Motion in Depth Constancy in Stereoscopic Displays

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ABSTRACT

In a stereoscopic 3D scene, non-linear mapping between real space and disparity could produce distortions when camera geometry differs from natural stereoscopic geometry. When the viewing distance and zero screen parallax setting are held constant and interaxial separation is varied, there is an asymmetric distortion in the mapping of stereoscopic to real space. If an object traverses this space at constant velocity, one might anticipate distortion of the perceived velocity. To determine if the predicted distortions are in fact perceived, we assessed perceived acceleration and deceleration using an animation of a ball moving in depth through a simulated environment, viewed stereoscopically. The method of limits was used to measure transition points between perceived acceleration and deceleration as a function of interaxial and context (textured vs. non-textured background). Based on binocular geometry, we predicted that the transition points would shift toward deceleration for small and towards acceleration for large interaxial separations. However, the average transition values were not influenced by interaxial separation. These data suggest that observers are able to discount distortions of stereoscopic space in interpreting the object motion. These results have important implications for the rendering or capture of effective stereoscopic 3D content.

Keywords: motion in depth, interaxial, nonlinear mapping, stereoscopic cinematography, acceleration

1. INTRODUCTION

The recent commercial success and interest in stereoscopic cinema has spurred renewed research into the tools, processes, and perceptual experiences of stereoscopic film. In almost all cases the stereoscopic imagery differs from what the viewer would experience when viewing the same scene directly. While the specific geometry of stereoscopic 3D (S3D) film is clearly documented[1–3], there have been fewer studies of how display and camera parameters affect the viewer's perceptual experience. Since, for a variety of reasons, camera geometry does not match natural binocular viewing geometry there is a non-linear mapping between real world space and stereoscopic space captured by the S3D camera system. This non-linear relationship can produce distortions of space in the stereoscopic image with relative expansion or compression of space in isolated parts of the scene[2]. Although these geometric distortions of space are tolerable to viewers to a certain degree, they can also contribute to an "unnatural" look or feel of space in the image[4].

It is also possible that distortions of space that are imperceptible in static scenes may become more visible (even disruptive) if a moving object passes through this region. The purpose of this paper is to evaluate how an object moving through stereoscopic space (with varying monocular cues) is perceived by the viewer.

Key parameters in stereoscopic cinematography include interaxial distance (IA) and zero-parallax setting (ZPS), along with other variables such as viewing distance, sensor size, screen size, and lens choice. ZPS refers to the point in the scene that will be imaged on the plane of the screen (and therefore have zero screen parallax). The ZPS can be manipulated by toe-in of the cameras during image capture, and/or via horizontal image translation during the post-production process. Adjusting the ZPS will also determine which parts of the scene appear in front of or behind the screen plane, and as outlined below, this has implications for the amount of depth predicted from binocular disparity.

Interaxial, or the lateral separation distance between the cameras, establishes the binocular parallax range of a shot. Like the separation of the eyes in the human visual system, increasing the interaxial separation increases the

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Stereoscopic Displays and Applications XXIII, edited by Andrew J. Woods, Nicolas S. Holliman,
Gregg E. Favalora, Proc. of SPIE-IS&T Electronic Imaging, SPIE Vol. 8288, 82880N
 · doi: 10.1117/12.910577

binocular parallax between points in a scene, even though their physical separation remains constant (and vice versa). Therefore IA determines the relationship between distances in the scene, and the predicted amount depth in the image. In stereoscopic cinematography considerable attention has been devoted to IA primarily because once a scene is shot with a given IA, it cannot be adjusted easily in post-production (unlike the ZPS, which simply requires adjustment of the relative horizontal position of the images). Instead, changing the amount of parallax requires depth reconstruction and view interpolation or 2D-3D conversion techniques[5] which are complex and costly operations.

1.1 Depth Distortions in Stereoscopic Space

Spatial distortions should be minimal in orthostereoscopic conditions. However, shooting under orthostereoscopic conditions is not always practical or desirable and in any case can only hold for a single position in the room or theatre. Because perceived depth is a function of several different stereoscopic parameters, spatial distortions can be introduced in any of the stages of stereoscopic transmission including capture, display, and /or viewing. The mapping of scene depth to screen parallax between two objects is a nonlinear function of their distance scaled by IA; a given depth interval projects to a larger relative parallax at near compared to far distances in the scene.

This non-linearity also applies to the natural stereoscopic system of the viewer, where the interocular separation between the eyes (IO) plays a role analogous to the camera IA. For a viewer with their head aligned (the baseline between the eyes parallel to the screen and centered on the image) the relationship between screen parallax, z_s, and predicted (re-projected) depth relative to the screen, d, for objects lying along a line perpendicular to the baseline through the centre of the screen is:

$$z_s = \frac{IO \cdot d}{V + d} \tag{1}$$

where V is the viewing distance. The relative parallax between two objects is the difference in their screen parallax:

$$z_{s_{2\text{-}1}} = \frac{IO \cdot \left(d_a + \frac{d_{2-1}}{2}\right)}{V + d_a + \frac{d_{2-1}}{2}} - \frac{IO \cdot \left(d_a - \frac{d_{2-1}}{2}\right)}{V + d_a - \frac{d_{2-1}}{2}} \simeq \frac{IO \cdot d_{2-1}}{V + d_a} \tag{2}$$

assuming the relative depth $d_{2\text{-}1}$ between the objects is small relative to their average distance from the viewer ($V+d_a$). Although this relationship is non-linear it is the natural geometry of stereopsis and, when possible, the viewer should account for distance to perceive depth without distortion. This ability is known as depth constancy and has been shown to hold for stereopsis, at least in part, at both near and far distances[6],[7]. However, when the scene has been captured and displayed with stereoscopic parameters that do not match the viewer's, the viewer must interpret the nonlinear transformation between stereoscopic space and real space acquired by the cameras based on his/ her natural interocular separation (IO). The differences in the nonlinear relationship caused by differences between IA and IO should be perceived as depth distortion if interpreted geometrically. Figure 1 below shows how relative depth between pairs of sample points in the real world maps nonlinearly to stereoscopic space with varying IA but fixed ZPS and screen distance.

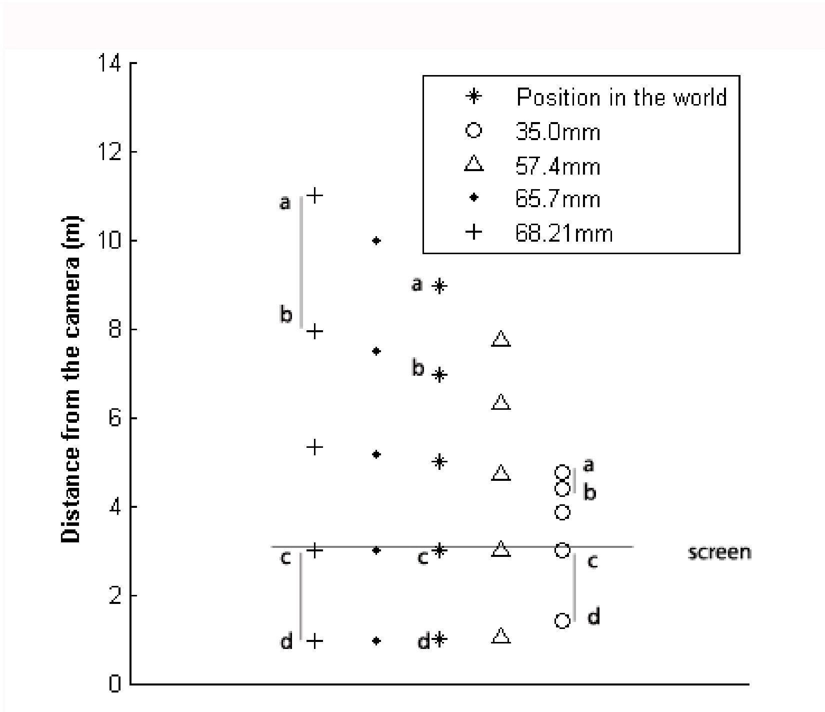

Figure 1: This figure shows how points in the real world map to positions in predicted stereoscopic space according to IA assuming a matched camera and screen field of view and camera convergence at 3 m (the screen distance). Stereoscopic images of points in the scene are re-projected assuming an IO of 62.5 mm. For an IA of 62.5 mm the re-projected points would correspond with the real world points. Distances between real world points a and b and between c and d are shown for IA of both 35mm and 68.21mm. All points would be perceived in the same direction and the x-axis offset between the groups of points is for illustrative clarity only.

1.2 Motion in Depth Cues in the Visual System

As noted above, with variation in IA the geometry of S3D predicts that there are non-linearities in the relationship between distances in the captured scene and perceived stereoscopic depth. These distortions of space in the 3D scene have implications for perceived velocity (first derivative of depth with respect to time) and perceived acceleration (the second derivative of perceived depth with respect to time) of an object passing through that space. That is, the object should be perceived to travel at a higher velocity when the space is expanded and at a lower velocity when the space is compressed. As can be seen in Figure 1, a small IA predicts an overall compression of stereoscopic space and thus lower perceived velocity; conversely a large IA predicts increased perceived velocity.

Figure 1 also demonstrates the compression and expansion of space is not uniform[8]. For a small IA the difference in predicted depth for a given real depth interval becomes increasingly larger as it is brought nearer (a-b < c-d); for a large IA the converse is true (a-b > c-d). By definition an object travelling at a constant velocity covers a constant real world distance per unit time. If the object approaches then this predicts that the object will appear to cover an increasing interval of stereoscopic space per unit time when captured with a small IA and hence appear to accelerate [9]. Conversely, an approaching object should appear to decelerate when captured with a large IA. As far as we know, it has not been determined if viewers do in fact perceive these accelerations and decelerations.

2. EXPERIMENTS

2.1 Experiment 1 - Effects of Interaxial on Perceived Acceleration

2.1.1 Introduction

Experiment 1 investigates how an observer's perception of the acceleration or deceleration of an object moving through stereoscopic space is affected by stereoscopic camera rig parameters, specifically the camera IA. Analysis of 3D geometry shows that the amount of depth predicted from stereopsis can vary non-linearly with the depth rendered/captured in the perspective images. It is an empirical question whether this dissociation will give rise to perceptual artefacts when viewing an object moving through that space.

As outlined in the Introduction, and illustrated in Figure 1, when image size (magnification), viewing distance and ZPS are kept constant, a change in the IA compresses or expands the predicted stereoscopic depth of the scene. It stands to reason that in a compressed space the object's predicted velocity will be less than in an expanded space since it traverses the two distances in the same interval of time. Thus, we predict that IA will affect the perceived acceleration of an object moving through space. That is, when an object moves through a scene containing these geometric distortions at a constant velocity, it should produce a non-linear velocity profile if it is seen according to the parallax, maintain a constant velocity if it is seen according to the monocular cues, or be perceived somewhere in between if monocular and binocular cues are combined. We evaluated this by varying the acceleration of an object moving through a computer generated scene. We determined the acceleration at which the percept changed from acceleration to deceleration and vice versa to determine how these 'null' points shift with IA. The prediction is that if stereoscopic distortion introduces a bias toward acceleration or deceleration then the object will need to be 'physically' decelerated or accelerated (or virtually in the case of an animation) to counteract this bias.

2.1.2 Method

Subjects

Participants (n=9) ranged in age from 19 to 35, had normal or corrected to normal acuity, and good stereoscopic vision (assessed using the Randot Stereotest). Six of the observers were female, three were male, and all were paid for their participation.

Apparatus and Stimuli

Stimuli were created using Houdini 11.1 software (Side Effects Software, Toronto) and consisted of a 3.5s movie clip of a green ball rolling on the ground plane from a simulated distance of 9 m towards the observer to a distance of 2 m. To investigate how the presence of monocular cues affects perceived acceleration, the stimulus was presented under two conditions, with a textured (black and white checker) and non-textured (uniform reddish) ground plane. Figure 2(a, b) show the stimuli in textured and uniform ground plane conditions.

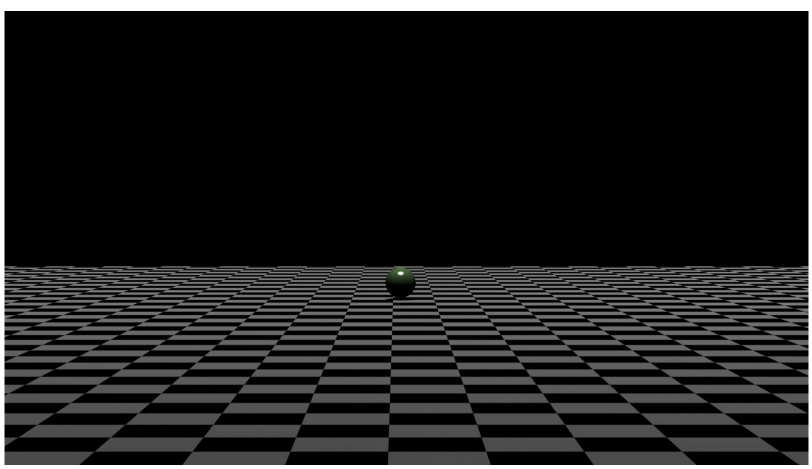

Figure 2(a): Stimulus with a textured ground plane.

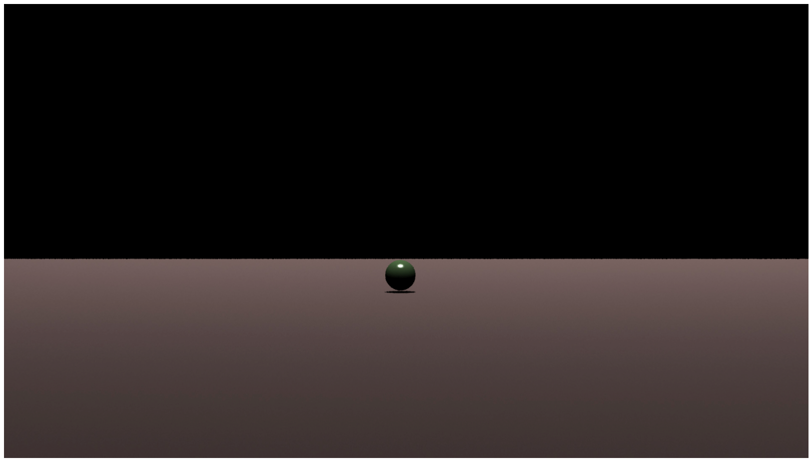

Figure 2(b): Stimulus with a uniform ground plane

The ZPS was fixed at 3 m from the camera by horizontally shifting the image, and the focal length of the cameras was 88.23 mm. Four IAs were used to generate the stimuli: 35, 57.4, 65.7, and 68.21 mm. We generated predictions for the perception of acceleration from the geometry of binocular disparity assuming an object moving at constant velocity. As the predicted distortion of space is non-linear, each IA has its own predicted acceleration value: 35 mm = 34.62 cm/s^2, 57.4 mm = 16.65 cm/s^2, 65.7 mm = -16.65 cm/s^2 and 68.21 mm = -34.62 cm/s^2.

A series of clips were rendered with the ball decelerating or accelerating during its motion through the virtual space. For each combination of background and IA, thirteen clips were generated with ‘physical’ acceleration of the stimulus (through the virtual world as opposed to induced by stereoscopic distortion) ranging from -51.84 cm/s^2 to 51.84 cm/s^2 in steps of 8.64 cm/s^2. The average velocity was fixed at a mean velocity of 200 cm/s so that the length of the clips was the same and the ball rolled out of the frame at the same point. Thus the initial velocities for each sequence differed depending on its acceleration value. The initial velocity values were 290 cm/sec, 275.5 cm/sec, 260.4 cm/sec, 245.3 cm/sec, 230.2 cm/sec, 215.0 cm/sec, 199.9 cm/sec, 184.8 cm/sec, 169.7 cm/sec, 154.6 cm/sec, 139.4 cm/sec, and 124.3 cm/sec for the thirteen trials.

Procedure

We used a classical psychophysical technique known as the method of limits to estimate the point at which the participant saw the ball as neither accelerating nor decelerating (the ‘null’ point). For each estimate of this point for each condition, the stimulus was shown repeatedly starting with it obviously accelerating or decelerating. For the ascending runs the stimulus initially appeared to decelerate and on each subsequent presentation the acceleration was increased in steps of 8.64 cm/s^2. After each presentation the subject indicated verbally whether the ball appeared to accelerate or decelerate. The ascending run was terminated when the participant first responded ‘accelerating’ and the velocity on that trial was recorded. The reverse procedure was used for descending runs starting with an obviously accelerating stimulus, and decreasing the velocity until deceleration was reported.

For each ground plane and IA combination, four measures were made of the transition points between perceived acceleration and deceleration (two ascending and two descending trials per condition) for a total of 16 ascending and 16 descending runs. Because in methods of limits, ascending and descending series often result in differences in threshold, it is necessary to average ascending and descending runs to obtain threshold estimate[10]. To familiarize the participants with the task and the stimuli, they were shown a sample series of both accelerating and decelerating trials prior to testing, and if it was needed, participants were given a short break at the half way point.

2.1.3 Results

Figure 3 shows the mean transition points (average of accelerating and decelerating runs) as a function of IA for the uniform and textured ground plane conditions. Also shown here are the geometrically predicted null values (white bars). The predicted null points are opposite in sign to the predicted bias because acceleration of the opposite sign must be ‘added’ to cancel this bias.

We predicted that the transition points would vary as a function of IA (see white bars in Figure 4). It is clear that these predictions were not born out. A repeated-measures ANOVA (with Greenhouse-Geiser corrections) confirmed that while there was a significant main effect of texture ($F(1,8)= 11.828$, $p=0.009$) there was no significant effect of IA ($F(3,24) = 0.853$, $p=0.465$). The interaction between IA and background did not reach significance ($F(3,24)=4.190$, $p=0.057$).

Figure 3 also shows that the presence or absence of texture in the ground plane influenced the acceleration/deceleration transition points. In the textured ground plane condition there was a bias towards seeing the stimuli decelerate (acceleration was required to null the bias). The converse was true in the uniform ground plane condition. This bias was consistent across IA in each background condition.

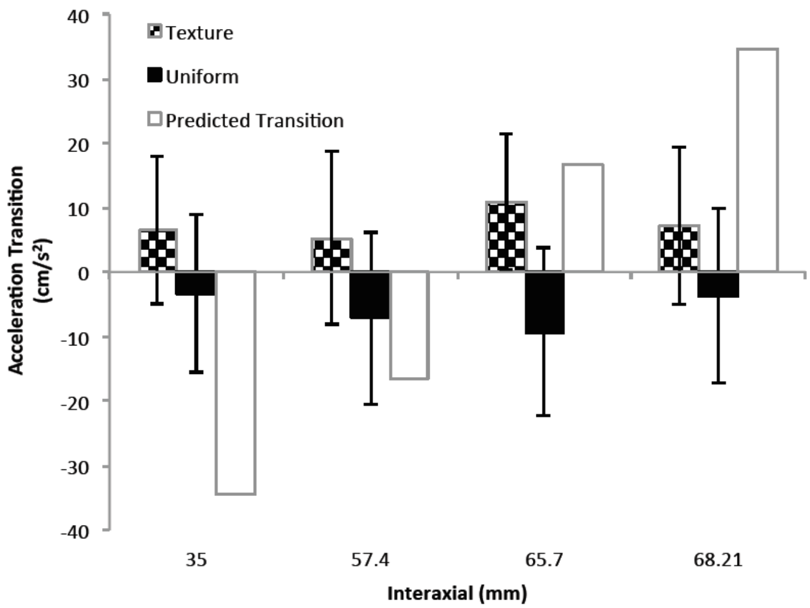

Figure 3: Perceived Mean Transition Points (average of ascending and descending runs) as a function of IA for the Uniform (black) and Textured (checked) background conditions. The error bars represent 95% confidence intervals and the white bars show the geometric predictions for each IA.

In summary, the results of Experiment 1 show that although observers' perception of the transition between perceived acceleration and deceleration differed significantly between the uniform and textured conditions, there was no consistent effect of IA in either condition.

2.2 Experiment 2 – Monocular and binocular contributions to acceleration bias

2.2.1 Introduction

In Experiment 1 we evaluated the effect of predicted distortions of stereoscopic space on an object moving through that space. While there was no effect of the primary stereoscopic manipulation (IA) there was an effect of the monocular cue (ground plane texture). However, the observed bias could be solely due to the monocular perspective cue or to associated changes in the strength of the stereoscopic cue. That is, in the textured background condition, there are vertical edges throughout the lower field which can be used by the stereoscopic system to specify the slant of the ground plane. Without these edges (in the uniform ground plane condition) the perceived slope of the ground plane will be much weaker. Therefore, in Experiment 2 we isolate the monocular depth cues (e.g. perspective, looming, distance from horizon) to evaluate their contribution to the acceleration/deceleration transitions reported in our first experiment.

2.2.2 Method

Subjects and Apparatus

Twelve participants (ages 19-35) who had normal or corrected to normal acuity were recruited. Of these seven were females and five were males. Stereopsis was assessed using the Randot Stereo test. The apparatus, camera parameters and viewing arrangement were the same as that described for Experiment 1.

Procedure

Observers viewed a moving ball sequence (as described in Experiment 1) either monocularly or binocularly. To equate as much as possible the monocular perspective views we used the smallest IA (35mm) employed in Experiment 1. The binocular trials were identical to those described in Experiment 1 while on monocular trials the participants wore an eye patch over their non-dominant eye. The method of limits was also used here to estimate the acceleration/decelaration transition points. Two ascending and two descending runs were performed for each combination of viewing condition (monocular/ binocular) and ground plane (textured/ uniform) for a total of 16 runs per observer.

2.2.3 Results

Figure 4 shows the averaged perceived transition points in the uniform and textured ground plane conditions with their associated confidence intervals in monocular and binocular conditions. The trends observed in Figure 4 are consistent with Experiment 1. While it appeared that there was a slight bias toward deceleration for textured backgrounds (nulled by a accelerating transition point) and acceleration for uniform backgrounds in the monocular viewing, the bias were not significant in any condition as indicated by confidence intervals in Figure 4.

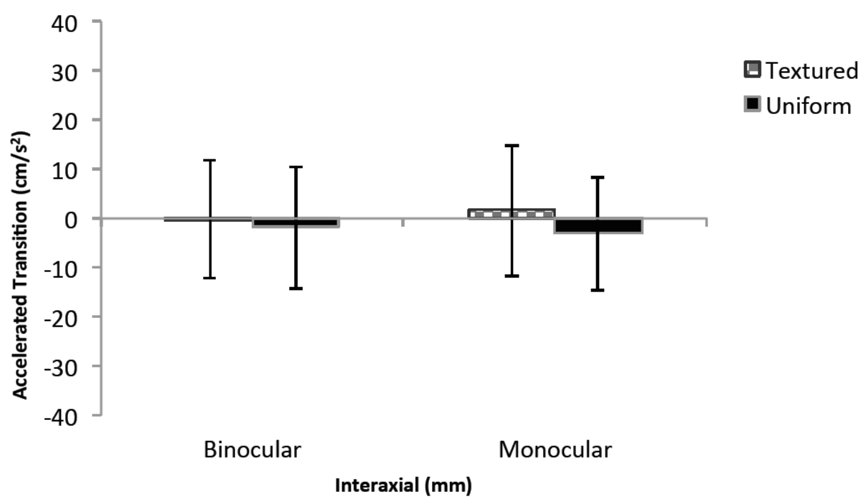

Figure 4: This figure shows the average of perceived transition points of ascending and descending runs in monocular and binocular viewing conditions with textured and uniform ground planes. The error bars indicate the 95% confidence intervals for each data set.

Taken together, the results of Experiments 1 and 2 suggest that the distortions of stereoscopic space predicted from binocular viewing geometry do not influence the change in perceived velocity of an object moving through that space. While there appears to be some indication of an effect of the presence of monocular depth cues in the uniform ground plane condition, it is weak and in the same direction as that seen in the stereoscopic viewing condition. Thus, the results of Experiment 2 suggest that the available monocular cues did not contribute to observers' inability to perceive differences in acceleration transition points according to IA in Experiment 1.

3. DISCUSSION

Experiment 1 shows that although observers' perception of the transition between perceived acceleration and deceleration was significantly affected by the presence or absence of additional depth cues (i.e., texture) in the ground plane, there was no consistent effect of IA. The effect of texture may be due to enhanced screen parallax, additional monocular depth cues, or some combination of these factors. Experiment 2 was conducted to examine how presentation of monocular depth cues in isolation contributed to the acceleration / deceleration transitions reported in Experiment 1. However, in Experiment 2 the bias was not significant and did not differ between monocular and binocular viewing conditions. Recall that the lack of bias in the binocular condition is consistent with the results of Experiment 1 as we used the smallest IA of 35 mm (though the bias is somewhat smaller in Experiment 2). Experiment 1 showed that strengthening the monocular and binocular depth signal changed the overall bias towards deceleration, suggesting that these cues do influence the perceived change in velocity. But this change occurred equally for all IAs, and the observed biases show no evidence of the predicted pattern, either in size or direction.

At the outset we outlined some relatively simple predictions regarding geometrically-defined distortions of S3D space and their possible effect on the perception of the motion of an object moving through that space (see Figure 1). We anticipated that the predicted depth distortions might influence the perceived acceleration / deceleration of an object moving through S3D space. However, it appears that such effects either do not occur, or are not captured using our methodology.

It may be that the predicted acceleration is simply too small to be detected or that the stereoscopic visual system is simply insensitive to acceleration. Humans have a notable lack of sensitivity to acceleration of objects across the retina. For example Gottsdanker et al found that thresholds for discriminating acceleration in the frontal plane when both viewing duration and acceleration were varied were better explained by the difference between final and initial velocity than by acceleration[11]. Similarly, Brouwer et al reported that acceleration thresholds for both acceleration matching and discrimination tasks varied with both presentation time and mean velocity[12]. However, expressed as a percentage change in velocity, the thresholds were constant at about 25%, independent of both presentation time and velocity. Thus, they also concluded that judgements of acceleration were made by comparing the initial and final velocity rather than directly detecting the acceleration. Practically, for our experiments it may not matter if perceived acceleration for motion in depth is sensed directly or through detection of change in velocity as both predict a perceptual artefact if the change is large enough.

Generally, subjects seem relatively insensitive to acceleration in the frontal plane (i.e. the plane of the screen) or to angular acceleration on the retina—thresholds for detecting the change in speed are typically 25% or more[12] which are significantly larger than the 5% typically reported for velocity discrimination[13]. Less is known about sensitivity to acceleration in depth. For an isolated disk stimulus observers are reportedly very poor at discriminating simulated acceleration based on looming alone and are unable to discriminate a stimulus undergoing a 2 m/s^2 acceleration from a subsequently presented constant velocity stimulus when the stimuli are presented for 1s[14]. To date sensitivity to monocular acceleration in depth in a full cue environment has not been investigated to our knowledge. It is also not clear how sensitive viewers are to acceleration in stereoscopic motion in depth. However, it has been reported that simulated acceleration had no influence on either monocular or binocular time to contact judgements[15]. While this suggests that the binocular visual system is not sensitive to acceleration it should be noted that the stimulus used was a single object with looming and changing disparity; results may differ if presented in an environment with both monocular and binocular cues to relative motion.

Past research on velocity discrimination shows that unlike size and depth constancy, which scale image size and disparity according to distance, there is no evidence for velocity constancy. There appears to be no efficient means of compensating for depth or distance in the binocular mechanisms that are used to estimate the linear velocity of a moving object[16]. Thus, even in a real world situation, given the variable relationship between changing disparity, changing depth, and the apparent lack of velocity constancy, it can be predicted that viewers should not be able to account for speed distortions of a moving object in depth. Consistent with this Rushton and Duke found that observers were unable to compensate for distance when judging velocity of motion in depth unless the stimulus was presented in a rich cue-laden environment[17]. If this is the case it may be that the insensitivity to stereoscopic acceleration distortions seen here may reflect adaptive mechanisms which downplay these distortions and create a bias toward perceiving constant velocity motion.

The presence of monocular cues to depth might also be expected to reduce the effects of IA-produced velocity distortions. The lack of a measureable effect of IA suggests that if cue conflict was the cause then the monocular cues were strong enough to result in cue dominance[18]. In Experiment 1 since there was no difference in the effects of IA between the textured and uniform backgrounds, the looming and height in the field cues would have to be sufficient for this dominance. There is an extensive literature concerning the combination of monocular and binocular cues to depth[19] and considerable evidence of interaction between these cues to produce the final percept[20,21]. Numerous studies report that there are individual biases towards perception of depth from one cue over another, for instance in the case of texture and disparity[22]. There is also evidence of suprathreshold monocular depth cues such as motion parallax, looming and perspective dominating stereopsis. However typically these strong biases are observed when the disparity signal is weakened, for instance by using absolute disparity[23] or when strong depth cues are placed in conflict[24,25]. In our case the predicted distortions are relatively large, and the parallax signal is above threshold, but it remains possible that the monocular cues were sufficient to override the parallax-based distortions.

Stereopsis can also interact with monocular cues in other ways. For example, the consistent disparity of the ball relative to the environment during the motion reinforces the relative position of the ball in the environment and supports the perception of motion in depth in the perspective image. As discussed in the Introduction, disparity needs to be scaled according to distance in order to recover metric depth. For many tasks in everyday life such scaling is not required and it has been argued that humans use simpler, non-metric relief transformations that preserve depth order and relief structure[26]. This relief transformation captures depth up to a scaling factor and would allow for an interpretation of the disparity to best match the depth from perspective, which could be thought of as a form of normalization.

It is possible that the absence of an effect of IA (and therefore stereopsis) seen here is due to a form of rescaling of perceptual space. Normalization processes operate in sometimes unexpected ways in stereoscopic media. In some cases, spatial distortions from nonlinear mapping of real world space to stereoscopic space can lead to an unnatural feel of the scene with artefacts such as the puppet theatre effect, cardboard effect, miniaturization and gigantism. Although varying IA can counter some of the artefacts in S3D content, at the extremes this variable can also cause unwanted distortions such as miniaturization (objects appear toy-like) and gigantism (objects appear over sized). Typically, these phenomena cause the scene to appear as it would if it was a scaled version viewed from a nearer or further distance [27,28] with the proportions of objects preserved but not their scale. If an object moved through such a normalized scene it might be expected that its velocity might also be normalized.

Our results are not consistent the proposal that observers should see distortions in motion in depth when IA is varied, and to our knowledge, this is the first evidence that the human visual system has this insensitivity. As outlined above, there are a number of likely causes of this insensitivity, and more research is needed to determine their relative contribution. In an effort to determine what the visual system does under typical viewing conditions, we used naturalistic motion and scene disparities (i.e. we did not distort the depth map). Our work shows that at least under such conditions, 3D content producers have flexibility in their choice of IAs without compromising the perception of an object's acceleration through stereoscopic space.

4. CONCLUSIONS AND FUTURE WORK

As outlined here IA, ZPS, viewing distance and a number of other camera parameters affect how distances in the real scene are mapped onto S3D space. Thus, modification of these variables has serious implications for perceived depth in S3D content. Recent advances in rendering software have made it possible to apply non-linear disparity mapping techniques to modify depth composition in previously captured content. The resulting content will have parallax-warped regions that do not obey the continuous geometry of visual space. Instead there may be abrupt transitions in stereoscopically defined depth between neighbouring regions in a scene. While in static scenes this distortion may not be noticeable, the motion of an object passing through these regions may be visibly distorted, drawing unwanted attention to that part of the scene. The experiments reported here investigate sensitivity to changes in velocity within regions that contain linear distortions that result naturally from binocular geometry. The next step will be to apply these methods to images containing non-linear disparity warping to determine if the observed insensitivity to S3D acceleration/deceleration is generalizable.

ACKNOWLEDGMENTS

The researchers thank Ontario Centre of Excellence (OCE) and Ontario Media Development Corporation (OMDC) for their support of this research program.

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