers to the ability of an observer to use this invariant relationship to maintain a constant (but possibly inaccurate) estimate of the objective size of an object at various distances. Classical experiments [15] demonstrated that binocular vision can be used to achieve size constancy although binocular vision and vergence alone as distance cues for size constancy appear to be ineffective beyond about 2m [16]. As most theatre viewing is beyond this range we expect little influence of vergence or accommodation. In a rich environment size constancy is robust but perceived size tends to increase with distance at far distances [17].

In a theatre the perceived size of an object can be influenced by monocular distance cues in the image, cues to the distance of the screen and binocular cues in the stereoscopic image. Convergence micropsia refers to the phenomenon where a target of fixed retinal size appears to decrease in size when the eyes converge [18], an effect that has been linked to miniaturization in stereograms [19]. Although convergence micropsia effects will be small in a theatre setting, note that apparent size is also influenced by perceived position in the theatre space due to an object's disparity relative to the screen and monocular and binocular cues to the distance of the screen and of objects in the scene.

### *Interaction of size and distance constancy*

The perceived shape of objects and their perceived scale depends on the extent to which size and depth constancy are achieved. In an orthostereoscopic arrangement, with perfect depth and size constancy, stereoscopic shape perception would be perfectly preserved. If a common distance estimate is used for scaling of depth and size and it were not accurate then we expect distortions of shape. This is because depth from disparity should scale with distance squared and the size from perspective scales linearly. So if distance is underestimated at half its true value, size and depth scaling predict scaling of depth by ¼ and size by ½, leading to perceptual flattening of the object. As mentioned above orthostereoscopic viewing situations are rare and depth and size are affected differentially by scaling, lens choice and interaxial separation which can give different geometrical predictions for size and depth scaling. This in turn can set the stage for distortions and the classic illusions of stereoscopic photography such as cardboard cutout effects and scale distortions such as gigantism discussed below.

The assumption that the visual system arrives at a perception of linear size that is geometrically consistent with the retinal size and the perceived distance is known as the Size-Distance Invariance Hypothesis. However, the assumption that depth and size are always scaled by the same judged distance is not necessarily valid. Examples of size-distance paradoxes suggest that such lawful links between size, depth and distance percepts are not always found [20]. For instance, Erkelens and Collewijn[21] found that changing the absolute disparity of a dot pattern filling the display resulted in no perceived motion in depth despite changes in apparent size (the image itself did not change size). Although the changes in apparent size introduce a potential cue conflict in Erkelens and Collewijn's study[22] the results reinforce the observation that distance and size percepts can be dissociated. In some cases, contradictory apparent size information may result in the paradoxical result of perceived distance being reported in the reversed order to that expected from the disparity information [23]. Similar paradoxes have been observed for slant and shape and other 'higher order' stereoscopic perceptions.

Perceptual paradoxes often suggest dissociation between perceptual systems or at different levels of the visual system. That disparity-produced apparent size changes can be perceived in the absence of corresponding changes in perceived depth suggests that depth and size judgments are both factors related to distance or binocular parallax but are not causally linked [24]. Similar explanations have been proposed for the moon illusion [25] and the paradoxical size distance effects seen with convergence micropsia [23]. This idea of separate judgments of size, depth and distance based on common sensory information but otherwise (at least partially) independent has been championed as a way of avoiding complications and apparent paradoxes in size-distance perception [14, 24]. Alternatively Mon-Williams & Tresilian [26] have argued that the paradox is due to cognitive phenomena and does not occur at a perceptual level.

In everyday viewing the visual system effortlessly achieves at least a functional level of depth and size constancy. To do so it relies on cues such as vergence to estimate and scale disparity information for objects at near distances. For more distant objects and scenes the visual system relies on a rich array of monocular depth cues to maintain a constant albeit inaccurate percept of object form. As outlined below, the stages of S3D capture, processing and projection can disrupt the perceived geometry of S3D film, resulting in unintended distortions and artifacts.

## Overview of geometrical S3D distortions of space

Most S3D content is created from real stereoscopic cameras or virtual cameras used to render CG scenes. The properties of these cameras influence the mapping of scene space to display space and eventually to perceptual space. The mapping of scene space to display (portrayed/predicted depth) can be described geometrically whereas perceived space also depends on perceptual and cognitive processes. The main parameters include convergence, interaxial, focal length and sensor to screen angular magnification.

### *Convergence*

Convergence in S3D content creation is a somewhat unfortunate term since the link to the convergence of the eyes is indirect. Camera convergence through toe-in or horizontal image translation (HIT) is used to shift the range of portrayed depth relative to the screen. Both toe-in and HIT are expected to affect object size and depth due to constancy effects. Bringing the images of objects perceptually nearer should theoretically decrease their size and also their depth. However, the depth changes should be larger which should 'flatten' the image. The degree of predicted flattening depends on the perceived distance of the object.

Toed-in camera configurations can produce additional depth distortion resulting from differential keystone distortion [27] that produces inconsistent horizontal [28] and vertical disparity [29]. Note that if the convergence distance is large with respect to the IA (common in current practice) then these effects will be very small.

### *Interaxial*

Interaxial settings control the disparity range in the images and hence the mapping from scene depth to portrayed depth. One of the consequences of using IAs larger and smaller than the inter ocular (IO) distance is miniaturization and gigantism, respectively. The perceived size of an object can vary depending upon the IA, bigger the IA is, the smaller objects in the scene will appear. This has been attributed to convergence micropsia but size and depth constancy can also be involved.

As outlined in the preceding sections, the visual system interprets cues to distance and size in a flexible manner to maintain object form or to resolve paradoxes. One of the consequences of using IAs much larger than the inter ocular (IO) distance (hyperstereopsis) is an illusion of reduced size called miniaturization or the puppet-theatre effect. In such cases objects appear tiny, but appropriately proportioned; that is, they do not exhibit shape distortions. The effect is enhanced by optical factors such as the use of long focal length lenses (typically in scenes with large vistas). While this phenomenon recalls convergence micropsia (described above) because it is a distortion of scale, the miniaturization effects tend to be more dramatic, and not specifically tied to changes in vergence.

Miniaturization on the other hand is closely tied to the IA used to capture S3D footage, as the base IA is increased there is a corresponding increase in binocular disparity both within single objects and between objects and the background. Note that when IA is increased, the size of the object does not change, but the additional disparity will cause a distortion in the apparent shape of the object. If we assume that the distance to a display or to the content presented in the scene is somewhat ambiguous, then the visual system compensates for the disparity-induced shape distortion by assuming it is closer to the observer and therefore smaller. In effect, the visual system ‘chooses’ an apparent distance where the ratio of depth from disparity and size from visual angle is normalized leading to a perception of a proportionate but scaled object. Such normalization depends on an internal model or bias for the shape of the object or scene.

The effect of large IA on distortions of perceived size are enhanced by the use of a lens with a long focal length (common when filming distant scenes). Such lenses, among other things, cause magnification of far objects and compression of distance or perspective. The perspective distortion is in the same direction as the putative compensation made by the visual system to maintain consistent shape/form. That is, it supports the interpretation of an object in the scene being closer to the observer than specified by geometry. To resolve this conflict the visual system miniaturizes the object.

The cardboard cut-out effect is another well-known phenomenon in S3D filmmaking and photography. It is related to the process described for puppet theater effect but without the normalization process that preserves proportions. It is characterized by the percept of flat objects lying on a series of layers in a scene at different depths rather than a continuous range of depths. A mismatch between perceived size and perceived depth is at the origin of this effect. In fact, this happens when the depth from disparity, which is scaled by the square of the viewing distance ($V^2$) is small compared to the perceived size from perspective which is proportional to the viewing distance $V$. As outlined by Howard and Rogers[3], if the viewing distance is underestimated the perceived depth will be small compared with the object size resulting in object flattening. This explanation does not explain why the spacing between the cutouts seems less compressed. Rogers has highlighted the role of cue conflict in these percepts[30].

Another factor which results in the card board effect is the use of long focal lenses combined with an inappropriate IA during S3D capture.[31] The optical 2D result of using large focal length is the magnification of background objects, which compresses the distances in depth because of the perspective reduction. As outlined above, this reduces both the perspective and the differential perspective (disparity) between the images. When displayed in S3D these images are usually displayed on screen planes much nearer than the distance of the original scene. This combination of factors results in severely foreshortened objects, and the compression of depth across the scene into separate layers. One way to minimize this effect is to give more volume to the scene by increasing the cameras' IA, however, this can be done only over a limited range of IA before it may cause miniaturization as described above.

### *Object-speed distortion*

To this point we have discussed static information in S3D content, but film footage is more complex as both the content and the camera can move both laterally and through depth. The size/scale distortions described above will also occur for moving content. Velocity constancy is a phenomenon similar to depth and size constancy and refers to the ability to compensate for distance in estimating physical motion from image motion. McKee and Welch [32] suggest that observers have a poorer ability to scale velocity for distance (compared to size or depth).

Theoretically[27], convergence shifts the range of depth from disparity due to the inverse squared relation with distance. However this results in a nonlinear distortion of stereoscopic space—depth is stretched in negative parallax (in front of the screen) and compressed into positive parallax (behind the screen)—which should distort perceived motion. For example consider a car moving in depth through a S3D scene. As showed in (Figure 2), due to convergence at a nearer distance , the distance CD seems to be smaller than AB, although they were are equal in the real scene.

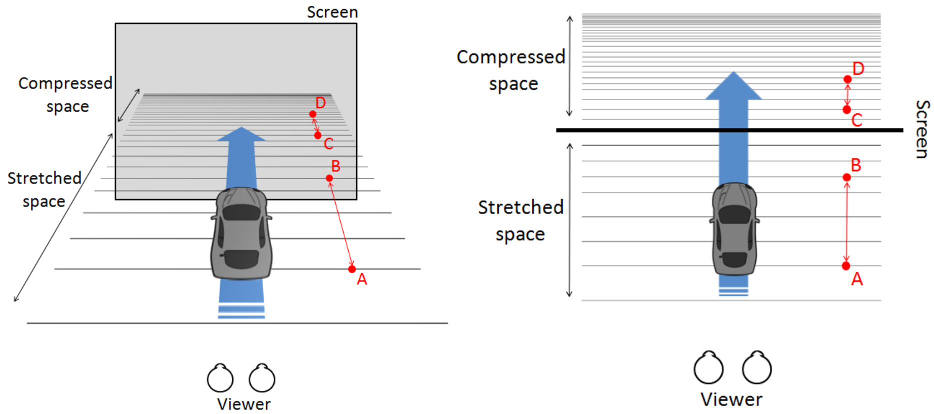


**Figure 2.** Object speed distortion: A car traveling away at constant velocity should appear to decelerate as it gets further away (Car graphic from http://www.clker.com)

Perceived speed is a function of distance and time, and if the distance is distorted, the object speed should appear unnatural to the viewer. For example, consider an object moving with a constant speed in depth from camera to infinity with convergence fixed at a middle distance. When displayed in S3D, as the object moves through both the negative and positive sides of the screen, the speed of the object will appear to speed up and then slow down.

## S3D display

S3D projection is the point at which an audience can view the complete product. Many of the important geometric aspects of the content will have been determined by this point through capture and post-processing. However, projection geometry and viewer position can also have a significant impact on the quality of the S3D content and the must be considered throughout the creation process to avoid additional distortions[33].

### *Viewing distance/position*

The position of the viewer in the theatre can be described as a set of two variables which are the viewing distance to the screen and the oblique position. Each of these variables influences the perceived image differently and are an important factors for a good S3D experience.

Depending of the screen size, standards such as SMPTE and THX determines the optimal viewing distance from the screen by specifying the best compromise between angular pixel size and viewing angle (THX specifies 36° for the furthest seat). The viewing distance determines the objects' stretching distortion in depth. Geometrically, the roundness factor (RF) which represents the ratio between the perceived width (W) of an object and its depth (D) such that RF = D/W, is directly influenced by the distance to the screen. As the viewer moves closer to the screen, the object will appear compressed, while moving further away will cause apparent stretching of the object (see Fig. 3).

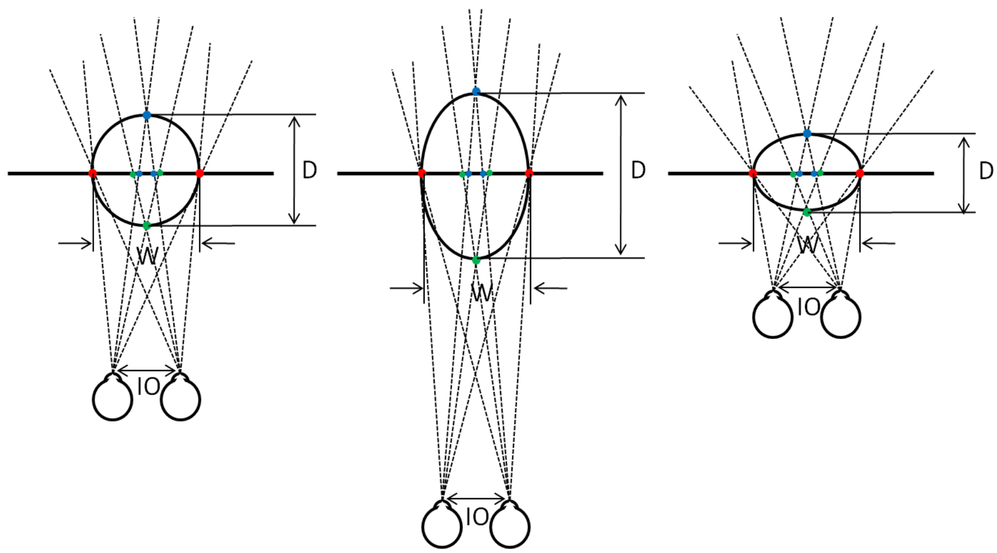


**Figure 3.** An illustration of the roundness factor. The perceived shape of a sphere is extended or compressed depending on the viewing distance.

An oblique viewing position affects the perspective projection of the image on retina, when watching a picture from the side the image appears distorted. A compensation mechanisms exists and offers the viewer a perceptual invariance of objects' shape over viewing oblique positions at least in 2D projection[34]. In S3D the compensation seems incomplete or absent resulting in "shear distortion" percepts[34].

The effects of IA on perceived depth from disparity is an important issue in stereoscopic film making as the camera separation determines the range of disparity and as content is scaled for displays of different size, the degree of conflict with other depth cues (eg. Linear perspective) can vary considerably.

We have explored the combined influence of IA, screen size and image content on stereoscopic depth perception. Contrary to geometrical expectations, we found that when complex scenes (scene containing depth cues, perspective and well known objects) are displayed, depth perception becomes overestimated on a small screen (22-Inch) compared with a larger (54-Inch) display. Surprisingly this percept was independent of the IA. In simple scenes with no real-world distance cues, depth varied with IA as expected.

Our results show that the presence of multiple realistic depth cues has a substantial effect on depth percepts from binocular disparity, to the extent that the effect of IA on perceived depth can be effectively eliminated. The consequences for creation of stereoscopic film are substantial particularly if the intended display size introduces additional cue conflicts.

## Conclusions

We have provided a brief overview of some of the geometric variables that influence scene appearance such as filming conditions (cameras and lens properties, shooting distance) and S3D projection (viewing distance and screen size). We described how perceptual interpretation of geometric factors can be considerably influenced by cue combination and cognition. As we have outlined here, these influences must be carefully considered in S3D filmmaking to avoid unwanted distortions.

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