ON THE DISTINCTION BETWEEN PERCEIVED & PREDICTED DEPTH IN S3D FILMS

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ABSTRACT

A primary concern when making stereoscopic 3D (S3D) movies is to promote an effective and comfortable S3D experience for the audience when displayed on the screen. The amount of depth produced on-screen can be controlled using a variety of parameters. Many of these are lighting related such as lighting architecture and technology. Others are optical or positional and thus have a geometrical effect including camera interaxial distance, camera convergence, lens properties, viewing distance and angle, screen/projector properties and viewer anatomy (interocular distance). The amount of estimated depth from disparity alone can be precisely predicted from simple trigonometry; however, *perceived* depth from disparity in complex scenes is difficult to evaluate and most likely different from the predicted depth based on geometry. This discrepancy is mediated by perceptual and cognitive factors, including resolution of the combination/conflict of pictorial, motion and binocular depth cues. This paper will review geometric predictions of depth from disparity and present the results of experiments which assess perceived S3D depth and the effect of the complexity of scene content.

Index Terms— S3D, stereoscopic depth perception, inter-axial, cue combination, stereopsis,

1. INTRODUCTION

Over the last decade, S3D technology has become increasingly viable and important in popular entertainment, especially in the filmmaking and broadcasting industries. In addition to providing another dimension (depth), S3D provides a greater sense of cinematic immersion [1]. Many cinematographers and stereographers rely on devices such as stereoscopic tables or calculators to predict stereoscopic depth and comfort from stereo-rig parameters. Generally such tools can effectively control ranges of binocular parallax, which can be calculated easily and precisely. However, seasoned stereographers know from experience that such tools do not reliably predict the viewer's experience and so they rely on their own heuristics to interpret the outputs of these tools. As a result, S3D content as captured may not meet the filmmakers' depth requirements and, in the worst case, will need adjustment during an expensive postproduction process. A number of factors contribute to the discrepancy between the predicted and observed depth percepts. This gap between what we 'should' see and what we actually do see can cause delays and increased expense in obtaining the final product. A better understanding of these distortions and their perceptual consequences at the early stages in the creation process will provide obvious advantages to develop a more sophisticated visual approach and to bypass time-consuming and costly attempts at correction in post-production.

2. OVERVIEW OF GEOMETRIC S3D VARIABLES INFLUENCING THE PERCEPTION OF DEPTH

Most S3D content is created from real stereo-rigs housing a matched pair of 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 most important camera parameters include convergence or zero-parallax setting (ZPS), interaxial distance, focal length and sensor to screen angular magnification.

2.1. 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 and/or horizontal image translation (HIT)—is used to shift the range of portrayed depth relative to the screen-plane and hence control the ZPS. Changes in ZPS are expected to affect object size and depth due to perceptual constancy effects. Bringing the images of objects perceptually nearer (setting the ZPS to a further point in the scene) should theoretically decrease their size and also their depth. However, the rate of decrease in depth should exceed the rate of decrease in size, which should 'flatten' the image. The degree of predicted flattening depends on the perceived distance of the object. Toed-in camera configurations can add additional depth distortion resulting from differential keystone distortion [2] that produces inconsistent horizontal [3] and vertical disparity [4]. Note that if the toe-in convergence distance is large with respect to the IA (common in current practice) then these effects will be very small.

2.2. Interaxial Distance (IA)

The interaxial distance is the horizontal separation between the centers of perspective projection of the left and the right cameras. 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 can be miniaturization and gigantism, respectively. Thus, the perceived size of an object can vary depending upon the IA; the bigger the IA is, the smaller objects in the scene will appear. This has been attributed to convergence micropsia [5] but size and depth constancy can also be involved.

2.3. Focal length

The term "normal lens" is used to describe a lens which reproduces the natural human field of view and makes the scene look natural. In order to get this effect, the focal length (f) has to be equal to the diagonal size of the photographic sensor (d). If "f > d" the lens is considered a long focus lens (Telephoto) and produces a narrow field of view. If "f < d" the lens is considered a wide-angle lens and, as its name indicates, it produces a wide field of view. For example, a lens with a 30 mm focal length mounted on a Super 35mm sized sensor produces a camera viewing angle similar to the viewing angle presented to the observer (30-60°) for typical displays (TV or Theatre).

The effects of large IA on distortions of perceived size (described above) 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 compensation made by the visual system to maintain consistent shape/form 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.

2.4. S3D display size

In most situations the use of large format theatre screens improves the S3D viewing experience by enhancing immersion. Depending of the screen size, standards such as SMPTE and THX recommend a viewing distance by specifying the best compromise between angular pixel size and viewing angle (THX specifies 36° for the furthest seat).

Geometrically, using the same viewing angle (for example 36°) for different screen sizes will allow the viewer to get exactly the same retinal projection of an object displayed on both screens. So why then does space seem bigger on a large screen? As shown in Figure 1, if we display a tree on a small screen and we display the same tree on a bigger screen (at a larger distance respecting the same viewing angle), the retinal angle will be the same. The observed change in perceived size is likely due to the fact that the observer takes into account their distance from the screen when determining the size of the image.

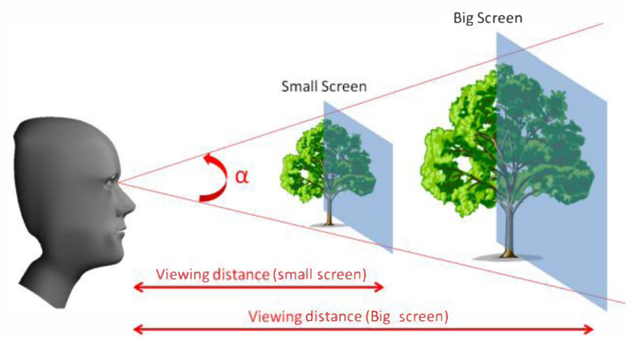

Fig. 1. Perceived size is a function of viewing distance. The two trees have the same retinal projection. If the viewing distance was not perceptible (completely dark space) the trees should appear to be the same size.

Projection geometry and viewer position can also have a significant impact on the perceived quality of S3D content and must be considered throughout the creation process to avoid additional distortions[6]. The position of the viewer in the theatre can be described as a set of two variables: the viewing distance to the screen and the oblique position. Each of these variables influences the perceived image differently and are important factors for a good S3D experience.

3. EXPERIMENTS

To assess the consequences of acquisition and display parameters on perceived depth in a S3D scene, we designed three experiments, each targeting a particular set of variables. Ten observers participated in the first and third experiments and eight participated in the second study. All participants were naïve as to the purpose of the experiments and had a good stereoacuity (<= 40 arc sec) as tested using the Randot Stereo Test prior to the start of the experiments. All observes had a normal or corrected-to-normal vision and their age ranged from 25 to 35 years.

3.1. Hardware Configuration

Two, Viera TCP54VT25VT Series 54" 1080p 3DTV Plasma TVs, were used to display stimuli. The position of the viewer relative to each screen was adjusted to obtain a horizontal viewing angle of 36° (1.8m from the 54" TV) (see Figure 2).

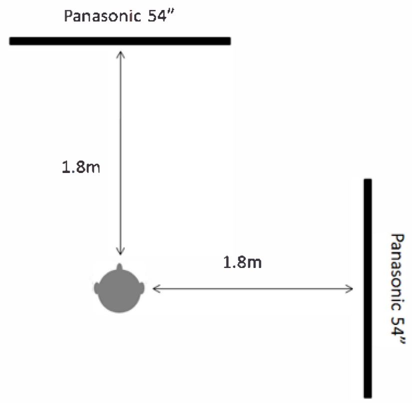

Fig. 2. – Two screens were positioned in front and beside of the participant. One screen was used as a reference and one as a test).

3.2. Stimuli and reference

Multiple shots were captured by a professional film crew. The aim was to recreate realistic conditions present during a commercial shoot (lighting, scene, cameras, and actors). Four poles were positioned in the studio set; each pole was labeled by an identification number (1, 2, 3 and 4). Three configurations were used for to create five 3D test distances. Our primary objective in using three viewing angles was to avoid using the identical scene repeatedly which might lead observers to simply repeat former estimates. Because the studio space was very large, the poles were in a similar central location, in each of the three views. The background varied in content (eg. pictures on the walls), but approximately the same range of distances were visible from the three positions.

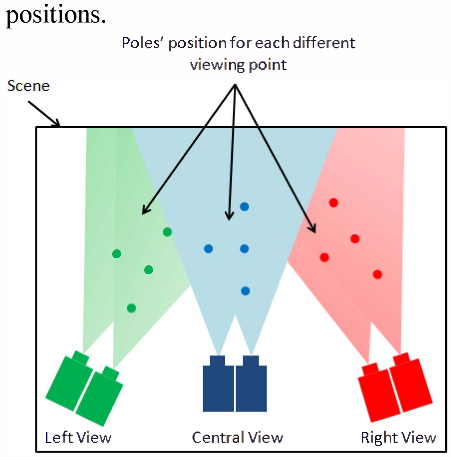

Fig. 3. Three positions of the stereo-rig. In each position, the poles were positioned at the same location relative to the cameras. Filming was repeated at each location for all combinations of camera parameters resulting in three different clips (replications) for each condition.

All combinations of the following stereo-rig parameters were filmed for each configuration of poles:

- Inter-Axial distance (IA): 3mm, 25mm, 50mm, 75mm, 95mm.
- Camera Lens: 9.5mm, 12mm, 16mm (2/3 inch sensor: 9.58 x 5.39mm).
- Three different point of views used for filming the scene: Centre, Left and Right (see Figure 3).

One condition was applied through horizontal image translation at the post-production stage:

- ZPS: on pole “2”, “3” or “4”.

Fig. 4. Stimuli at Right, Reference at Left

A static image of two actors playing chess provided a reference for the distance estimates. We assigned the distance between the nearest (to camera) shoulder of the man and the nearest shoulder of the woman as a reference distance for depth and size judgments (Figure 4).

Task

A magnitude estimation task was used to make estimates of 3D distances in the scene. Participants were asked to make 5 separate estimates of 3D distances in the display (indicated with red arrows Figure 5) using the reference distance described above. When making the magnitude estimates, observers were instructed to assign the reference distance a nominal value of 100, and judge all other distances relative to this.

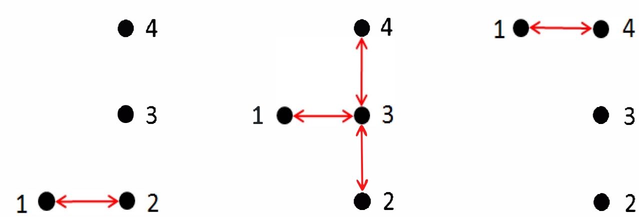

Fig. 5. Three configurations of the poles resulted in five distance to estimates. Three of these were lateral and two were in depth.

3.3. Predictions

Using geometrical calculations, we calculated the expected amount of depth between the poles for a standard observer assuming an interocular distance of 64 mm, given the disparities in the images.

Figure 6 shows the predicted lateral distances (distances parallel to the camera's projection plane) as a function of IA. Lateral distances within the zero-disparity plane are constant regardless of the IA (distance 1-3 in Figure 6 since the figure shows data for ZPS at pole 3).

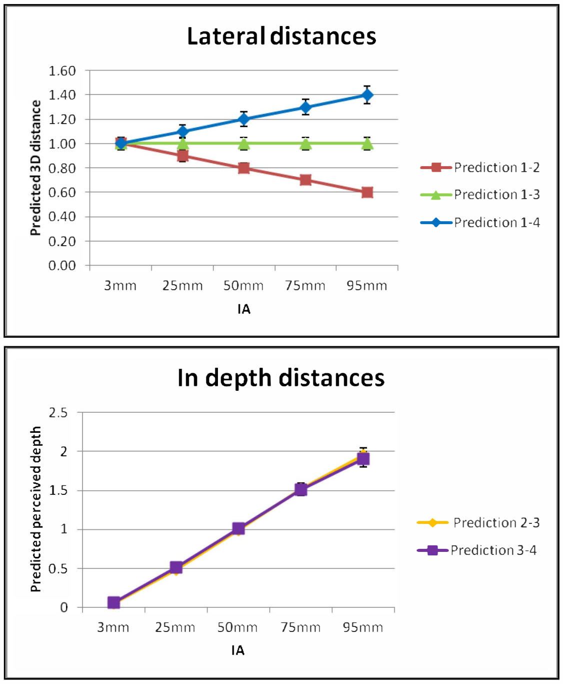

Fig. 6. Normalized (average of individual data divided by the average of each participant) predicted lateral separations (top) and separations in depth (bottom) as a function of IA (ZPS on pole 3)

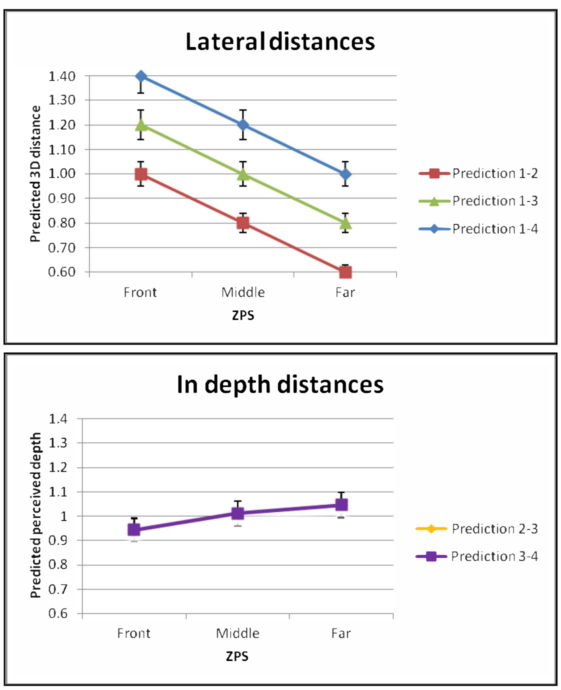

Fig. 7. Normalized predicted lateral separations (top) and separations in depth (bottom) as a function of ZPS (IA = 50mm)

However, when the IA is increased, objects situated behind the screen plane should be perceived to be further away and objects situated in front of the screen should be perceived to be closer to the viewer. Hence, the predicted lateral distances in planes behind and in front of the screen plane increase and decrease, respectively, with increasing IA. Depth distances (distances orthogonal to the screen plane) are expected to increase when IA becomes larger. Figure 7 shows the amount of predicted perceived depth as a function of ZPS (IA = 50mm) and convergence.

3.4. Experiment 1: Effect of IA and ZPS

The aim of this experiment was to quantify the effect of both 'camera convergence' or ZPS (point in the image with zero screen parallax) and IA on perceived depth using full-cue stimuli (complex scene containing several depth cues). ZPS was adjusted during post production by horizontal image translation of one image relative to the other (with cropping to maintain a constant image size across conditions).

Five IAs (3mm, 25mm, 50mm, 75mm, and 95mm) and three ZPSs (Front (Pole 1), Middle (Pole 2) and Far (Pole 3)) were assessed. The 3 points of view were treated as repeated measures of the IA-ZPS conditions.

Results: Experiment 1

The effect of IA on lateral distances was not significant and independent of the ZPS. Increasing IA resulted in significant increases in the depth estimates but the effect of IA was much smaller than predicted (Figure 8).

We did not detect any influence of ZPS on either lateral or depth estimates (Figure 9).

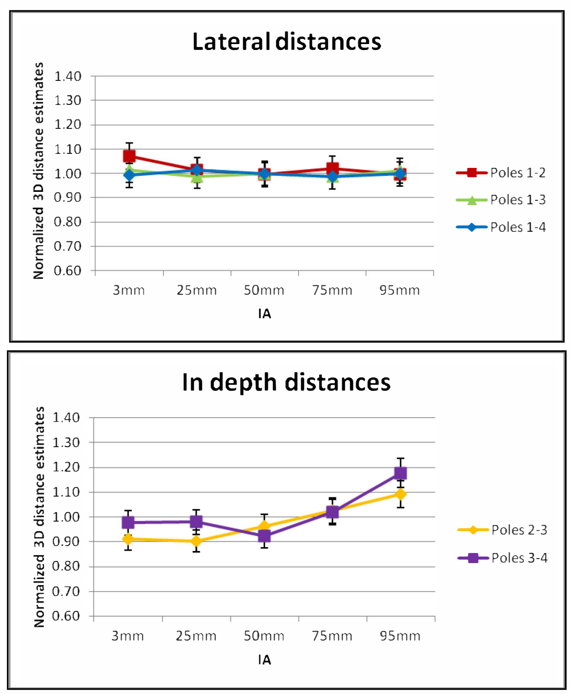

Fig. 8. Lateral (top) and depth (bottom) estimates as a function of IA (ZPS on pole 3) in Experiment 1.

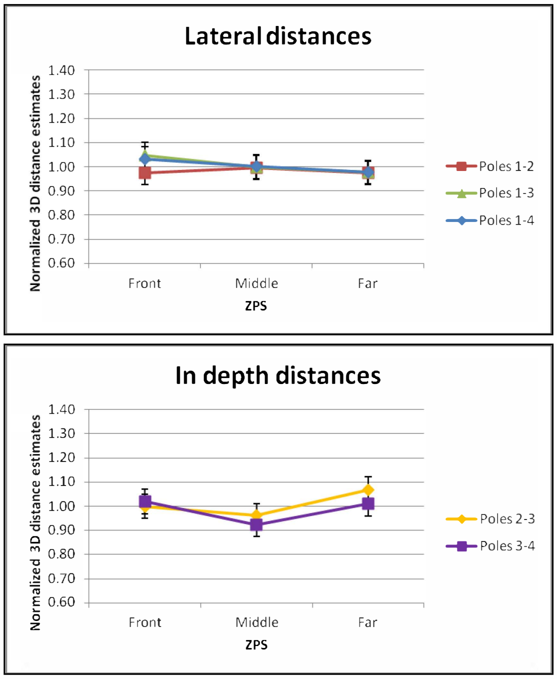

Fig. 9. Lateral (top) and depth (bottom) distance estimates as a function of ZPS (IA=50mm) in Experiment 1.

The effect of IA on depth estimates was also much less than predicted from the geometry of stereopsis. It is likely that this, in part at least, reflects the influence of monocular cues to size and depth which do not change as IA and ZPS are varied, and therefore are in conflict with the stereoscopic depth signal. IA and ZPS and thus are in conflict with changes in the stereo cue.

3.5. Experiment 2: Simple Line Stimuli

In addition to the effect of geometrical variables on local depth perception between objects in the scene, the scene's depth cues may exaggerate or diminish the sense of space of the overall set and can affect the perceived size of objects in S3D space.

Fig. 10. One eye's view of the line stimuli. The lines were located in the image position corresponding to the poles in each condition of Experiment 1; otherwise the display was featureless.

To quantify the influence of monocular cues in Experiment 1, we repeated it using simple line stimuli (bars) in place of the poles, in an otherwise featureless display (see Figure 10). We were careful to arrange the bars so that they were positioned in the same relative location on the display, and we tested the same IA and ZPS values.

Results: Experiment 2

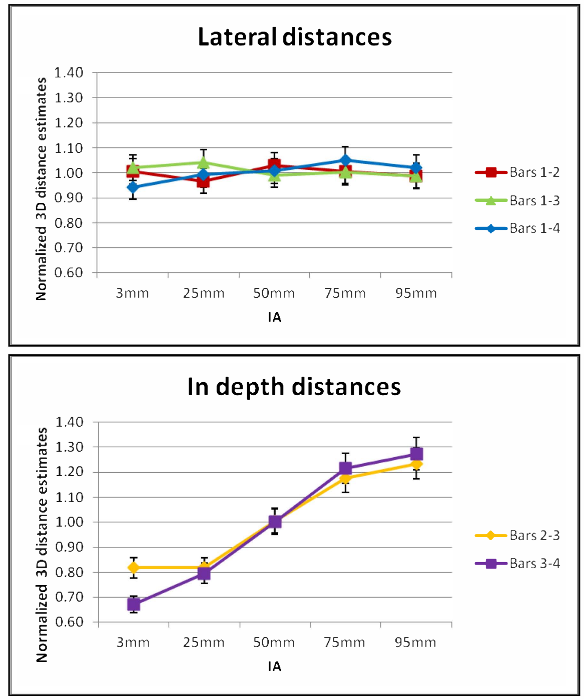

Fig. 11. Lateral (top) and depth (bottom) distance estimates as a function of IA in Experiment 2 (ZPS on pole 3).

The observed effect of ZPS was not significant and confirms the weak effect of this parameter on depth estimation in these displays. As predicted, the IA substantially influenced the estimated depth although its influence still fell well short of geometrical predictions (Figure 11).

Comparison: Results of experiment 1 and 2

Both experiment 1 and 2 showed a no effect of ZPS. While IA does affect reported depth, the use of complex footage as stimuli showed that the multiple depth cues contained in the scene considerably influenced the range and amplitude of depth estimation.

Figure 12 (top and bottom) shows two graphs representing the estimated depth using complex and simple stimuli. The upper graph of Figure 12 represents normalized 3D depth estimates (y axis), it shows that there is a noticeable range difference between the complex and simple stimuli data. The cue conflict limits the influence of IA on depth perception in the complex scenes. However, the amplitude of the non-normalized data is much bigger using the complex stimuli (Figure 12 bottom), suggesting that the depth cues present in the scene's context increase the perceived estimates of depth, consistent with the scale of the scene.

The perception of lateral distances was not influenced by the degree of cue combination/conflict, the data was similar for both complex and simple stimuli.

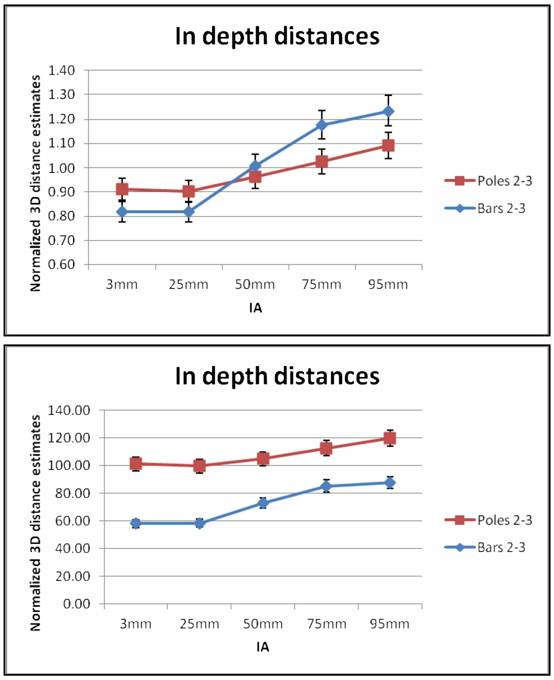

Fig. 12. Comparison of complex (in red) and simple (in blue) stimuli (ZPS on pole 3). The upper graphs shows normalized data as a function of IA. The bottom graphs shows raw averaged data as a function of IA.

3.6. Experiment 3: Focal length

The aim of this experiment is to quantify the effect of lens choice (Focal Length) on perceived depth given IA and ZPS. Two IAs (25mm and 75mm), two convergence points (Front (Pole 1) and Far (Pole 3)) and 3 lenses (9.5mm, 12mm and 16mm) were used as conditions in the experiment. The scene was shot from 3 different points of view, each time with the same parameters. The 3 points of view were again used as replications of the shooting conditions.

Results: Experiment 3

It is generally accepted that long focal length lenses result in a compression of perceived space in a scene along with a stretching of its perceived width. Thus the optical effect of increasing the focal length is a reduction in the perceived depth in the scene making objects appear closer (Figure 13). The perceived lateral distances were directly linked to their on-screen size (though they should be scaled by distance) (see Figure 14). The larger the focal length, the bigger the object appears, resulting in larger width estimates by the majority of participants. This effect on lateral distances shows a partial absence of size constancy when focal length is used to optically change the apparent distance instead of moving the objects closer or further from camera.

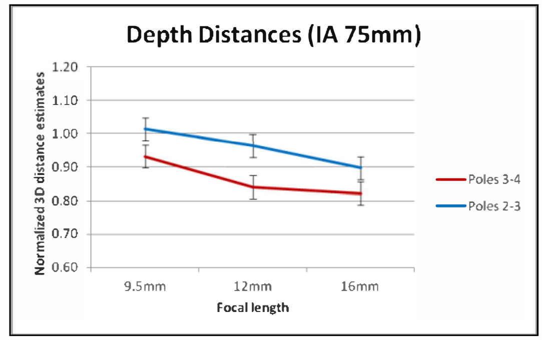

Fig. 13. Estimated depth distances as a function of focal length (IA = 75mm) in Experiment 3.

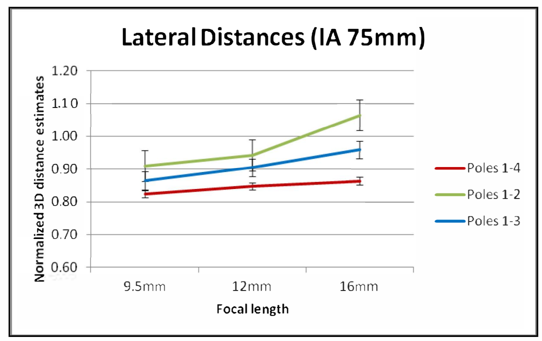

Fig. 14. Top graphs show the estimated lateral distances as a function of focal length (IA = 75mm).

As in the previous experiments, the ZPS did not have a significant effect on depth estimates. However, focal length changes produced changes in space perception. Indeed, increasing the focal length stretched the lateral distances and compressed the depth distances (Figure 15).

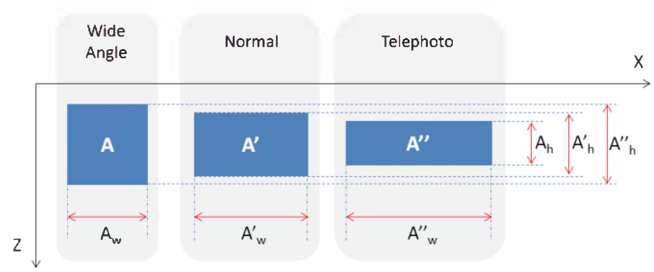

Fig. 15. A top view of how the perceived S3D length and depth of a cube change with focal length

4. GENERAL DISCUSSION

All observers reported a compelling sense of 3D depth and variation in the strength of this sense of space across the shots. Despite this, subjects appeared to provide depth and size estimates more consistent with pictorial depth cues or image (2D) properties. While we had no expectation that stereoscopic depth and size percepts would correspond strictly to geometry the most surprising findings from the current study are the lack of a measureable effect of stereoscopic depth on reports of lateral distance and the degree of attenuation of stereoscopic scaling due to IA.

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.

Similarly, the size of the image that a target projects on the retina is related to its objective size scaled by distance [7]. 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.

The perceived shape of objects and their perceived scale depends on the extent to which size and depth constancy are achieved. While both depth from disparity and size from perspective scale with viewing distance they do not do so in the same manner. That is depth from disparity should scale with distance squared while size from perspective should scale linearly. This difference in scaling means that if size and depth constancy use a common distance estimate then we expect distortions of perceived shape.

In a sense, our subjects achieved near ‘perfect’ size constancy in terms of the pictorial cues to depth in the scene and in terms of the physical scene. This was reflected in Experiments 1 and 2 by the invariance of the size estimates with changes in stereoscopically portrayed depth and the fact that lateral distances at all three distances were judged equal. Our observers were able to ignore the influence of stereoscopic depth when making judgments of lateral distance between the poles. In Experiment 3, the subjects did show a significant effect of focal length on these judgments. Because the viewing distance and camera distance were fixed, changes in focal length creates a mismatch between expected and displayed field of view (magnification). This has well-known effects on apparent perspective depth and size. However, it appears that again observers relied on pictorial and/or image characteristics to make their judgements; there was little variation in depth estimates despite large changes in disparity.

In terms of pictorial cues, depth constancy was considerable as well in that depth variation was small between the conditions (consistent with unchanging true scene depths and pictorial cues). The effects of focal length are also consistent with modification of the pictorial cues [8] and demonstrate that while constancy is not achieved over changes in focal length, once again, the percepts are resilient to the effects of changing disparity.

Classical experiments [9] have 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 [10]. Wallach & Zuckerman [11] 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 [12, 13]. It may be that the scale of the scene affected the use of binocular cues to space constancy.

Beyond 1-2 m there is little binocular information about distance as the vergence signal becomes unreliable. Allison and al. [13] demonstrated that the accuracy and precision of binocular depth estimation can be significantly improved by the presence of monocular cues to distance. In our scene the true distance of the poles ranged from 3.65 to 7.31 m. Based on the pictorial information in the scene the observer should localize the poles beyond the normal range of vergence (and the distance of the screen was near the limit of this range as well). If monocular cues dominated the perceived distance of the poles then this may explain the lack of an effect of ZPS on size and depth, as these effects are predicated on the ZPS shifting the range of perceived depth relative to the screen.

However, this explanation does not account for the weak effect of IA on perceived depth. Subjects seemed to default to ‘image measurements’ and either did not perceive or did not report the stereoscopic depth.

Failure to perceive variation in stereoscopic depth with variation of IA in our S3D footage is most likely due to the presence of cue conflicts. The relationship between the reference depth and the depth specified by the pictorial cues in these stimuli did not change with IA and ZPS (it did, however, with focal length). The consistent depth and lateral separations specified by pictorial cues across IAs conflicts with the changes in disparity as IA is varied. The fact that perceived depth increased significantly with IA more with IA in the reduced cue conditions of Experiment 2 is consistent with this proposal. Effects of IA and ZPS were still less than predicted even for the reduced cue conditions, presumably reflecting residual cue conflict. Specifically, vergence/ accommodation conflict and vergence/focal length inconsistency have been shown to affect depth judgments and produce apparent depth distortion [14].

However, while variation in disparity was not accompanied by variation in pictorial cues, the depth specified by the two cues was consistent in sign and not greatly discrepant in terms of the layout of the scene. According to popular models of cue combination we expect such a relatively weak cue conflict to be resolved by the visual system by ‘fusion’, a weighted combination of the two cues [15]. While it is not surprising that perspective and other pictorial cues influenced the stereoscopic perceptions in these scenes, the extent of this influence is remarkable. Within this literature this degree of cue dominance would be referred to as 'vetoing' and typically has only been reported under conditions of extreme cue conflict. As described above, this is not the case in our stimuli, the depth cues signal different degrees of depth but not different sign.

It is important to recognize that our results are a product of the task we used. It is possible that it did not fully capture the observers' experience of stereoscopic depth, or may have been subject to other cognitive factors. For example, the same scene was used throughout the experiment and provided a frame of reference for the judgments. Such a stable environment may have biased observers to respond on the measures in the context of the 'actual environment' rather based on the percept from trial to trial. Similarly, it may have been easier for observers to judge the size of the lateral separations in terms of extent in the image ('number of pixels'). This would be consistent with the lateral judgments made when focal length was varied. However, it is contrary to the typical finding that it is difficult to estimate image properties in perspective images when they effectively portray depth [16]. Other researchers have demonstrated the effect of task on estimations of depth and distance. For example, verbal estimates of the distance of objects from the observer are often underestimated, particularly in virtual environments and other mediated representations but observers are much more accurate in a "Blind Walking" test where people had to walk blind folded to a target previously visualized [17]. To investigate the degree to which task affects our findings, we plan to measure the effects of IA and ZPS in our stimuli using alternative measures including active responses such as pointing.

5. CONCLUSION

This paper investigated how different acquisition and display parameters influence the quantitative perception of space through a S3D display. We found that perception in such rich displays cannot be simply predicted by stereoscopic geometry and this deviation can be very large. We argue that expectation, cue conflict and task are important factors in the depth response provided by observers watching S3D film clips and these factors have important implications for evaluation of S3D content.

In sum, the perception of space experienced by a viewer watching an S3D movie is a complex interplay of many factors. Measurement and evaluation of this stereoscopic experience needs to consider the role of content cue conflict, expectation and the task used in evaluation.

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