Space Perception in Virtual Environments: Displacement from the Center of Projection Causes Less Distortion than Predicted by Cue-Based Models

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Virtual reality systems commonly include both monocular and binocular depth cues, which have the potential to provide viewers with a realistic impression of spatial properties of the virtual environment. However, when multiple viewers share the same display, only one viewer typically receives the projectively correct images. All other viewers experience the same images despite displacement from the center of projection (CoP). Three experiments evaluated perceptual distortions caused by displacement from the CoP and compared those percepts to predictions of models based on monocular and binocular viewing geometry. Leftward and rightward displacement from the CoP caused virtual angles on the ground plane to be judged as larger and smaller, respectively, compared to judgments from the CoP. Backward and forward displacement caused rectangles on the ground plane to be judged as larger and smaller in depth, respectively, compared to judgments from the CoP. Judgment biases were in the same direction as cue-based model predictions but of smaller magnitude. Displacement from the CoP had asymmetric effects on perceptual judgments, unlike model predictions. Perceptual distortion occurred with monocular cues alone but was exaggerated when binocular cues were added. The results are grounded in terms of practical implications for multiuser virtual environments.

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1. INTRODUCTION

Virtual environments have proven useful for a broad range of applications, including training simulations [Grantcharov et al. 2004] as well as physical [Jack et al. 2001] and psychological [Glantz et al.

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2003] rehabilitation programs. One particularly compelling and immersive feature of many virtual reality systems is the capacity to present scenes stereoscopically. Inclusion of stereoscopic (binocular) cues provides additional depth information above and beyond those provided by pictorial (monocular) depth cues and has the potential to improve perception of egocentric (self-to-object) and exocentric (object-to-object) extents. However, improper display of virtual scenes can lead to distortions in perceived space (e.g., Kuhl et al. [2009]), and this problem is particularly visible in virtual reality systems designed for multiple users.

To show the same virtual environment to multiple users, the virtual scene is usually displayed on one or more projection screen surfaces. Users wear specialized glasses that interact with the display in order to receive the left and right eye images necessary for experiencing stereopsis. When viewed by a single user, the stereoscopic images are rendered from that user's specific location, thereby providing the single user with projectively correct stereo images. When head tracking is incorporated with a single user, that user always experiences the projectively correct images. Because the images are continually updated from his or her current location, the user is always standing at the center of projection (CoP). When multiple users view the same virtual environment presented on the same screen, image presentation becomes more complicated. Each user occupies a unique position in the environment, but the scene is rendered from a single location—the CoP. Usually, the CoP corresponds to the location of the head-tracked user, and all other users view the same stereo images from their unique locations, giving them a spatially distorted percept of the virtual environment. The resulting discrepancy between the perceptual experiences of the various users adversely impacts communication about spatial properties of the environment [Pollock et al. 2012]. The goal of the current project was to evaluate the perceptual distortions that occur as a result of viewing the environment from locations displaced from the CoP, as commonly occurs in multiuser virtual environments.

As an example of the perceptual distortions that can occur in multiuser virtual environments, consider the case of two users viewing a virtual surgery scene. One user (the "Leader") is head-tracked, and the scene is rendered from his or her perspective. The other user (the "Follower") views the same stereoscopic images from his or her unique location. When both users stand in approximately the same location as one another (e.g., when standing side by side), the Leader and Follower both receive relatively accurate stereo images of the surgery environment. However, when the Leader decides to walk around the surgery table in order to view the scene from a new perspective, the images displayed on the projection screen(s) change drastically, and the Follower experiences dramatic changes in visual input despite having remained in a fixed position. Furthermore, the Leader and Follower now occupy different physical locations, and the images experienced by the Follower are no longer appropriate for his or her location. When viewing stereo images generated from a different location (i.e., when viewing the environment from a location displaced from the CoP), the Follower is more likely to experience measurable perceptual distortions of spatial layout [Banks et al. 2009].

Perception of space (e.g., perception of depth extents on a ground plane) is influenced by both monocular and binocular depth cues [Sedgwick 1986]. Monocular depth cues are abundant in both real and virtual environments, and examples include linear perspective and texture gradients. Binocular depth cues are limited to convergence (the converging angle of the two eyes) and binocular disparity (slight differences in the images received by the two eyes). When judging spatial properties such as the slant of a surface, humans can combine monocular and binocular cues in a statistically optimal fashion [Hillis et al. 2004], indicating that both cue types simultaneously influence perceived spatial layout.

The perceptual distortion experienced when viewing a virtual environment after displacement from the CoP can be predicted on the basis of either the monocular or binocular depth cues. Using monocular depth cues, the predicted distortion is given by the geometry of perspective projections [Sedgwick 1991], and the relationship between displacement and perceptual distortion is herein referred to as

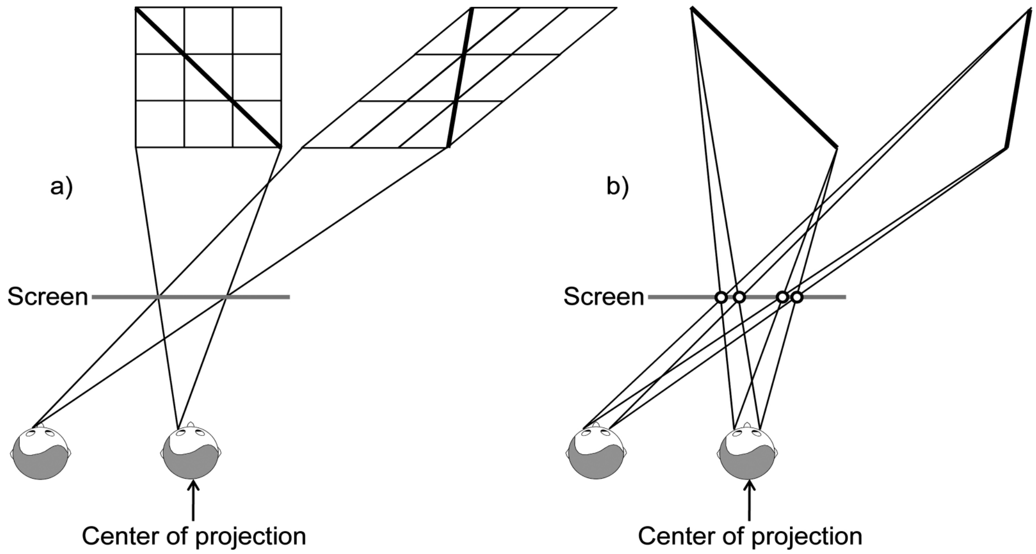

Fig. 1. Two viewers experiencing the same virtual environment displayed in stereo on a single projection screen. (a) The user on the right stands at the center of projection (CoP), and the virtual scene is projected as an image on the screen (only the left eye image is shown). The virtual scene contains a ground plane with a grid texture and a line segment (thick line) oblique relative to the screen surface. The user on the left is displaced from the CoP and views the image generated from the CoP. His perception of the line, as predicted by the perspective model, is rotated and displaced to the right. (b) The user on the right stands at the CoP, and the circles on the screen correspond to the left and right eye image points corresponding to the endpoints of the virtual line. The user on the left is displaced from the CoP and views the same stereo images generated from the CoP. His perception of the line, as predicted by the ray-intersection model, is rotated and displaced to the right.

the perspective model. Figure 1(a) illustrates the predictions generated by the perspective model. In this scenario, two users view a virtual line segment placed on a virtual ground plane at an orientation of 45° relative to the projection screen surface. The user depicted on the right stands at the CoP and, therefore, receives accurate monocular depth cues. The user depicted on the left is displaced laterally from the CoP and views the images that were generated from the CoP. The perspective model predicts that the virtual line will be perceived as being displaced to the right relative to its intended location and rotated in depth relative to its intended orientation. The grid lines indicate the global effects of displacement, whereby lateral displacement from the CoP causes the vanishing points of lines to shift in the direction opposite the direction of displacement.

On the basis of binocular depth cues, the predicted distortion can be also determined by using a ray-intersection approach [Banks et al. 2009; Held and Banks 2008; Woods et al. 1993], herein referred to as the stereo model. As depicted in Figure 1(b), every point in the virtual environment corresponds to two image points on the projection screen surface, one of which is seen by the left eye and one by the right eye. This is accomplished by wearing specialized glasses that filter out unique light wavelengths or flicker in synchrony with the display. The left and right eye image points are rendered from the CoP, but a viewer located elsewhere sees the same two images on the screen. By drawing rays from the centers of the viewer's left and right eyes, through the corresponding image points on the screen, and out into the virtual space, the intersection point of the two rays corresponds to the predicted perceived location of the virtual point based on the geometry of the stereoscopic cues. By considering multiple points on the same virtual object (e.g., the four corners of a virtual square placed on a ground plane), the stereo model can predict the perceived location and dimensions of a virtual shape.

Figure 1(b) demonstrates the predictions generated by the stereo model using the same scenario as in Figure 1(a). The circles on the projection screen surface correspond to the left and right eye image points corresponding to the two endpoints of the line. The user depicted on the left is displaced laterally from the CoP and views the images that were generated from the CoP. Just like the perspective model, the stereo model predicts that the virtual line will be perceived as being displaced to the right relative to its intended location and rotated in depth relative to its intended orientation. By comparing Figure 1(a) and 1(b), it can be seen that the perspective model and the stereo model both predict the same perceptual distortion in this example.

Under the viewing conditions tested in the current experiments, predicted perceptual distortions generated by the perspective model and the stereo model are nearly identical.[1] Generally speaking, the model predictions indicate that lateral displacement from the CoP will cause the vanishing point of straight lines to shift in the direction opposite the displacement, and forward (backward) displacement will cause depth extents to shrink (expand). Furthermore, both models predict that greater displacement will lead to greater perceptual distortion, although the predicted distortions caused by displacement are not always linearly related to the amount of displacement.

Research on space perception when viewing images after displacement from the CoP indicates that humans are largely susceptible to the distortion predicted by the perspective and ray-intersection models, but that humans are able to partially compensate for the distortion under certain viewing conditions. Vishwanath, Girshick, and Banks [2005] had participants monocularly view images on a screen through an aperture, which removed cues about the slant of the image surface. After angular displacement from the CoP (i.e., after rotation of the image surface relative to the viewing direction), spatial judgments about objects in the scene were almost completely predicted by the perspective model. However, inclusion of monocular and binocular cues about image surface slant led to spatial judgments that were nearly as accurate as judgments made from the CoP, especially when the angular displacement was less than 45°. Todorovic [2009] had participants judge orientations of objects in a line drawing of a three-dimensional (3D) scene while standing at the CoP or after backward displacement from the CoP (i.e., displacement away from the drawing). Displacement caused distortion in orientation judgments in the same direction but of smaller magnitude than the predictions of the perspective model, perhaps because there were abundant cues regarding the image surface orientation and distance. Similar reports of perceptual distortions of smaller magnitude than model predictions have led some to propose a compensatory process that allows viewers to partially correct for geometric distortions [Adams 1972; Yang and Kubovy 1999], although the necessity of such an explanatory mechanism has been debated (e.g., Sedgwick [1991]).

Although some studies using monocular images report partial compensation for the distortion introduced by displacement from the CoP when there are abundant cues regarding the position and slant of the image surface (see Adams [1972], Lumsden [1983], Todorovic [2009], Vishwanath et al. [2005], and Yang and Kubovy [1999]; but for evidence of failure to compensate, see Bengston et al. [1980], Kraft and Green [1989], and Smith and Gruber [1958]), recent research indicates that perceptual distortions when viewing stereoscopic images might be fully predicted by model predictions [Banks et al. 2009]. In that study, participants adjusted a virtual hinge until it appeared to form a 90° angle. Adjustments made from locations displaced from the CoP were almost perfectly predicted by the stereo model, suggesting that stereo viewing geometry can fully account for the perceptual distortions experienced after displacement. It is possible that the addition of stereo depth cues reduces the viewer's awareness of the screen orientation, thereby preventing any compensation for the effect of displacement from the CoP.

[1]Perceptual distortions predicted by the perspective model and the stereo model differed by less than 0.1% across all viewing conditions in all three experiments.

In sum, past work indicates that viewers at least partially compensate for perceptual distortions when viewing monoscopic displays after displacement from the CoP, especially when information about the screen orientation is available and the displacement is not too large [Goldstein 1987; Vishwanath et al. 2005], but that viewers do not compensate when viewing stereoscopic scenes [Banks et al. 2009]. However, the stereo displays used in past research have typically included relatively few monocular depth cues. It is, therefore, unknown whether stereoscopic displays will undergo significant perceptual distortion when both monocular and binocular cues are available.

The objective of the current project was to evaluate the perceptual distortions caused by displacement from the CoP when viewing objects in a virtual scene containing both monocular and binocular depth cues. Participants viewed virtual objects on a textured ground plane and made spatial judgments about those objects while standing at the CoP or at locations displaced from the CoP. Monocular depth information was provided primarily by the textured ground plane, and binocular depth information was provided by the stereo images. The perspective and stereo models of perceptual distortion based on viewing geometry predict that forward and backward displacement from the CoP will cause distortion in the perceived distance (egocentric extent from the viewer to the object) and depth (exocentric extent from the front of the object to the back of the object) of shapes. According to model predictions, after backward displacement of the viewer from the CoP, a virtual circle on the ground will look like an oval elongated in the depth dimension and will appear farther away in egocentric distance. Furthermore, the models predict that leftward and rightward displacement from the CoP will cause distortion and displacement of perceived angles. After leftward displacement of the viewer from the CoP, a right angle formed by two virtual lines (with the vertex on the right side) placed on the ground should look like an obtuse angle, and the angle should appear displaced to the right (see Figure 1). In order to better understand these distortions, participants in the current studies made depth judgments (i.e., judgments of the distance from the front edge to the back edge of a virtual object) and width judgments while viewing virtual rectangles, and also made angle judgments (i.e., judgments of the angle formed by two line segments) while viewing virtual angles. Although model predictions indicate that displacement from the CoP should change perceived object shape and location, these studies only addressed changes of perceived shape.

Past work on perception of virtual environments indicates that depth is underestimated by up to 50%, even when viewing from the CoP [Bodenheimer et al. 2007; Gooch and Willemsen 2002; Kelly et al. 2004; Knapp and Loomis 2004; Kuhl et al. 2009; Messing and Durgin 2005; Steinicke et al. 2009; Thompson et al. 2004; Waller and Richardson 2008; Witmer and Sadowski 1998; Ziemer et al. 2009]. In real-world environments, depth is typically perceived accurately, especially under full-cue viewing [Loomis and Knapp 2003]. The exact cause of depth compression in virtual environments is unclear, although it may be due to competing depth cues indicating the flatness of the image surface (similar sensory conflicts have been proposed to explain errors in picture perception; Hagen et al. [1978]; Sedgwick [1991]). For example, the lens of the viewer's eye accommodates at the distance of the screen, even when other depth cues indicate that virtual objects are located beyond the screen. In this project, we assumed that distortion caused by displacement from the CoP would occur in addition to the underestimation that is found in most virtual environments.

2. EXPERIMENT 1

2.1 Method

2.1.1 Participants. Twenty students at Iowa State University participated in exchange for course credit or monetary compensation.

2.1.2 Stimuli and design. The experiment was conducted within the C6 (Figure 2), a virtual reality system with a six-sided cubic configuration of projection screens measuring 10 × 10 × 10 ft (3.05 ×

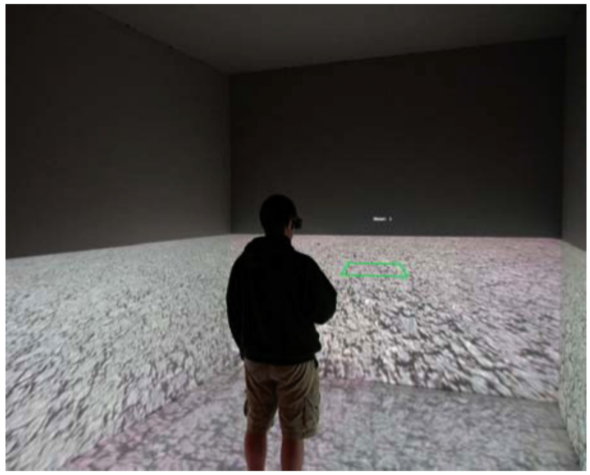

Fig. 2. A participant stands in the C6 viewing the virtual environment used in Experiment 1. The virtual green rectangle in front of the participant is one of the stimuli used to evaluate perceived depth and width.

3.05×3.05 m). The virtual environment was created using OpenSceneGraph and VR Juggler [Cruz-Neira et al. 2002], a commonly used application programming interface for clustered graphics applications. Each screen of the C6 was back-projected with $4{,}000 \times 4{,}000$ pixel stereo resolution and updated at 60Hz (30Hz per eye in stereo). The retractable rear screen was not used due to its location directly behind the participant (i.e., outside of the participant's field of view). Stereoscopic images of the virtual environment were generated using a fixed interpupillary distance of 6.5cm. Participants wore shutter glasses synchronized with the projectors in order to view the stereoscopic images.

The stimuli displayed in the virtual environment consisted of angles and rectangles placed on a ground plane. Angle stimuli were formed by a green line, perpendicular to the participant's view, and a red line rotated in depth. The angle vertex was always on the right side of the shape. The green and red lines were each 3ft (0.914m) in length, and the angle formed by the two lines ranged from 15 to 165° in 15° increments, resulting in 11 unique angles. Angles were placed either 10ft (3.05m) or 16ft (4.88m) in front of participants in the virtual environment, resulting in 22 total combinations of angle and distance. Rectangle stimuli were formed by four green lines in the outline of a rectangle (see Figure 2 for an example). The depth and the width of the rectangle could be 2ft (0.61m), 4ft (1.22m), or 6ft (1.83m), resulting in nine rectangles of varying depth and width. Rectangles were placed either 10 or 16ft in front of participants, resulting in 18 total combinations of object depth, width, and distance. Angles and rectangles appeared on an infinite ground plane covered with an irregular texture. The height of the ground plane was identical to the floor height in the C6.

Participants made angle judgments while standing at the CoP or after displacement by 3.5ft (1.07m) leftward or rightward from the CoP (see Figure 3, left panel). Participants made depth and width judgments while standing at the CoP or after displacement by 2.5ft (0.76m) forward or backward from the CoP (see Figure 3, right panel). Forward and backward displacements were smaller than leftward and rightward displacements due to visual discomfort experienced when viewing the front projection screen from a very close distance. All standing locations were marked with tape on the floor, and participants were directed to stand at marked locations corresponding to the relevant conditions.

Angle judgments and depth/width judgments were blocked, and block order was counterbalanced. Within each judgment-type block, viewing position was blocked and order was randomly determined. For each viewing position, stimuli were presented in a random sequence.

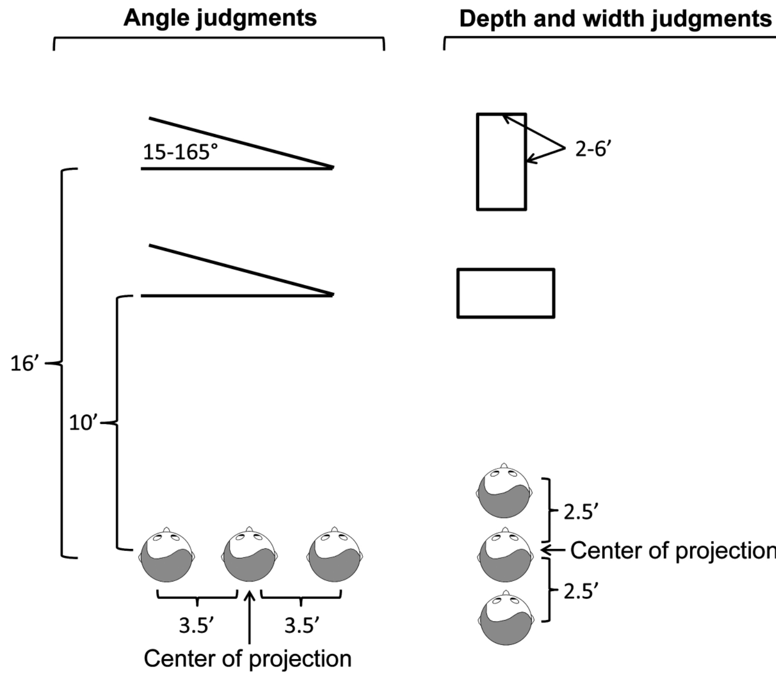

Fig. 3. Stimuli used in the experiments. The left panel shows the shapes and viewing locations used for angle judgments. The right panel shows shapes and viewing positions used for depth and width judgments.

2.1.3 Procedure. Upon providing informed consent, the participant was given a brief real-world training session in which the experimenter showed the participant angles and rectangles formed by lines on the laboratory floor. The purpose of training in the real environment was to familiarize the participant with making judgments of angle, width, and depth, and to make sure the participant understood how to report those judgments in the relevant units of measurement. For each type of judgment (angle, width, and depth), the participant was first shown a sample object and told the correct answer. After this demonstration, the participant was shown a new sample object and was asked to report what he or she believed to be the correct answer, and feedback was provided. When making width and depth judgments, the participant was allowed to use the unit of measurement with which he or she felt most comfortable. Most participants chose to use feet, and responses that were given in alternative units were converted to feet prior to analysis.

After training, the participant donned shutter glasses and was directed into the C6. The participant was placed at the center viewing position, facing the front screen, and the head tracking system was locked at that position. Locking the head tracking mechanism at the center position ensured that the CoP did not change when the participant was moved to a new location. The participant was instructed on which type of judgment he or she would be making first and where to stand. Standing locations were indicated by marks on the floor, and participants were instructed to remain at the marked location until further instruction, but their movements (e.g., head, neck, and trunk movements) were otherwise unconstrained.[2] Once the participant was in position, the virtual objects appeared and the

[2]Participant head position during the experiments was not recorded, but subsequent observations indicate that head position in this task rarely deviates by more than 4in (0.1m) from the intended viewing position.

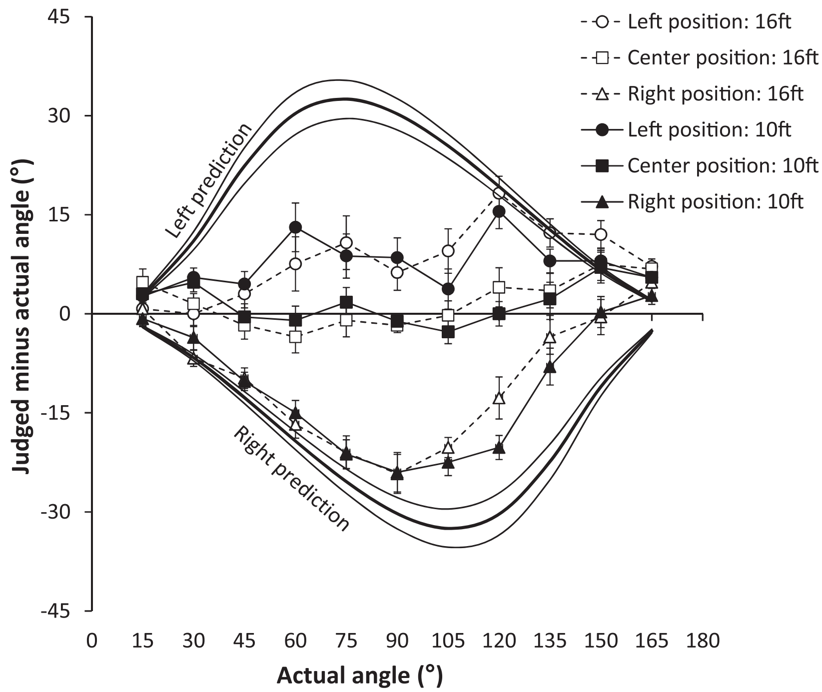

Fig. 4. Judged-minus-actual angle in Experiment 1 as a function of actual angle, participant viewing position, and object distance. Error bars indicate ±1 standard error. Model predictions after leftward and rightward displacement are also depicted (thick lines indicate predictions calculated from the intended viewing positions; thin lines indicate predictions calculated from viewing positions ±4in away from the intended viewing positions).

trial sequence began. Responses to angle, depth, and width judgments were given verbally, and the experimenter recorded the responses.

2.2 Results

2.2.1 Angle judgments. Angle judgments made from each viewing position and for each object distance are shown in Figure 4 as a function of actual angle. The main finding was that angle judgments made from the left and right viewing positions were larger and smaller, respectively, than those made from the center position, and the magnitude of this effect of viewing position was exaggerated for midrange angles compared to the largest and smallest angles. Additionally, angle judgments depended on object distance: obtuse angles were overestimated and acute angles were underestimated at the 16ft distance compared to the 10ft distance. These conclusions were supported by statistical analyses. Angle judgments were analyzed in a repeated measures ANOVA with terms for object angle (15–165°), object distance (10ft or 16ft), and participant viewing position (center, left, or right). Main effects of object angle [$F(10,190) = 1{,}829.39$, $p < .001$, $\eta_p^2 = .99$] and participant viewing position [$F(2,38) = 71.23$, $p < .001$, $\eta_p^2 = .79$] were qualified by interactions between angle and position [$F(20, 380) = 14.86$, $p < .001$, $\eta_p^2 = .44$] and between angle and distance [$F(10,190) = 3.94$, $p < .001$, $\eta_p^2 = .17$]. No other main effects or interactions were significant.

Model predictions of perceived angle based on monocular and binocular depth cues were nearly identical. The predictions of the (binocular) ray-intersection model are shown in Figure 4. Error bars on the model predictions indicate the effect of head displacement by ±4in (10cm), which was observed

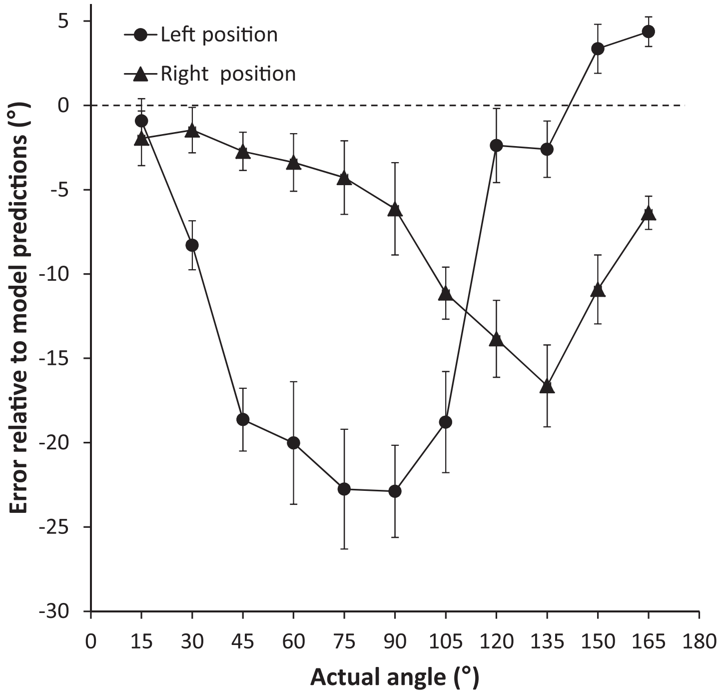

Fig. 5. Average errors in angle judgments in Experiment 1 relative to the model predictions in Figure 4. Error bars indicate ±1 standard error. Positive errors are errors that were more distorted (i.e., farther from the correct angle) than predicted by the model, and negative errors are errors that were less distorted (i.e., closer to the correct angle) than predicted by the model.

to be the largest typical deviation of head position. Despite the significant over- and underestimation of angles when standing at the left and right viewing positions, respectively, angle judgments showed significantly less distortion than predicted by the model. In order to statistically evaluate judgments relative to the model, angle judgment errors were calculated relative to model predictions. The two object distances were combined for this calculation because object distance did not interact with viewing position. The resulting error data are shown in Figure 5. Responses that were less distorted than the model predictions were coded as negative errors, and responses that were more distorted than the model predictions were coded as positive errors. As seen in Figure 5, model-relative errors were generally negative, indicating that judgments were smaller than predicted by the model. Furthermore, the largest and smallest angles were most likely to be biased by the predicted amount, but this is probably due to the similarity between model predictions and actual object angles for very large and small angles (see Figure 4). Distortion was less than predicted for a middle range of angles; however, leftward displacement caused this range to shift toward smaller angles, and rightward displacement caused this range to shift toward larger angles. These conclusions were supported by statistical analyses. Errors relative to model predictions were analyzed in a repeated measures ANOVA with terms for stimulus angle (15–165°) and participant viewing position (left or right). Significant main effects of angle [$F(10, 190) = 17.84$, $p < .001$, $\eta_p^2 = .48$] and viewing position [$F(1, 19) = 5.08$, $p = .036$, $\eta_p^2 = .21$] were qualified by a significant interaction between the two variables [$F(10, 190) = 22.84$, $p < .001$, $\eta_p^2 = .55$].

2.2.2 Depth judgments. Depth judgments are shown in Figure 6 as a function of actual object depth, participant viewing position, and object distance. The main finding is that depth judgments

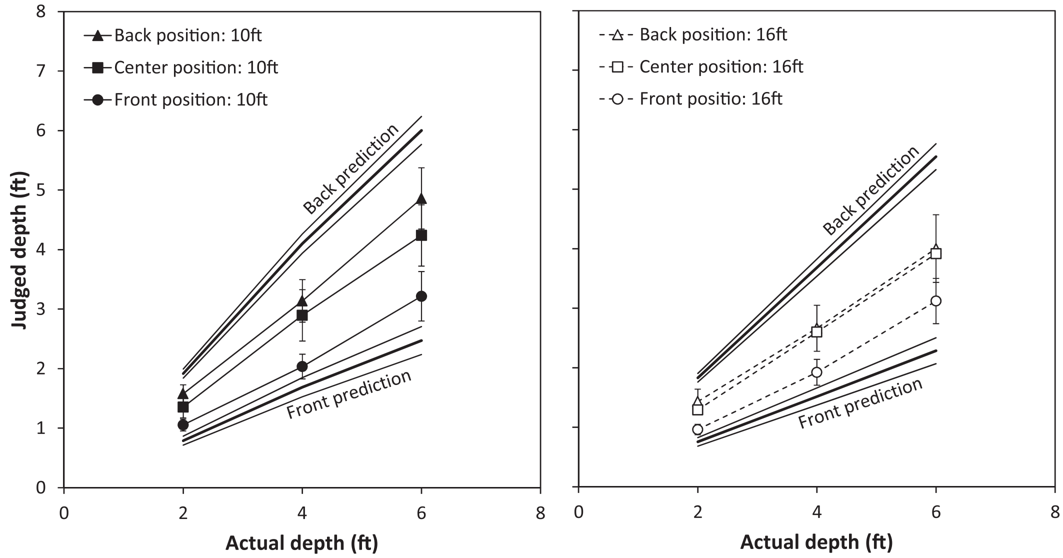

Fig. 6. Depth judgments in Experiment 1 shown as a function of actual object depth, participant viewing location, and egocentric distance to the object (Left panel: 10ft distance; Right panel: 16ft distance). Error bars indicate ±1 standard error. Model predictions after forward and backward displacement are also depicted (thick lines indicate predictions calculated from the intended viewing positions; thin lines indicate predictions calculated from viewing positions ±4in away from the intended viewing positions).

made from the back viewing position and the front viewing position were larger and smaller, respectively, than depth judgments made from the center viewing position, although the difference between the back and center viewing positions only reached statistical significance for objects at the 10ft distance. Furthermore, object distance also significantly affected depth judgments: objects at the 10ft distance were judged to have greater depth than objects at the 16ft distance, and the effect of viewing position was diminished for objects at 10ft compared to those at 16ft. These conclusions were supported by statistical analyses. Depth judgments were analyzed in a repeated measures ANOVA with terms for actual object depth (2, 4, or 6ft), viewing position (front, center, or back position), and object distance (10 or 16ft). Main effects of object depth, [$F(2, 38) = 58.72$, $p < .001$, $\eta_p^2 = .76$], viewing position [$F(2, 38) = 26.27$, $p < .001$, $\eta_p^2 = .58$], and object distance [$F(1, 19) = 26.30$, $p < .001$, $\eta_p^2 = .58$] were qualified by interactions between object depth and viewing position [$F(4, 76) = 133.25$, $p < .001$, $\eta_p^2 = .41$]; object depth and object distance [$F(2, 38) = 10.65$, $p < .001$, $\eta_p^2 = .36$]; viewing position and object distance [$F(2, 38) = 10.96$, $p < .001$, $\eta_p^2 = .37$]; and a three-way interaction between object depth, viewing position, and object distance [$F(4, 76) = 4.23$, $p = .004$, $\eta_p^2 = .18$].

Depth judgments made from the center viewing position were significantly foreshortened relative to veridical, averaging 70.2% of actual object depth for objects at the 10ft distance [$t(19) = 3.17$, $p = .005$] and 64.9% of actual object depth for objects at the 16ft distance [$t(19) = 3.59$, $p = 0.002$]. These findings are consistent with previous reports of perceived distance and depth compression in virtual environments [Loomis and Knapp 2003]. Based on the compressed depth judgments when participants stood at the center viewing position (i.e., at the CoP), model predictions were scaled accordingly. Specifically, model-predicted depth was scaled by 70.2% for the 10ft object distance and by 64.9% for the 16ft object distance (scaled predictions for forward and backward displacements are labeled as “front prediction” and “back prediction” in Figure 6). Model predictions of perceived depth based on monocular and binocular depth cues were nearly identical, thus only the predictions of the (binocular) ray-intersection model are shown. Error bars on the model predictions indicate the effect of head displacement by ±4in, which was observed to be the largest typical deviation of head position.

Manipulation of viewing position caused distortion of perceived depth in the direction of model predictions, but the magnitude of the distortion was less than predicted. When viewing objects at the 10ft distance, depth judgments made from the front viewing position were 21.0% smaller than judgments made from the center viewing position, and this difference was significant [$F(1, 19) = 21.94$, $p < .001$, $\eta_p^2 = .54$]. However, this compression was significantly less than the scaled model prediction that depth judgments made from the front viewing position would be 41.7% smaller than judgments made from the center viewing position [$t(19) = 7.47$, $p < .001$]. Depth judgments made from the back viewing position were 18.2% larger than judgments made from the center viewing position, and this difference was significant [$F(1, 19) = 19.17$, $p < .001$, $\eta_p^2 = .50$]. However, this expansion was significantly less than the scaled predictions of the model, in which depth judgments in the back viewing position were predicted to be 41.7% larger than judgments made from the center viewing position [$t(19) = 8.27$, $p < .001$].

When viewing objects at the 16ft distance, depth judgments made from the front viewing position were 16.6% smaller than judgments made from the center viewing position, and this difference was significant [$F(1, 19) = 11.49$, $p = .003$, $\eta_p^2 = .38$]. However, this compression was significantly less than the scaled predictions of the model, in which depth judgments made from the front viewing position were predicted to be 41.7% smaller than judgments made from the center viewing position [$t(19) = 6.89$, $p < .001$]. Depth judgments made from the back viewing position were 14.5% larger than judgments made from the center viewing position, and this difference was not significant ($p > .5$). This expansion was significantly less than the scaled predictions of the model, in which depth judgments in the back viewing position were predicted to be 41.7% larger than judgments made from the center viewing position [$t(19) = 5.05$, $p < .001$].

Regardless of object distance, forward displacement caused larger distortion than did backward displacement, and this was especially apparent at larger object depths [$F(2, 38) = 3.67$, $p = .035$, $\eta_p^2 = .16$]. This asymmetric effect of position on perceived depth was not predicted by the model.

2.2.3 Width judgments. Width judgments are shown in Figure 7 as a function of actual object width, viewing position, and object distance. The main finding is that width judgments made from the front viewing position were larger than judgments made from the center or back viewing position, and this effect of viewing position was exaggerated with larger object widths. This finding is counter to the model predictions based on monocular or binocular cues, which predict that perceived width will be unaffected by forward or backward displacement from the CoP. These conclusions were supported by statistical analyses. Width judgments were analyzed in a repeated measures ANOVA with terms for actual object width (2, 4 or 6ft), viewing position (front, center, or back position), and object distance (10 or 16ft). Main effects of object width [$F(2, 38) = 69.49$, $p < .001$, $\eta_p^2 = 79$] and viewing position [$F(2, 38) = 3.86$, $p = .03$, $\eta_p^2 = .17$] were qualified by a significant interaction between object width and viewing position [$F(4, 76) = 2.98$, $p = .024$, $\eta_p^2 = .14$]. No other main effects or interactions were significant.

2.3 Discussion

The primary purpose of Experiment 1 was to evaluate the perceptual distortions that occur when viewing virtual environments containing both monocular and binocular depth cues after displacement from the CoP, as commonly occurs when displaying virtual environments to multiple viewers. To that end, lateral displacement of the viewing position relative to the CoP led to large errors in judgments

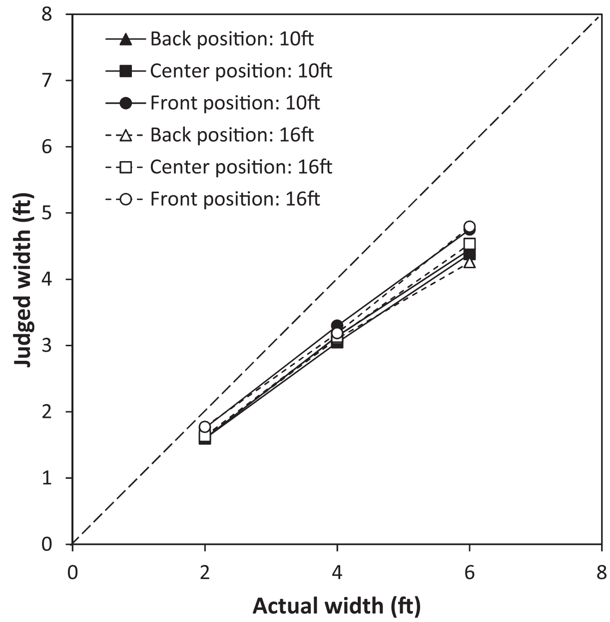

Fig. 7. Width judgments in Experiment 1 shown as a function of actual object width, participant viewing location, and egocentric distance to the object.

of angles formed by two line segments on the ground plane. Fore-aft displacements from the CoP led to large errors in judgments of the depth of rectangular shapes on the ground plane and more subtle errors in judgments of object width. Angle judgments and depth judgments were both distorted in the directions predicted by models based on either monocular or binocular depth cues: angles were judged as smaller and larger after rightward and leftward displacement, respectively; depths were judged as smaller and larger after forward and backward displacement, respectively. However, the magnitude of those distortions was consistently less than model predictions.

The effect of displacement from the CoP had asymmetric effects on angle judgments and depth judgments. For angle judgments, leftward displacement from the CoP led to greater distortion of obtuse angles, whereas rightward displacement from the CoP led to greater distortion of acute angles. The cause of this asymmetry in angle judgments is unclear and is not predicted by the monocular or binocular cue-based models. Past work has shown that the perceived orientation of line segments parallel to the image surface is asymmetrically affected by viewing angle [Goldstein 1987] despite model predictions to the contrary, and this might have resulted in the asymmetric relationship between displacement and perceived angle, especially because the angle vertex was always on the right side. Switching the angle vertex to the left side could result in a reversal of this pattern, but further work is needed to evaluate this. For depth judgments, forward displacement from the CoP led to greater distortion of perceived object depth than did backward displacement. This asymmetry in depth judgments is not predicted by the cue-based models, and its underlying cause is unclear.

Previous work on space perception after displacement from the CoP indicates that viewers can partially compensate for displacement when viewing monocular scenes [Adams 1972; Banks et al. 2009; Todorovic 2009; Vishwanath et al. 2005; Yang and Kubovy 1999], but that viewers show no compensation when viewing images with stereoscopic depth cues [Banks et al. 2009]. The current studies demonstrate partial compensation for displacement using a virtual scene containing both monocular and stereoscopic depth cues. One possible explanation for the discrepant findings is that the current study evaluated the effect of depth displacement on perceived space, whereas Banks et al. [2009] tested the effect of angular displacement. Another possible cause of the discrepant findings is the presence of strong monocular depth cues in the current study. Participants in Experiment 1 judged shapes appearing on a virtual ground plane, which provided monocular depth cues in addition to the stereo depth cues. The primary monocular depth cues present in Experiment 1 were defined by the texture gradient on the ground plane [Wu et al. 2004], the angle of declination from the eyes to the object on the ground [Ooi et al. 2001], and the shape of the rectangular object in the perspective image. However, the latter cue was only available when making depth judgments, whereas partial compensation was found in depth judgments as well as angle judgments; thus, complete reliance on this cue seems unlikely. In the study by Banks et al. [2009], participants viewed a hinge at eye level, and depth was defined primarily by stereo cues and linear perspective provided by the outline of the hinged surfaces and a grid like texture on those surfaces. The availability of richer monocular depth cues in the current study may have allowed participants to partially correct for the perceptual distortion caused by displacement from the CoP, because similar compensation can occur when viewing scenes with purely monocular depth cues. However, such partial compensation for the distortion introduced by displacement from the CoP typically requires abundant cues regarding the position and slant of the image surface [Goldstein 1987], and such cues were not explicitly present in Experiment 1.

A second experiment was conducted in order to evaluate whether the presence of strong monocular depth cues in Experiment 1 allowed participants to partially compensate for displacement from the CoP despite the presence of stereoscopic depth cues. Increased reliance on binocular cues was expected to result in perceptual distortions that could be better described by the cue-based models.

3. EXPERIMENT 2

In Experiment 1, the perceptual distortion caused by displacement from the CoP was less than predicted by cue-based models. If the reduced distortion found in Experiment 1 was due to the presence of strong monocular depth cues, which may have allowed participants to partially correct for displacement from the CoP, then removing some of those monocular depth cues should cause perceptual judgments to shift toward model predictions. Therefore, Experiment 2 manipulated the presence of the textured ground plane. A textured ground plane can provide depth information on the basis of its texture gradient (i.e., far texture elements are smaller than near texture elements in the retinal image). Furthermore, a viewer could infer the relative size of an object on the ground plane by counting the number of texture elements covered by that object [Sedgwick 1986, 1991]. Although removal of the textured ground plane removes depth cues associated with ground texture, it does not affect the perspective cue defined by the converging sides of a rectangle. However, removal of all monocular depth cues, as when viewing a random-dot stereogram [Julesz 1971; Loomis et al. 2006; Macuga et al. 2006], causes dramatic compression of perceived egocentric distance (e.g., Philbeck et al. [1997]). Therefore, the manipulation of ground plane texture represents a balance between removal of monocular depth cues and relative preservation of perceived distance. Furthermore, Experiment 2 was intended to bridge the contrasting results of Experiment 1 and those reported by Banks et al. [2009]. Abundant monocular cues were available in Experiment 1, whereas only linear perspective cues defined by the virtual shapes were available in the stimuli used by Banks et al. Therefore, the no-texture condition of Experiment 2 is conceptually closer to the viewing conditions in the Banks et al. study.

In addition to manipulation of the ground plane, Experiment 2 only tested depth judgments (i.e., the angle judgments from Experiment 1 were excluded in Experiment 2). This was done because removal of the ground texture was expected to have a direct effect on perceived depth, whereas the predicted effect of perceived depth on angle judgments is less straightforward. Finally, the verbal judgments used in Experiment 1 were replaced with a perceptual matching task in Experiment 2. The perceptual matching task involved adjusting the depth of one object that could be accurately perceived until it appeared to match the depth of the virtual object being tested. This was done to ensure that Experiment 1 findings reflected perceptual processing per se and not the intrusion of higher-level cognitive processes on verbal responses [Carlson 1977; Gogel 1974].

3.1 Method

3.1.1 Participants. Eighteen students at Iowa State University participated in exchange for course credit or monetary compensation.

3.1.2 Stimuli and design. There were two significant changes to the rectangle stimuli, herein referred to as the test rectangles. First, test rectangles only appeared at the 10ft distance. Second, an additional virtual rectangle, herein referred to as the match rectangle, appeared on the floor projection screen surface in the center of the C6. The match rectangle had no virtual stereo disparity, because it was located directly on the floor projection screen surface (the left and right eye images of the match rectangle on the floor projection screen were identical to one another). The width of the match rectangle was fixed, and the depth dimension of the match rectangle could be adjusted in 1in (2.54cm) increments until it appeared to match the depth of the test rectangle. Adjustment of the match object depth was controlled using a joystick held by the experimenter. To ensure that the match object was visible to the participant, all three viewing positions were shifted 3ft left from the center of the C6. The CoP was also shifted so that the center viewing position still coincided with the CoP.

In the texture condition, the virtual ground plane was covered with the same irregular texture used in Experiment 1. In the no-texture condition, the virtual ground plane was covered with a uniform gray color containing no texture elements.

The independent variables were the depth of the test rectangle (2, 4, or 6ft), the viewing position (front, center, or back), and the ground plane texture (texture or no texture). All variables were manipulated within participants. Texture condition was blocked, and order was counterbalanced. Within each texture block, viewing position was also blocked and order was randomized. Within each viewing position block, test object depth was randomized. The dependent variable was the adjusted depth of the match rectangle. Angle stimuli were eliminated from this experiment. Stimuli and design were otherwise identical to Experiment 1.

3.1.3 Procedure. Upon providing informed consent, the participant donned shutter glasses and was directed into the C6. The participant was placed at the center viewing position, facing the front screen, and the head tracking system was locked at that location. The participant was then led to the first viewing position. On each trial, the participant viewed a test rectangle and verbally directed the experimenter to adjust the depth of the match rectangle until it appeared to match the depth of the test rectangle. Once the participant was satisfied with the depth of the match object, the experimenter pressed a button on the joystick to log the response and the next trial began.

3.2 Results

Depth judgments are shown in Figure 8 as a function of actual object depth, viewing position, and texture condition. Depth judgments made from the back and the front viewing positions were larger and smaller, respectively, than depth judgments made from the center viewing position. Contrary to the hypothesis, removal of the ground plane texture reduced the effect of displacement from the CoP: depth judgments were closer to veridical and farther from model predictions without ground plane texture compared to with ground plane texture. These conclusions were supported by statistical analyses.

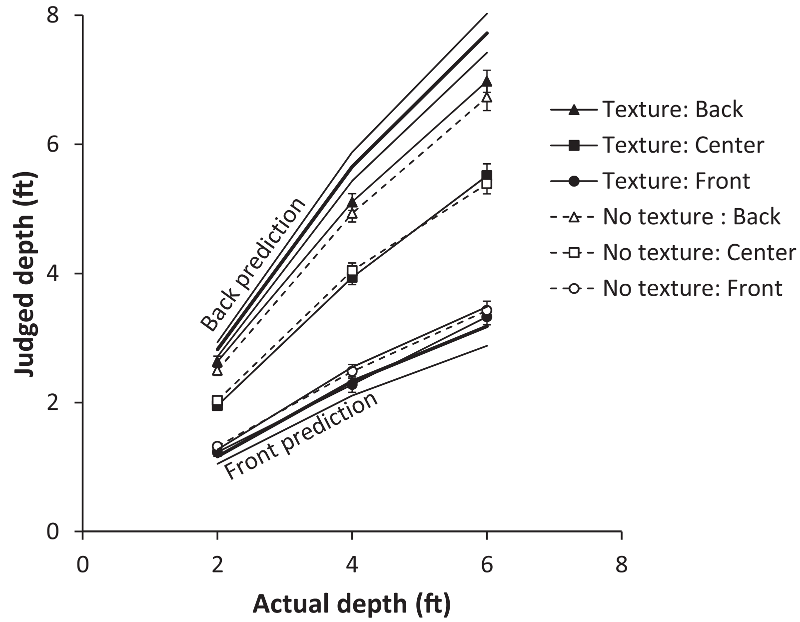

Fig. 8. Depth judgments in Experiment 2 shown as a function of actual object depth, participant viewing location, and texture condition. Error bars indicate ±1 standard error. Model predictions after forward and backward displacement are also depicted (thick lines indicate predictions calculated from the intended viewing positions; thin lines indicate predictions calculated from viewing positions ±4in away from the intended viewing positions).

Depth judgments were analyzed in a repeated measures ANOVA with terms for actual object depth (2, 4, or 6ft), viewing position (front, center, or back), and texture condition (texture or no texture). Main effects of object depth [$F(2, 34) = 870.30$, $p < .001$, $\eta_p^2 = .98$] and viewing position [$F(2, 34) = 429.29$, $p < .001$, $\eta_p^2 = .96$] were qualified by interactions between object depth and viewing position [$F(4, 68) = 105.13$, $p < .001$, $\eta_p^2 = .86$] and between viewing position and texture [$F(2, 34) = 7.65$, $p = .002$, $\eta_p^2 = .31$]. When standing at the front viewing position, judgments with texture were smaller than judgments without texture [$F(1, 17) = 13.435$, $p = .002$, $\eta_p^2 = .44$]. When standing at the back viewing position, judgments with texture were larger than judgments without texture [$F(1, 17) = 5.77$, $p = .028$, $\eta_p^2 = .25$]. When standing at the center viewing position, there was no effect of the texture manipulation ($p = .73$).

Depth judgments made from the center viewing position averaged 96% and 98% of actual object depth for texture and no-texture conditions, and these values did not differ significantly from veridical ($ps > .15$). For consistency with Experiment 1, model predictions were scaled according to judgments made from the center viewing position (scaled predictions for forward and backward displacements are labeled as "front prediction" and "back prediction" in Figure 8).

Manipulation of viewing position caused distortion of perceived depth in the same direction as predicted by the cue-based models, but the magnitude of the distortion was less than predicted in all but one condition. In the texture condition, depth judgments made from the front viewing position were 39.4% smaller than judgments made from the center viewing position [$t(17) = 22.50$, $p < .001$], which was not significantly different from the scaled model prediction that depth judgments made from the front viewing position would be 41.7% smaller than judgments made from the center viewing position ($p = .21$). Depth judgments made from the back viewing position were 31.4% larger than judgments made from the center viewing position, and this difference was significant [$t(17) = 11.96$, $p < .001$]. However, this expansion was significantly less than the scaled predictions of the model, in which depth judgments in the back viewing position were predicted to be 41.7% larger than judgments made from the center viewing position [$t(19) = 3.92$, $p = .001$].

In the no-texture condition, depth judgments made from the front viewing position were 36.2% smaller than judgments made from the center viewing position, and this difference was significant [$t(17) = 16.40$, $p < .001$]. However, this compression was significantly less than the scaled model predictions, in which depth judgments made from the front viewing position were predicted to be 41.7% smaller than judgments made from the center viewing position [$t(17) = 2.48$, $p = .024$]. Depth judgments made from the back viewing position were 24.2% larger than judgments made from the center viewing position, and this difference was significant [$t(17) = 8.76$, $p < .001$]. However, this expansion was significantly less than the scaled model predictions, in which depth judgments in the back viewing position were predicted to be 41.7% larger than judgments made from the center viewing position [$t(17) = 6.36$, $p < .001$].

Regardless of the presence or absence of texture, forward displacement caused larger distortion than did backward displacement [$F(1, 17) = 14.38$, $p = .001$, $\eta_p^2 = .46$]. This asymmetric effect of position on perceived depth was not predicted by the cue-based models.

3.3 Discussion

The primary purpose of Experiment 2 was to evaluate the effect of ground plane texture, a monocular depth cue, on the perceptual distortions experienced after displacement from the CoP. It was expected that removal of the ground plane texture would result in depth judgments that were closer to the predictions of the cue-based models compared to judgments made with the texture. Fore-aft displacements from the CoP led to large errors in judgments of the depth of rectangular shapes, and those errors were in the directions predicted by the cue-based models: depths were judged as smaller and larger after forward and backward displacement, respectively. However, the magnitude of those distortions was consistently less than model predictions in all but one condition. Furthermore, depth judgments were closer to veridical after removal of the ground plane texture, which was opposite the hypothesis.

One potential explanation for the finding that removal of the texture cue resulted in more accurate depth judgments comes from prior research demonstrating that, in the absence of any depth cues, the perceived egocentric distance of an object is approximately 6.5ft (2m; Gogel [1969]; Gogel and Tietz [1973]), a finding known as the specific distance tendency. Based on that finding, removal of the textured ground plane in the current experiment likely caused virtual objects to appear closer to the specific distance. Perceived egocentric distance from the viewer to the rectangle was not directly measured in this study, but it can be estimated using the size-distance invariance hypothesis. According to this hypothesis, perceived object size (S') is directly related to perceived egocentric object distance (D') and angular object size (α), such that S' = 2D'$\times$tan(α/2) [Gilinsky 1951; Gogel et al. 1985; Hutchison and Loomis 2006; Sedgwick 1986]. For objects of the same angular size, objects that appear farther away in egocentric distance will also appear larger, and vice versa. Working backward, perceived depth can be used to determine perceived distance. On the basis of depth judgments in Experiment 2, participants in the texture condition perceived the rectangles to be at egocentric distances of 5.8ft (1.77m) and 12.5ft (3.81m) when standing at the front and back viewing positions, respectively. According to the specific distance tendency, removal of the texture cues caused perceived egocentric distances from both viewing positions to shift toward the specific distance of 6.5ft, such that rectangles appeared farther away and larger when standing at the front viewing position and closer and smaller when standing at the back viewing position. In sum, size-distance invariance and the specific distance tendency together provide a parsimonious explanation of the finding that depth judgments were closer to veridical after removal of the textured ground plane.

The effect of displacement from the CoP had asymmetric effects on depth judgments, such that forward displacement from the CoP led to greater distortion of perceived object depth than did backward displacement. This asymmetry in depth judgments, which was not predicted by the cue-based models, replicates the findings of Experiment 1.

It was expected that removal of the ground plane texture in Experiment 2 would lead to perceptual distortions of the magnitude predicted by models based on perspective and stereo geometry. This prediction was based on the fact that Banks et al. [2009] found that perceptual distortions when viewing a stereoscopic scene with few monocular cues could be fully accounted for by model predictions, although that study addressed displacements of viewing angle rather than distance. Instead, the results of Experiment 2 showed that the texture gradient was not the cause of the smaller-than-predicted perceptual distortion. It is possible that the remaining cues after texture removal were still too strong, allowing participants to partially compensate for displacement from the CoP. However, removal of all monocular depth cues (e.g., by using a random-dot stereogram) would cause dramatic compression of perceived egocentric distance (e.g., Philbeck et al. [1997]), which would complicate evaluation of depth judgments after displacement from the CoP. An alternative approach to evaluating the relative contributions of monocular and binocular depth cues is to compare judgments made in environments containing only monocular cues or both monocular and binocular cues. This was the approach taken in Experiment 3.

4. EXPERIMENT 3

In Experiments 1 and 2, displacement from the CoP distorted perceived space in ways predicted by cue-based models, but the magnitude of distortion was smaller than model predictions. It is unclear whether the perceptual distortion found in Experiments 1 and 2 is driven primarily by the monocular or binocular cues alone, or whether the distortion reflects both cue types. Experiment 3 was designed to identify the relative contributions of monocular and binocular cues to perceptual distortion after displacement from the CoP. This was done by comparing depth judgments in virtual environments containing only monocular depth cues or monocular plus binocular depth cues.

4.1 Method

4.1.1 Participants. Eighteen students at Iowa State University participated in exchange for monetary compensation.

4.1.2 Stimuli, design, and procedure. The test and match rectangles and the viewing positions were identical to those used in Experiment 2. Unlike Experiment 2, the ground plane was textured in all conditions. Furthermore, the presence of stereoscopic cues was manipulated. This was done by either displaying the environment binocularly (as was done in Experiments 1 and 2) or by displaying the environment biocularly, whereby the same image was seen in both eyes. The biocular display removed stereoscopic depth cues defined by convergence and binocular disparity but preserved the monocular depth cues as well as other characteristics of the viewing environment (e.g., the shutter glasses were still worn in the biocular condition, and the field of view was equivalent across conditions). Past research has shown that egocentric distance perception in virtual reality is similar under biocular and monocular viewing [Willemsen et al. 2008]. For ease of exposition, this condition is herein referred to as the monocular condition. When stereo cues were available, the visual stimulus was identical to the texture condition of Experiment 2.

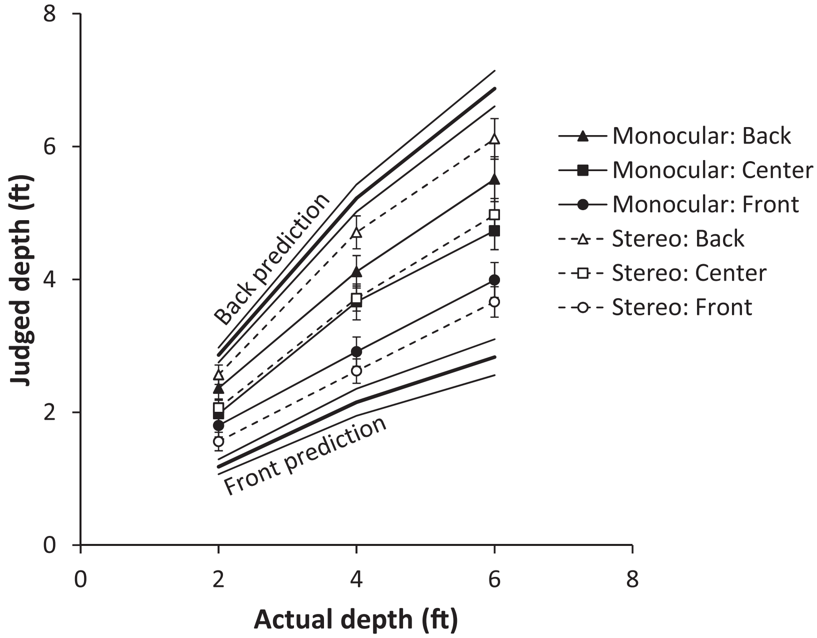

Fig. 9. Depth judgments in Experiment 3 shown as a function of actual object depth, participant viewing location, and texture condition. Error bars indicate ±1 standard error. Model predictions after forward and backward displacement are also depicted (thick lines indicate predictions calculated from the intended viewing positions; thin lines indicate predictions calculated from viewing positions ±4in away from the intended viewing positions).

All independent variables were manipulated within participants. The stereo viewing condition (stereo or monocular) was blocked, and order was counterbalanced. Within each stereo viewing condition block, viewing position (front, center, or back) was also blocked and order was randomized. Within each viewing position block, test object depth (2, 4, or 6ft) was randomized. The dependent variable was the adjusted depth of the match rectangle. Stimuli, design, and procedure were otherwise identical to Experiment 2.

4.2 Results

Depth judgments are shown in Figure 9 as a function of actual object depth, viewing position, and stereo viewing condition. Depth judgments made from the back and the front viewing positions were larger and smaller, respectively, than depth judgments made from the center viewing position. This influence of viewing position was found in both the stereo and monocular conditions but was more pronounced in the stereo condition. These conclusions were supported by statistical analyses.

Depth judgments were analyzed in a repeated measures ANOVA with terms for actual object depth (2, 4, or 6ft), viewing position (front, center, or back), and stereo viewing condition (stereo or mono). Main effects of object depth [$F(2, 34) = 278.96$, $p < .001$, $\eta_p^2 = .94$] and viewing position [$F(2, 34) = 61.93$, $p < .001$, $\eta_p^2 = .79$] were qualified by interactions between object depth and viewing position [$F(4, 68) = 30.46$, $p < .001$, $\eta_p^2 = .64$]; between viewing position and stereo viewing condition [$F(2, 34) = 16.25$, $p < .001$, $\eta_p^2 = .49$]; and between object depth, viewing position, and stereo viewing condition [$F(4, 68) = 2.74$, $p = .035$, $\eta_p^2 = .14$]. When standing at the front viewing position, judgments with stereo cues were smaller than judgments without stereo cues [$F(1, 17) = 20.563$, $p < .002$,

$\eta_p^2 = .55$]. When standing at the back viewing position, judgments with stereo cues were larger than judgments without stereo cues [$F(1, 17) = 5.90$, $p = .034$, $\eta_p^2 = .24$]. When standing at the center viewing position, there was no effect of the stereo cue manipulation ($p = .34$). The effect of stereo cues on depth judgments made from the front and back viewing positions was exaggerated for the two larger object depths compared to the smallest object depth [$F(1, 17) = 7.25$, $p = .015$, $\eta_p^2 = .30$].

Depth judgments made from the center viewing position averaged 90% and 93% of actual object depth for monocular and no-stereo conditions, and these values did not differ significantly from veridical ($ps > .10$). For consistency with Experiments 1 and 2, model predictions were scaled according to judgments made from the center viewing position (scaled predictions for forward and backward displacements are labeled as "front prediction" and "back prediction" in Figure 9).

Manipulation of viewing position caused distortion of perceived depth in the same direction as predicted by the cue-based models, but the magnitude of the distortion was less than predicted. Compared to judgments made from the center viewing position, depth judgments made from the front viewing position were 14% and 25% smaller in the monocular and stereo conditions, respectively, and those differences were both significant [monocular: $t(17) = 3.43$, $p = .003$; stereo: $t(17) = 4.66$, $p < .001$]. Furthermore, depth judgments from the front viewing position under monocular and stereo viewing conditions were significantly different from the scaled model prediction that depth judgments made from the front viewing position would be 41.7% smaller than judgments made from the center viewing position [monocular: $t(17) = 6.89$, $p < .001$; stereo: $t(17) = 3.03$, $p = .008$].

Depth judgments made from the back viewing position were 18% and 27% larger in the monocular and stereo conditions, respectively, compared to judgments made from the center position, and those differences were both statistically significant [monocular: $t(17) = 4.89$, $p < .001$; stereo: $t(17) = 5.07$, $p < .001$]. Furthermore, depth judgments from the back viewing position under monocular and stereo viewing conditions were significantly different from the scaled model prediction that depth judgments made from the back viewing position would be 41.7% larger than judgments made from the center viewing position [monocular: $t(17) = 6.66$, $p < .001$; stereo: $t(17) = 2.89$, $p = .01$].

4.3 Discussion

The primary purpose of Experiment 3 was to evaluate the contributions of monocular and binocular depth cues to distortions in perceptual judgments made after displacement from the CoP. Depth judgments were biased in the direction of model predictions whether the virtual environment contained only monocular or both monocular and binocular depth cues. Judgments showed greater bias toward model predictions when the environment contained both monocular and binocular depth cues than when the environment contained only monocular depth cues, indicating that both types of cues contribute to the perceptual distortions caused by displacement from the CoP. A complete theoretical account of the relative contributions of monocular and binocular depth cues requires comparison of environments containing only monocular cues and only binocular cues with an environment containing both monocular and binocular cues. However, an environment containing only binocular depth cues is likely to cause profound underperception of egocentric distance (e.g., Philbeck et al. [1997]); therefore, future studies on this topic will likely require novel stimuli and dependent measures in order to appropriately compare across conditions.

5. GENERAL DISCUSSION

The current project was designed to evaluate the perceptual distortion caused by displacement from the CoP, and to compare those distorted percepts to model predictions based on distortions in perspective and stereo viewing geometry (models based on perspective and stereo geometry made nearly identical predictions under the conditions tested in these experiments). In Experiment 1, leftward and rightward displacement of the viewing position relative to the CoP caused leftward-opening angles on the ground plane to be judged as larger and smaller, respectively, compared to judgments made from the CoP. Backward and forward displacement from the CoP caused rectangles on the ground plane to be judged as larger and smaller in depth compared to judgments made from the CoP. Although distortions of perceived angle and depth after displacement were biased in the directions predicted by the cue-based models, the magnitude of judgment biases was significantly less than model predictions. Experiment 2 was conducted to evaluate whether the smaller-than-expected biases were the result of monocular depth cues, which participants might have used to partially correct for the distorted stereoscopic depth cues. To that end, the second experiment tested the effect of forward and backward displacement on depth judgments in a virtual environment with and without a textured ground plane. It was expected that removal of the ground texture would result in errors that were more consistent with the model predictions. Contrary to the hypothesis, judgments were closer to veridical when the texture was absent than when the texture was present, a finding that may be attributable to the specific distance tendency (see Experiment 2 Discussion section). Experiment 3 evaluated the relative contributions of monocular and binocular depth cues by comparing depth judgments made after displacement from the CoP when the scene contained only monocular depth cues or both monocular and binocular depth cues. Depth judgments were biased in the direction predicted by the cue-based models, but the magnitude of the bias was greater when the scene contained both monocular and binocular depth cues than when it contained monocular cues alone.

Displacement from the CoP had asymmetric effects on angle judgments and depth judgments. Leftward displacement from the CoP led to greater distortion of obtuse angles, whereas rightward displacement from the CoP led to greater distortion of acute angles. Furthermore, forward displacement from the CoP led to greater distortion of perceived object depth than did backward displacement. These asymmetries are not predicted by the cue-based models. One possible explanation for the front/back asymmetry is the monocular distance cue defined by the accommodative state of the lens. The human lens reflexively accommodates to the distance of the screen in order to focus images on the retina, and this occurs even in virtual environments intended to convey depths beyond or in front of the screen [Hoffman et al. 2008]. The resulting accommodative state of the lens serves as a cue to egocentric distance [Wallach and Norris 1963]. In the current study, forward displacement caused the lens to accommodate at a closer distance and backward displacement caused the lens to accommodate at a farther distance, relative to the accommodative state of the lens when standing at the CoP. Although forward and backward displacements were equal in linear distance from the CoP, the resulting change in the lens accommodation (measured in diopters) is not linearly related to displacement. Instead, forward displacement from the CoP caused a greater accommodative change than did backward displacement, and this may have contributed to the front/back asymmetry found in depth judgments. However, this logic does not explain the left/right asymmetry found in angle judgments, which could be due to the asymmetric effect of viewing angle on perception of line orientation [Goldstein 1987].

Taken together, the smaller-than-expected biases and asymmetric biases caused by displacement from the CoP point to a complex interaction between stereo and monocular depth cues. Past research has found that when viewing purely monocular images, displacement from the CoP has a relatively small effect on judgment errors as long as there are abundant cues regarding the orientation of the display surface [Adams 1972; Banks et al. 2009; Todorovic 2009; Vishwanath et al. 2005; Yang and Kubovy 1999]. In contrast, when viewing stereoscopic images, judgment errors after angular displacement from the CoP are almost completely predicted by the viewing geometry [Banks et al. 2009]. Immersive virtual environments commonly contain both monocular and stereo depth cues and lack a visible frame; thus, a better understanding of their interaction is critical to predicting viewers' experiences of those environments. The current studies indicate that viewing a virtual environment from a vantage point displaced from the CoP will cause some perceptual distortion, although not as much as predicted by cue-based models. Furthermore, if reducing perceptual distortion is the primary goal for a particular application (e.g., one in which communication about spatial properties between multiple viewers is of utmost importance), then removal of stereoscopic depth cues will cause perception of spatial relationships to shift toward veridical.

Past work on space perception in virtual environments indicates that egocentric distances are typically underperceived, even in projection-based virtual reality systems in which the viewer stands at the CoP [Ziemer et al. 2009]. Although the current experiments did not directly measure perceived egocentric distance, judgments of object depth can be used to infer perceived egocentric distance assuming size-distance invariance [Gilinsky 1951; Gogel et al. 1985; Hutchison and Loomis 2006; Sedgwick 1986]. Using depth judgments in the current experiments, inferred egocentric distances when standing at the CoP were underperceived in Experiment 1 (judgments were 65% and 70% of actual distance for objects placed at the 10ft and 16ft distances, respectively) but more accurately perceived in Experiment 2 (96% of actual distance; all objects were placed at the 10ft distance) and Experiment 3 (91% of actual distance). Experiment 1 results are similar to past findings of distance underperception in virtual environments, but Experiment 2 and 3 results show surprising accuracy. The discrepancy between the results of Experiment 1 and Experiments 2 and 3 is likely due to the different response modes. Verbal reports, used in Experiment 1, have previously been shown to produce reliably smaller egocentric distance judgments compared to action-based judgment types such as blind walking [Loomis et al. 1998], possibly due to misestimation of the standard unit of measurement used for verbal reports (e.g., a foot or a meter), rather than underestimation of the perceived distance per se. We believe that the matching task used in Experiments 2 and 3 reflects a purer perceptual response, similar to action-based judgments, compared to the verbal reports used in Experiment 1, which may have been biased by a failure to accurately represent standard units of measurement. However, further studies in which egocentric distance perception is directly assessed are needed to verify these claims.

The finding that displacement from the CoP had asymmetric effects on perceptual distortions may have practical implications for displaying virtual environments to multiple users. For example, because backward displacement typically caused less distortion than forward displacement, the average distortion experienced by multiple users will be reduced if the scene is always rendered from the location of the front-most user. As multiple users walk around the environment, the CoP could be switched to the user closest to the projection screen. Of course, this solution requires that all users are head-tracked. Furthermore, this approach would be most appropriate in virtual reality systems with a clear primary display, but multiple users commonly share the same focus of attention even in six-sided virtual reality systems. Additional research is needed to determine whether switching the CoP between users is a feasible solution to the problem of perceptual distortions caused by displacement from the CoP.

When viewing stereoscopic virtual environments, displacement from the CoP introduced errors in judgments of perceived space, but those errors were smaller than predicted by cue-based models based on perspective and stereo geometry. These findings suggest that perceived space is influenced by a complex relationship between stereo and monocular depth cues. Further work is needed to refine existing models of perceived space and to evaluate the implications of flexibly switching the CoP between viewers in order to minimize the perceptual errors experienced by a group of viewers in multiuser virtual reality systems.

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