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The Perceptual Consequences of Curved Screens

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Flat panels are by far the most common type of television screen. There are reasons, however, to believe that curved screens create a greater sense of immersion, reduce distracting reflections, and minimize some perceptual distortions that are commonplace with large televisions. To examine these possibilities, we calculated how curving the screen affects the field of view and the probability of seeing reflections of ambient lights. We find that screen curvature has a small beneficial effect on field of view and a large beneficial effect on the probability of seeing reflections. We also collected behavioral data to characterize perceptual distortions in various viewing configurations. We find that curved screens can in fact reduce problematic perceptual distortions on large screens, but that the benefit depends on the geometry of the projection on such screens.

CCS Concepts: • **Interaction devices** → **Displays and imagers**; • **Human-centered computing** → *Displays and imagers*;

Additional Key Words and Phrases: Television screen, field of view, reflections, perceptual distortions, focal length

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1 INTRODUCTION

The challenge for television manufacturers is to create an immersive and natural-looking experience for the viewer. There are many display properties that affect that experience, including color, contrast, brightness, resolution, field of view, and accuracy of perceived shape. Here we focus on how the viewing experience is affected by curving the screen along its horizontal dimension.

In just 5 years in the early 1950s, the proportion of American households with a television increased from 8% to 64% [7]. Television was becoming the predominant source of mass entertainment. In response, the movie industry developed several innovative processes that were meant to provide more immersive experiences. *The Cinerama* consisted of a unique capture and display system providing a wide, curved display screen. But the Cinerama never gained wide acceptance due to technical issues. For example, the images the system projected onto the viewer's retina were only geometrically correct if he or she were centered in front of the screen at an appropriate distance. The images appeared to be distorted from any other viewing position. Moreover, the capturing format required specific training for the directors and could not be adapted for flat cinema screens or television.

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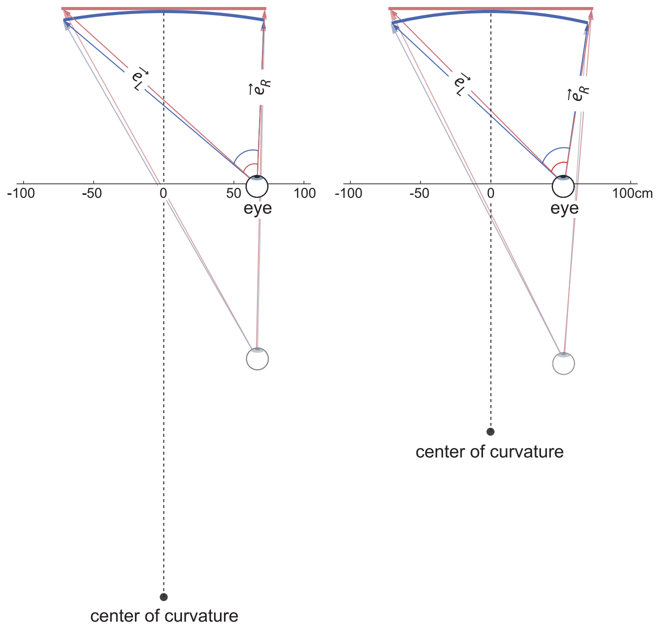

Fig. 1. Geometry underlying horizontal field of view. Plan views of the viewer and screen. The thick red and blue contours represent flat and curved screens, respectively. The radii for the curved screen are 418 and 300 cm on the left and right, respectively. The two recommended viewing distances (UHD at 1.55 times screen height, and HD at 3.1 times screen height) are indicated by the darker and lighter contours, respectively.

The history of the Cinerama illustrates a potentially critical trade-off with curved screens. On the one hand, they could engender an increase in immersion. On the other, they may reduce the size of the viewing region from which undistorted imagery can be seen.

Recently, television manufacturers have developed and commercialized curved screens. According to those manufacturers and some reviewers [2, 11], such screens create wider fields of view, reduce ambient light reflections, and create a greater sense of immersion. In contrast, some technical journalists, consumers, and competing manufacturers claim that curved screens induce more distracting reflections and create perceptual distortions when viewing the screen both from a centered viewpoint and from off to the side [2, 11]. Curved screens are more expensive to manufacture than flat screens, so whatever benefit they may provide to the viewer must be weighed against the additional cost.

We examined how the field of view, detectability of light reflections, and perception of shape are affected by the use of curved versus flat screens for a variety of viewing positions. We consider horizontal curvature only. Said another way, the screens under consideration are sections of vertical cylinders.

2 FIELD OF VIEW

The field of view is the angle the screen subtends at the viewer's eye. Larger fields of view create a somewhat greater sense of immersion or presence [9, 13, 20], so larger fields should be beneficial to the viewing experience.

We calculated the horizontal field of view for curved and flat screens of the same size (i.e., same surface area). We did this for the viewing distances recommended for HD and UHD screens, which are 3.1 and 1.55 times screen height, respectively [4, 5] (Figure 1). Two radii of curvature were modeled: 418 and 300 cm. The 418cm radius corresponds to the Samsung HU9000 UHD 65-inch curved screen.

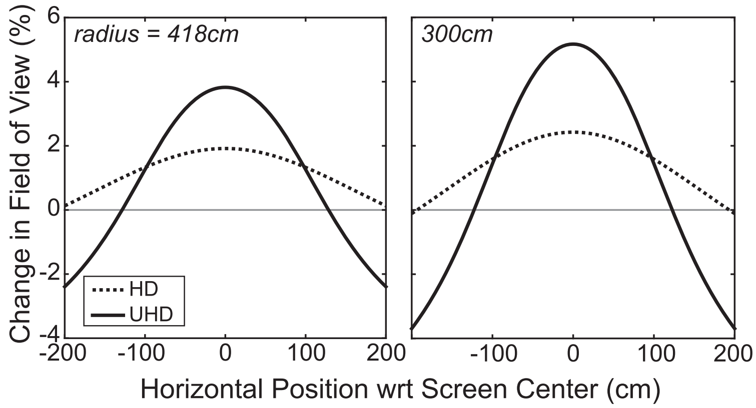

Fig. 2. Change in horizontal field of view for curved screens relative to flat screens. The percentage change is plotted as a function of the viewer's horizontal position relative to screen center. The left panel shows this comparison when the radius of curvature of the curved screen is 418cm; the right panel shows it when the radius is 300cm. The dashed and solid contours represent the changes in field of view for HD and UHD viewing distances, respectively. Percentages greater than zero represent cases in which the curved screen provides a wider field of view.

The horizontal field of view is

$$\theta = \cos^{-1}\left[\frac{\vec{e_L} \cdot \vec{e_R}}{||\vec{e_L}|| \cdot ||\vec{e_R}||}\right], \tag{1}$$

where $\vec{e_L}$ and $\vec{e_R}$ are the vectors from the eye to the left and right edges of the screen and $\cdot$ is dot product (see Figure 1). Figure 2 shows the change in horizontal field of view for curved screens relative to flat screens as a function of the viewer's horizontal position. Left and right panels show the results for curvatures of 418 and 300 cm, respectively. Dashed and solid curves represent the results at the recommended distances for HD and UHD, respectively. As you can see, curving the screen increases the field of view when the viewer is not too far to the left or right of screen center. The maximum increase is, however, only 4% to 5%. Reducing the radius of curvature increases the field of view: a radius of 300cm widens the field by 5% and 2.5% at the UHD- and HD-recommended viewing distances compared to the less curved screen.

We conclude that curving the screen provides a slightly wider field of view when the viewer is positioned reasonably close to screen center. The increase is small, however, and therefore may have no discernible effect on the viewing experience.

3 REFLECTIONS

Light sources in the room often create visible reflections off the screen that disrupt the viewing experience. The reflected light adds to the light from the screen content, creating two related effects: *glare* (difficulty seeing content when bright light is present in nearly the same direction as the content) and *veiling glare* (reduction in contrast and desaturation of color caused by adding desaturated light in the same direction as the content) [10, 15, 19]. Naturally, manufacturers recommend viewing television in a darkened environment to reduce these annoying effects. But people often watch television with the room lights on or with outdoor light streaming through windows. Here we consider how screen curvature affects the probability of seeing reflections of environmental light sources.

Figure 3 illustrates the geometry. Whether a reflection of an environmental source will be seen depends on the position of the light source relative to the screen, the viewer's position relative to the screen, and the size and curvature of the screen. As you can see, curving the screen generally causes a displacement of the apparent

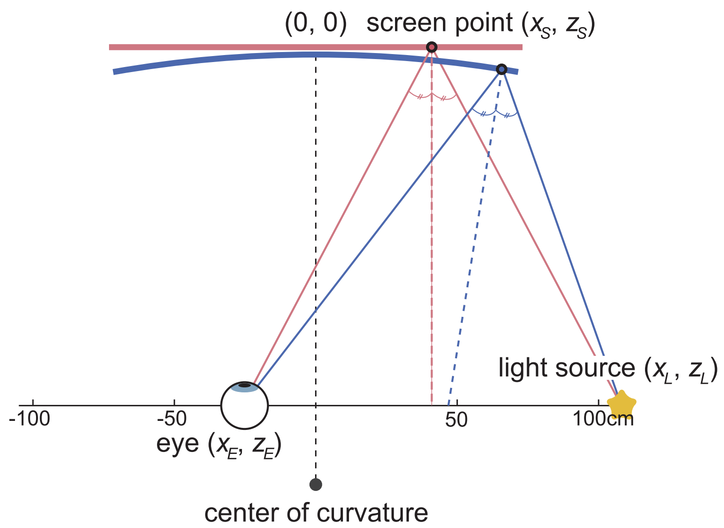

Fig. 3. Geometry of screen reflections. The red and blue contours represent the flat and curved screens. The radius of curvature for the curved screen is 418cm. The viewer is positioned at the recommended distance for UHD. The yellow star represents a light source at the same distance. The lines from the light indicate reflections the viewer would see. On a curved screen, the apparent direction of the reflection moves away from screen center relative to its apparent direction on a flat panel. The XZ coordinates of points on the screen, light source, and viewer's eye are defined with an origin at screen center.

direction of the reflection of the light source away from screen center, and this reduces the likelihood of seeing a reflection on a curved screen as compared to a flat screen.

We set the distance of the source from the screen equal to the viewer's distance from the screen. Greater source distances yielded similar results. We then calculated for different horizontal viewing positions the range of horizontal positions of the light source that would create visible reflections.

For screen curvatures ranging from 300cm to infinity (i.e., flat), we solve for X_L, the horizontal position of a light source whose reflection is seen on the screen. To enter the viewer's eye, X_S, the apparent horizontal position of the reflection, must be on the screen. In other words,

$$X_L = X_S + \tan\left[\tan^{-1}\left(\frac{X_S - X_E}{Z_E - Z_S}\right) - 2\tan^{-1}\left(\frac{X_S}{R_S - Z_S}X_S\right)\right](Z_E - Z_S), \tag{2}$$

where X_E and Z_E indicate the viewer's position relative to screen center and X_L is the position of the light source. Thus, we find the light source positions X_L that yield an apparent reflection on the screen.

From Equation (2), we calculated the range of horizontal light positions that would yield a visible reflection for a viewer at the HD- and UHD-recommended distances. The left panel of Figure 4 shows the results for curved relative to flat screens when the curved screen has a radius of 418cm; the right panel shows the same for a radius of 300cm. Curving the screen generally reduces the horizontal range of light positions that create visible reflections. The reduction is greatest at the shorter viewing distance and when the viewer is centered in front of the screen. The reduction is larger when the radius of curvature is shorter.

Thus, the probability of experiencing glare and/or veiling glare is reduced by curving the screen, thereby improving the viewer's experience. This effect is somewhat offset by the fact that reflections off a curved screen are magnified relative to those off a flat screen, so the area of the screen affected by a reflection may be greater when the screen is curved.

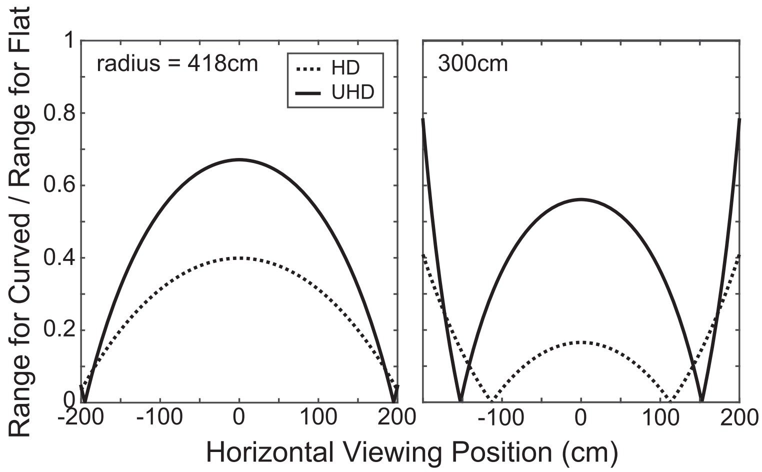

Fig. 4. The range of light positions causing visible reflections for curved versus flat screens. The abscissas are the horizontal position of the viewer. The ordinates are the ratio of ranges, specifically the horizontal range of visible light positions for the curved screen divided by the same range for the flat screen. A value of 1 means that widths of the reflection-inducing zones (hence also reflection-free zones) are the same for curved and flat screens. A value of 0 means that the width is zero for the curved screen. Note that for specific eccentric viewing positions, the ratio of ranges drops to zero, indicating that all point light sources (for which $Z_E = Z_S$) are reflected away from the viewer.

4 PERCEIVED DISTORTIONS

We next investigated how perceived shape is affected by screen curvature. To explain how we did this, we must first explain the geometry that underlies the displaying and viewing of images on displays.

4.1 Perspective Projection

Pictures presented on a display screen are based on perspective projection. As shown in Figure 5, the 3D scene is projected through a center of projection (CoP) onto a projection surface, which is usually a plane. The projection onto that surface is then presented on the display screen for projection onto the viewer's retina. When the viewer's eye is at the CoP, the retinal image is that same as it would be when viewing the original real scene.

The dimensions of the image of an object in a picture are affected by *projective scaling* (magnification as the distance between the projection plane and the CoP increases) and *projective stretching* (lengthening in the tilt direction, the direction in which distance along the projection plane changes most rapidly). In Figure 5, the tilt direction is horizontal, so the stretching is horizontal. Thus, the horizontal and vertical dimensions of the projected object on the projection plane are

$$a \approx \frac{Ap}{d\cos(S_P)}, \tag{3}$$

$$b \approx \frac{Bp}{d}, \tag{4}$$

where A and B are orthogonal dimensions of the object in the scene (A is aligned with the tilt, which is horizontal in the figure), d and p respectively are the distances from the CoP to the object and from the CoP to the projection plane, and S_P is the slant of the projection surface at the position of the projected object on the projection plane

$$S_P = \cos^{-1}\left[\frac{\vec{CoP}\cdot\vec{N}}{|\vec{CoP}|\cdot|\vec{N}|}\right], \tag{5}$$

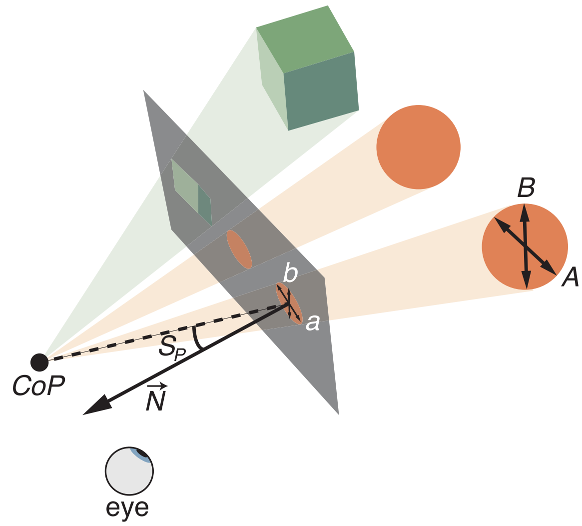

Fig. 5. Geometry of perspective projection. Light rays from the 3D scene that go through the CoP are recorded in the projection plane (gray rectangle), thereby creating a perspectively correct picture. The orientation of the projection plane at a given point can be described by slant and tilt. Slant S_P is the angle between the surface normal $\vec{N}$ and $\vec{CoP}$. Tilt is the direction of slant: here horizontal. The slant of the region where the middle sphere projects is 0 here, and the slant of the region where the right sphere projects is nonzero. Consequently, the middle and right spheres respectively create a circle and ellipse in the projection plane. If the viewer's eye is at the CoP, the retinal images created by the original scene and the picture are the same. In Equations (3) and (4), the dimensions of the occluding contours of the depicted objects are measured in the tilt direction A and the orthogonal direction B; a and b are aligned with A and B.

where $\vec{CoP}$ is the vector from the object on the projection surface to the CoP and $\vec{N}$ is the surface normal from the point on the screen where the object is displayed. Equations (3) and (4) become exact as the size of the region on the surface approaches zero.

S_P depends, of course, on the curvature of the projection surface (Figures 6 and 7) and on the distance from the CoP to the screen. As the curvature of the projection surface increases, S_P decreases, so images on eccentric positions on the surface become less stretched in the tilt direction. Indeed, if the CoP is at the center of curvature of the projection surface, S_P is zero for all positions along the horizontal meridian of that surface, which means that the aspect ratio of the projection of a simulated object becomes the same as the aspect ratio of the original object. For example, if the simulated object is a sphere, the aspect ratio on the projection surface becomes 1 everywhere along the horizontal meridian.

The second projection from the picture to the retina also causes scaling and stretching, but now the stretching is foreshortening. The dimensions of the image at the retina are

$$\alpha \approx \frac{af \cos(S_{local})}{v}, \tag{6}$$

$$\beta \approx \frac{bf}{v}, \tag{7}$$

where v is the distance from the eye to the picture surface, f is the eye's focal length, and S_{local} is the viewing slant

$$S_{local} = \cos^{-1}\left[\frac{\vec{e} \cdot \vec{N}}{|\vec{e}| \cdot |\vec{N}|}\right], \tag{8}$$

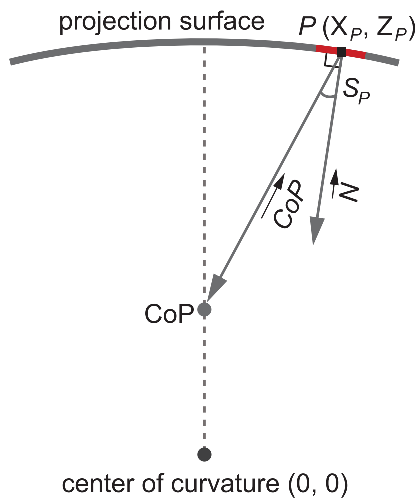

Fig. 6. Perspective projection on a curved surface. The surface slant at P with respect to the CoP is S_P. The slant with respect to the eye is S_{local} (not shown).

where $\vec{e}$ is the vector from the point of interest on the screen to the eye and $\vec{N}$ is the surface normal at that point.

Thus, the retinal image is foreshortened in the tilt direction and scaled according to the viewing distance and focal length. Changes in the shape of the retinal image created by the object on the projection surface are affected only by the viewing slant S_{local}, which varies as a function of screen curvature and viewer position. For a centered viewer, S_{local} decreases when the screen curvature increases and goes to zero when the radius of curvature of the screen equals the viewing distance. S_{local} is larger for short viewing distances and for off-to-the-side viewing positions.

4.2 Perceptual Invariance

When a picture is viewed from the CoP, the effects of the two projections (the *capture parameters* from object to projection plane and the *viewing parameters* from projection plane to retina) cancel, so as we said before, the relative dimensions (i.e., aspect ratios) of the retinal image are equal to those that would be created by the original scene. But viewers are usually farther from the screen than the CoP distance and are frequently not centered with respect to the screen. In those cases, the retinal image of the picture differs from the retinal image that would be created by the scene. This could lead to a distorted perception of the scene, but previous studies have shown that the perceived aspect ratio remains similar to the actual aspect ratio [8, 18, 21]. In other words, the visual system compensates effectively for off-to-the-side viewing and somewhat effectively for viewing from the wrong distance. This is a very good thing because it means that viewers do not have to be precisely positioned at the CoP to perceive a distortion-free image. The visual system accomplishes the compensation by estimating the slant of the picture surface (S_{local}) at each point of interest and using those estimates to perceptually compensate for what otherwise might be objectionable distortions [21]. This adjustment leads to a perceived aspect ratio of

$$\frac{\hat{A}}{\hat{B}} = \frac{\alpha}{\beta \cos(S_{local})}. \tag{9}$$

Vishwanath et al. [21] measured perceived shape as a function of S_{local} and showed that perceptual invariance is achieved as long as $|S_{local}|$ is less than 30°. When it is greater than 30°, the visual system is no longer able to

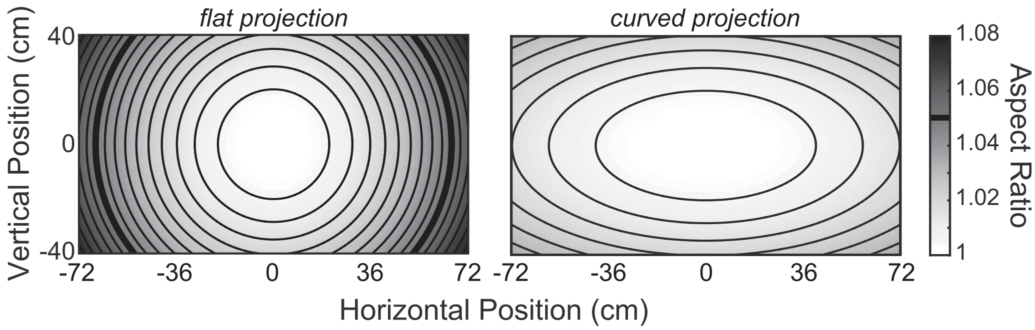

Fig. 7. Aspect ratios of spheres projected on flat and curved surfaces. Each panel plots projection aspect ratios as a function of screen position: left for flat screens and right for curved (curvature radius = 418cm). The aspect ratios are represented by grayscale and iso-ratio contours. Ratios greater than 1.05 (thick contour on left) should be perceived as noncircular. Projection focal length is 50mm.

compensate for the eccentric view and perceptual invariance starts to break down. In normal viewing conditions, $|S_{local}|$ is often greater than 30° near the edges of the screen (Figure 8). For example, on a 65-inch flat screen viewed from the UHD-recommended distance, $|S_{local}|$ exceeds 30° near the left and right screen edges, and near screen center for a viewer positioned off to the side by 70cm. When the screen is curved, $|S_{local}|$ is reduced near the screen edges, which should enable better perceptual compensation.

4.3 Wide-Angle Distortions

Perceptual compensation is based on measuring S_{local}, and that measurement does not seem to depend on the contents of the picture [21]. Although the compensation is generally effective in reducing perceived distortions, it does not always yield a geometrically correct solution. For example, consider a viewer who is close to the CoP. In this case, S_P is approximately equal to S_{local}, so shape changes in the scene-to-picture projection (Equations (3) and (4)) and the picture-to-retina projection (Equations (6) and (7)) cancel. As a result, the shape of the retinal image is correct or nearly correct (i.e., the same as it would be when viewing objects in the original scene). But the perceptual compensation mechanism still operates, which means that the visual system uses its estimate of S_{local} to adjust perceived shape according to Equation (9). As a result, the perceived aspect ratio $\frac{\hat{A}}{\hat{B}}$ is equal to the aspect ratio of the image on the screen $\frac{a}{b}$ and is solely determined by the stretching factor $\frac{1}{\cos(S_P)}$. This, unfortunately, produces a distortion of perceived shape even though the retinal image has the correct shape as demonstrated in Figure 9. This effect is called *wide-angle distortion* and is well known in the photography and computer graphics communities [1, 12, 16, 23]. To minimize this effect, photography texts recommend lens focal lengths that are 40% to 50% greater than the film width. For example, with 35mm film, the focal length should be 49 to 53 mm [12].

Figure 7 represents the aspect ratios on the screen of correctly projected spheres. On the flat screen, the sole determinant of the aspect ratio is radial eccentricity from screen center. Contours of constant aspect ratio are therefore circular, with the largest ratios in the screen corners. The curved screen is cylindrical, so aspect ratios vary differently with horizontal and vertical eccentricity. As a consequence, contours of constant aspect ratio are elliptical. It is important to consider what deviations from correct shape are objectionable. Of course, the answer will depend on how familiar the viewer is with the true shape. In other words, distortions will undoubtedly be most objectionable with objects of known shape. A particularly challenging shape is the circle, so judging its shape represents a worst-case scenario. Psychophysical research has shown that viewers do not perceive a shape as circular when its aspect ratio deviates by more than 5% from the correct value of 1 [17]. Thus, for the

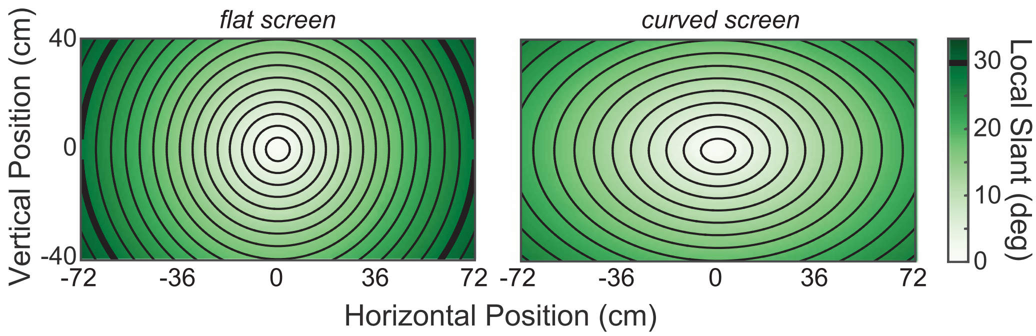

Fig. 8. Local slant $|S_{local}|$ as a function of screen curvature and position on the screen. Values for flat and curved screens are on the left and right, respectively. The radius of curvature of the projection plane is either infinite (flat) or 418cm (curved). The local slant is shown for different screen positions for a centered viewing position at the UHD-recommended viewing distance. Different colors represent different values of $|S_{local}|$: darker shades for successively greater values. The thick contour on the left indicates where $|S_{local}| = 30°$.

worst case, we predict that a viewer at the CoP will perceive wide-angle distortions at any screen eccentricity where the aspect ratio exceeds 1.05. Curving the screen displaces the critical aspect ratio toward the edges of the screen, so we argue that wide-angle distortion will generally not be experienced on curved screens but will often be experienced on flat ones. This statement assumes that perspectively correct projections were used and that the viewer was positioned such that $|S_{local}|$ does not exceed 30°.

4.4 Expectations

When creating and displaying content on a screen, the projection from the real scene onto the projection plane (the capture parameters) and from the image to the retina (viewing parameters) can create two different distortion effects: (1) failure of perceptual invariance (Section 4.2) when the viewing slant $|S_{local}|$ exceeds 30° and (2) wide-angle distortion (Section 4.3) when the projected shape on the screen deviates by more than 5% from the true shape. We expect that curving the screen will reduce the likelihood and magnitude of both distortion effects. We tested these expectations in a psychophysical experiment with flat and curved screens.

5 METHODS

5.1 Participants

Five young adults with normal or corrected-to-normal vision participated. All were unaware of the experimental hypotheses. They gave informed consent under a protocol approved by the Institutional Review Board of the University of California, Berkeley. As the reader will see, the results were very consistent across the five participants, so we did not find it necessary to include more.

5.2 Apparatus

The left side of Figure 10 is a schematic of the apparatus. Stimuli were presented on 65-inch television screens, one flat and one curved horizontally. The radius of curvature for the curved screen was 418cm. The stimuli were viewed from one of two distances: 125.5cm, the recommended distance for UHD, and 251cm, the recommendation for HD. At each distance, viewers were positioned at one of three horizontal positions: 0°, 20°, or 40° rightward from straight ahead of screen center. Stimuli were presented at five different positions on the screen: center, middle left, middle right, top left, and top right (see Figure 10, upper right). The subject's position relative to the screen was constrained with a chin rest.

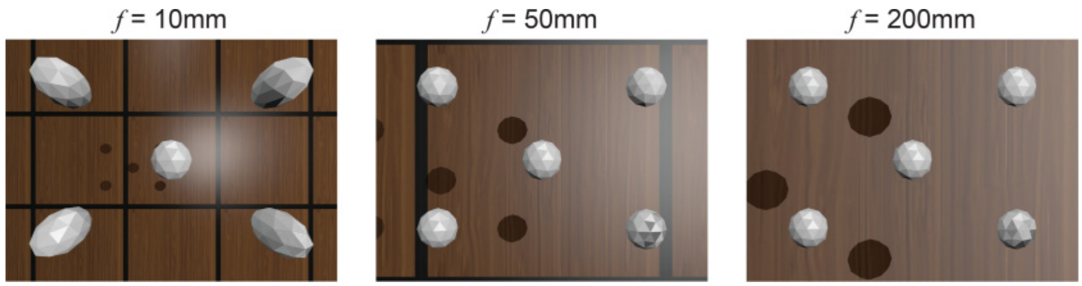

Fig. 9. Wide-angle distortions. A scene composed of spheres in front of a background is rendered with different focal lengths. From left to right, the focal lengths are 10, 50, and 200 mm. CoP distance is focal length multiplied by picture magnification [6].

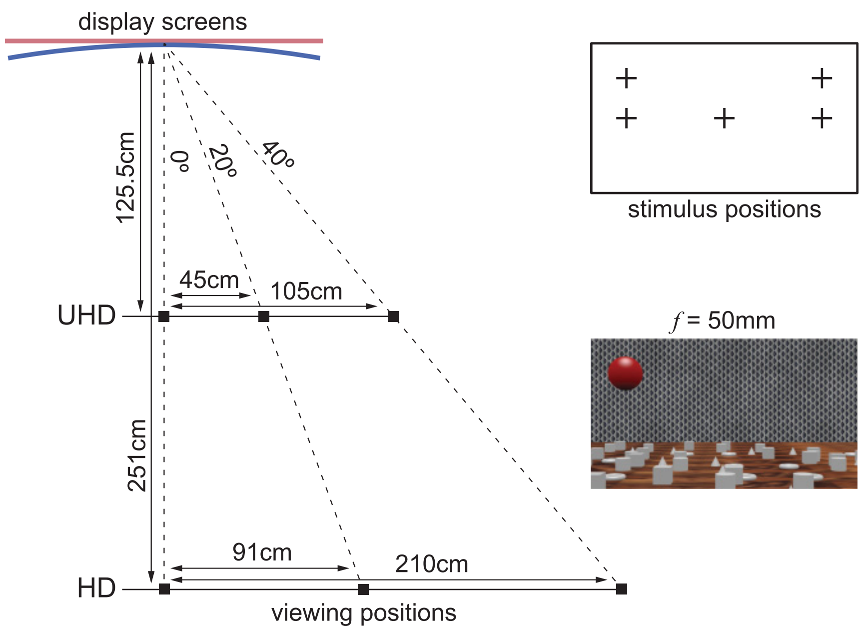

Fig. 10. Experimental design. Left: Plan view of the curved and flat screens and the viewing positions. The viewer was positioned at one of three positions along one of the two horizontal lines in the figure. One line represents the recommended distance for UHD and the other the recommendation for HD. Viewing angle (0°, 20°, or 40°) is the angle between a line from the viewer to screen center and a surface normal at screen center. Right: Stimuli were presented at one of five positions on the screens as indicated by the upper right panel. The lower panel shows one of the stimuli. In this case, the target object is in the upper left.

5.3 Stimuli

The stimuli were realistic, computer-generated scenes created with Blender [3]. They consisted of a textured floor and background, one red ovoid, and several small gray objects scattered on the floor. An example is provided in Figure 10. The scene was illuminated by a simulated distant point light source and ambient light. Images had a resolution of 1920×1080 pixels with a focal length of 50mm. The images were magnified for display on the 65-inch screens. The CoP was orthogonal to screen center at a distance of 205cm. The stimuli were rendered with a planar projection surface in all conditions.

To simulate different curvatures of the projection surface, we manipulated the aspect ratio of the ovoid presented on the screen. We did this rather than changing the projection to the entire screen because we know that the perceptual mechanism that underlies compensation operates locally (i.e., it is unaffected by imagery on other parts of the displayed image [21]). The spatial distribution of pixels was the same for flat and curved screens, so the aspect ratio (measured on the screen) of a rendered object was identical whether displayed on the flat or curved screen. For each of the five screen positions, we varied the aspect ratio of the simulated ovoid $\frac{A}{B}$. The ratios (measured on the screen) ranged from 0.90 to 1.25. Larger values represent more elongation in the tilt direction.

5.4 Procedure

Before each stimulus presentation, the location of the upcoming ovoid was indicated by a white cross. Stimulus presentations were initiated by a key press. Each lasted 1 second and was followed by a black screen. Subjects then indicated whether the ovoid had appeared to be wider than its height or taller than its width. They did this by using two pairs of keys: one pair made coarse adjustments (steps of 0.04) and the other made fine adjustments (0.01). The key press was recorded and the next stimulus was determined according to the subject's response. This is a 1-down/1-up staircase procedure. For each experimental condition, subjects made 10 responses for each stimulus screen position for a total of 50. The average of the subject's last two responses was our estimate of the aspect ratio that appeared spherical for that condition. If the measured aspect ratio was 1, the subject perceived a circle on the screen as spherical. If it was greater than 1, the subject saw an ellipse elongated in the tilt direction as spherical.

From trial to trial, the overall size of the ovoid was randomized to force subjects to use the perceived shape, not just perceived width or height. Subjects viewed the images binocularly. They were not told where to look, but they usually fixated the ovoid. None had difficulty doing the task, and all produced repeatable settings. Each combination of screen curvature, viewing distance, and viewing slant was tested in a separate block.

5.5 Predicted Results

There are two simple predictions for the on-screen shape that is perceived as spherical. First, perceived shape may be the same as the shape of the retinal image. Thus, a circle on the retina will look like a sphere. We call this the *retinal prediction*. Such behavior would be a failure of shape constancy [22]. Second, perceived shape may be the same as shape on the screen. We call this the *invariance prediction* because it means that subjects will perceive the same shape from different viewing angles. Such behavior would be complete shape constancy. Vishwanath et al. [21] showed that the invariance prediction is a good description of experimental data when the stimulus is viewed binocularly, the frame of the display is visible, and the viewing slant $|S_{local}|$ is less than approximately 30°.

5.6 Results

The data were quite consistent across the five subjects for all experimental conditions, so we present averaged data. From left to right in Figure 11, the panels plot the data for different viewing angles. From top to bottom, they plot the data for different viewing distances. Each panel shows the aspect ratio of the stimulus on the screen that was perceived as a sphere as a function of stimulus position: blue symbols for the curved screen and red for the flat screen. The aspect ratio that was perceived as spherical was often greater than 1 (i.e., ellipses elongated in the tilt direction were perceived as spherical). The retinal-prediction curve represents the aspect ratios that would be perceived as circular if perceived shape were dictated by only the shape of the image on the retina. By this hypothesis, this ratio is

$$\frac{\hat{A}}{\hat{B}} = \frac{\alpha}{\beta} = \frac{a}{b\cos(S_{local})}, \tag{10}$$

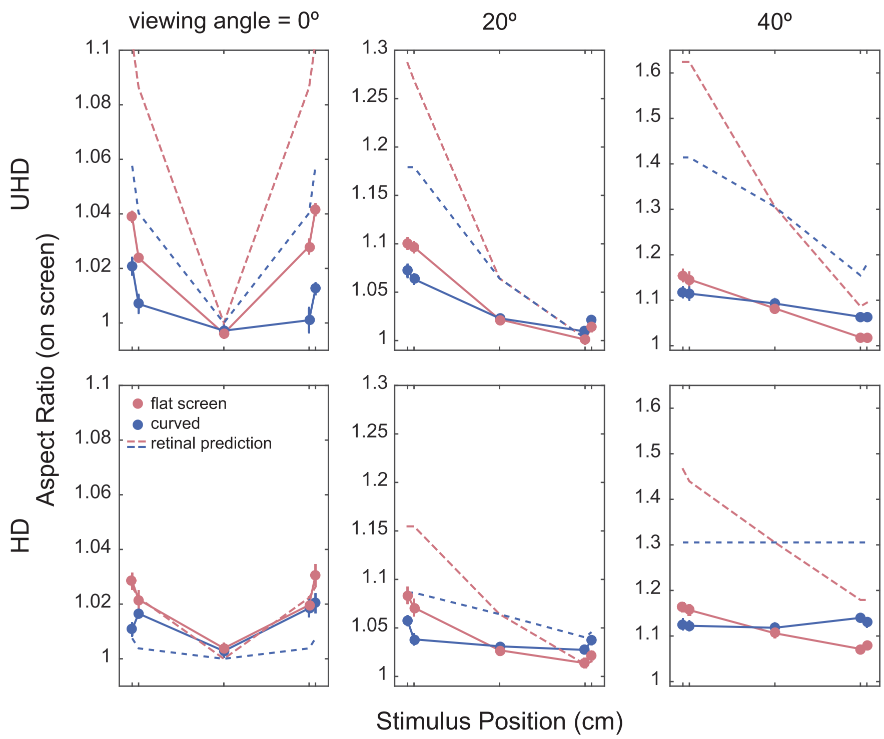

Fig. 11. Results of perceptual distortion experiment. Each panel plots the aspect ratio (on the screen) of the ovoid that was perceived as spherical as a function of horizontal stimulus position. The left, middle, and right columns show the data for viewing angles of 0°, 20°, and 40°, respectively. Top and bottom rows show the data for viewing distances of 125.5 and 251cm, respectively. Red and blue symbols represent the data for flat and curved screens. The data were normalized for each subject to take into account the vertical-horizontal bias. The normalized data were then averaged across the five subjects. The red and blue dashed curves represent the retinal predictions, the former for flat screens and the latter for curved (Equation (10)). These predictions would hold if a circular retinal image were perceived as circular. The dotted horizontal lines through an aspect ratio of 1 represent the invariance predictions.

where a and b are the lengths of the major and minor axes of the elliptical image on the screen and S_{local} is the local slant of the screen surface at that point. The invariance predictions (horizontal lines through 1) represent the aspect ratios that would be perceived as circular if perceived shape were dictated only by the shape of the image on the screen. By this hypothesis, the ratio is

$$\frac{\hat{A}}{\hat{B}} = \frac{a}{b}. \tag{11}$$

When the viewing angle was 0°, subjects at the UHD-recommended distance accepted aspect ratios closer to 1 when the stimuli were presented on the curved as opposed to the flat screen. This means that a centered viewer at a short distance perceives less distortion when the screen is curved.

When the viewing angle was larger, the data were quite dependent on the position of the stimulus on the screen. When stimulus position was on the side of the screen farther from the viewer, perceived distortions were greater for the flat screen than for the curved screen. But when stimulus position was on the near part of the

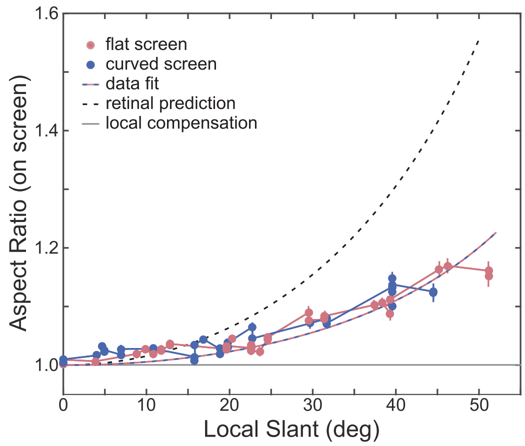

Fig. 12. Aspect ratios and local slant. Data replotted from Figure 11. The aspect ratio of an ellipse on the screen that was perceived as circular is plotted as a function of $|S_{local}|$. Red and blue symbols represent data from flat and curved screens, respectively. Error bars are standard errors of the mean. The black dashed curve represents the retinal predictions. The horizontal solid line represents the invariance predictions. The curve running through the data points is the best fit to the data (Equation (12)).

screen, perceived distortions were greater for the curved than for the flat screen. The accepted aspect ratios generally fell in between the invariance and retinal predictions.

In summary, curving the screen reduces distortions of perceived shape provided that the viewer is centered. When the viewer is off to the side, the magnitude of distortion depends on stimulus position.

From previous work [21], we expect that the magnitude of perceived distortion will depend on S_{local}, the slant of the screen surface at the point of interest. We evaluated this expectation by replotting the data from Figure 11 in terms of the viewing slant $|S_{local}|$. Figure 12 shows the aspect ratio that is perceived as spherical as a function of $|S_{local}|$ for all of the experimental conditions (i.e., flat and curved screens, two viewing distances, three viewing angles, and five stimulus positions). When plotted this way, there is no difference between the perceived aspect ratios for the flat and curved screens. This is clear evidence that viewing slant is the critical factor in determining when perceptual compensation does and does not occur. For slants less than approximately 30°, the measured aspect ratios are close to 1, indicating that complete compensation for viewing angle occurs. For slants greater than approximately 30°, the measured ratios increase with increasing slant, indicating that only partial compensation occurs.

We fit the data in Figure 12 with the following:

$$AR_{screen} = \omega_{comp} + \frac{1 - \omega_{comp}}{\cos(S_{local})}, \tag{12}$$

where $\omega_{comp} = 0.64$ provided the best fit. From this equation, one can predict the perceptual distortions that will occur for any stimulus position, viewing position, and screen curvature. Accordingly, Figure 13 plots the perceived aspect ratio for all stimulus positions on the screen, for flat and curved screens viewed from the six tested positions. A curved screen produces less distortion than a flat screen when viewed along the orthogonal axis of the screen at the UHD-recommended distance. At larger viewing angles, there is less perceptual distortion for the curved screen than for the flat screen except close to the near edge of the screen. Thus, the screen area for which distortion remains low is generally wider for curved than for flat screens. The thick contours in Figure 13 represent an aspect ratio of 1.05, the smallest deviation from 1 that is thought to be readily seen as noncircular

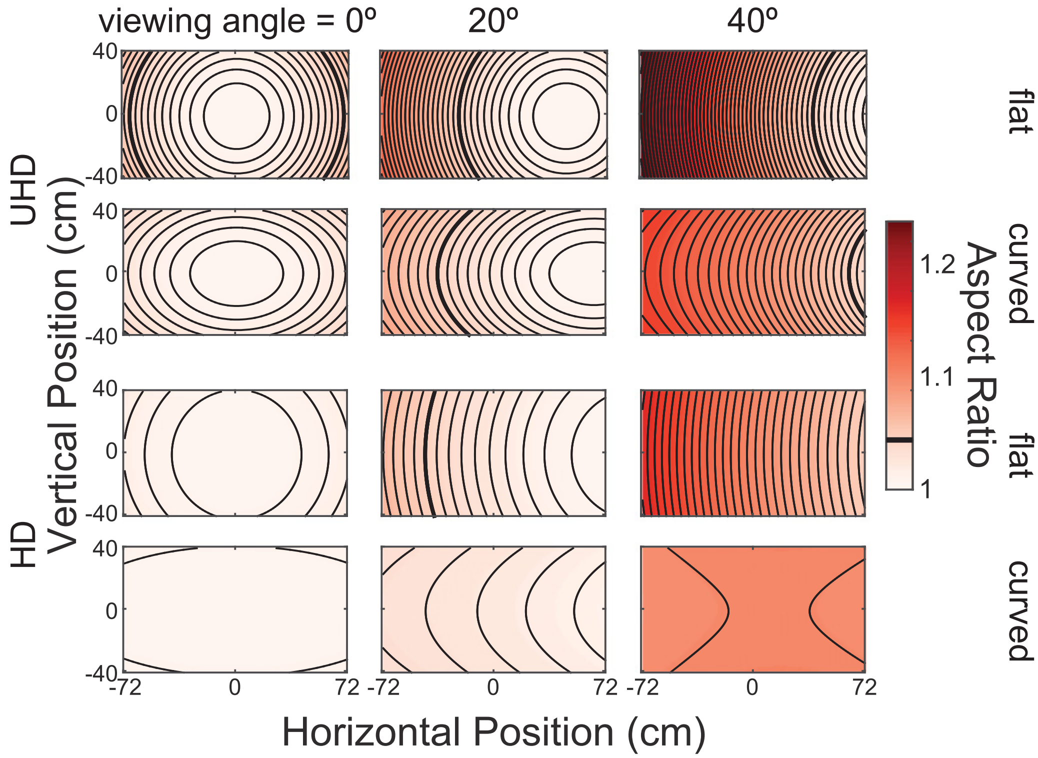

Fig. 13. Aspect ratios on the screen perceived as circular. The upper two rows show data when viewing distance was 1.55 times screen height (recommended distance for UHD). The lower two rows show data for 3.1 times screen height (HD). The first and third rows show data for flat screens and the second and fourth data for curved screens. The left, middle, and right columns show data when the viewing angle was respectively 0°, 20°, and 40°. Each panel plots the data as a function of horizontal and vertical position on the screen where (0,0) is screen center. The color bar on the right indicates the aspect ratios that must be rendered on the screen for the viewer to perceive a circle. The contours in each panel are iso-aspect-ratio contours. The thicker ones correspond to a ratio of 1.05.

[17]. From Equation (12), the aspect ratio becomes greater than 1.05 when the slant exceeds 28.6°, which is quite close to the value of 30° reported by Vishwanath et al. [21].

It is very useful to consider what these findings mean in terms of where viewers can sit and perceive distortion-free imagery, and on what parts of the screen the imagery will appear distortion free. We refer to the distortion-free viewing as the *sweet zone.* Figure 14 plots these sweet zones for curved and flat screens. The zone is somewhat larger for curved screens, indicating a benefit for curving the surface.

Although our data and calculations were based on the perceived shape of ellipses, they should generalize well to other shapes such as squares, faces, and other familiar objects.

6 DISCUSSION

6.1 Effect of Focal Length

The images in Figure 9 are the correct projected images to depict spheres provided that the viewer sits at the correct distance for each focal length (shorter distance for shorter focal length). To the degree that viewers compensate for the slant of the screen surface, they will perceive the shape on the surface and not the shape on

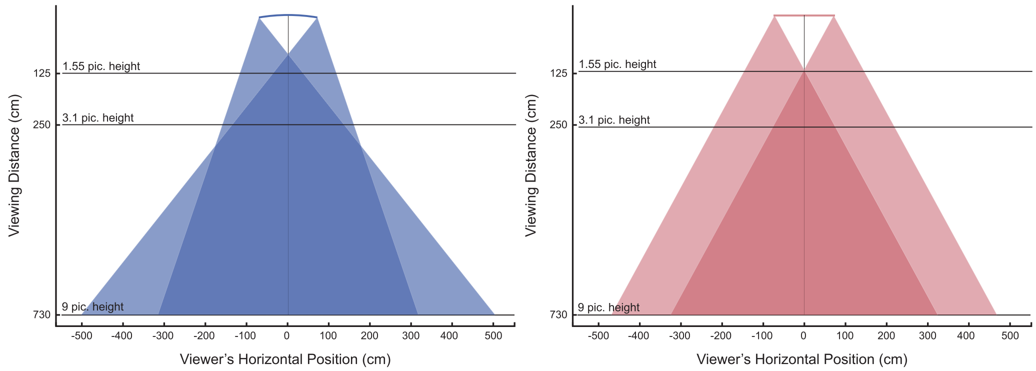

Fig. 14. Sweet zones for curved and flat screens (left and right, respectively). The curved screen's radius is 418cm. The horizontal and in-depth positions of the viewer relative to the screen are represented by the abscissas and ordinates, respectively. The lightly shaded triangles represent the areas in which a viewer can be positioned while looking at the left or right edge of the screen and the slant will be less than 28.6° at that edge. The dark shaded regions represent the areas in which the viewer can be positioned and the slant will be less than 28.6° across the entire screen.

the retina. This is problematic for short focal lengths because it means that they will tend to perceive an ovoid instead of the intended sphere. One could argue, therefore, that content should be always be created with long focal-length cameras because that generates an image whose aspect ratio is similar to that of the original object. Unfortunately, increasing focal length produces another undesirable perceptual distortion: *depth compression* [6, 14]. Imagery created with long focal lengths looks compressed along the depth axis: a distortion in the perceived 3D layout of the scene. Photographers know this and typically recommend a lens focal length of 50 to 60 mm (35mm format) to avoid the compression effect (see Figure 5 in London et al. [14]).

6.2 Curvature of the Projection Surface

A key advantage of curving the screen is that it reduces the slant of the picture surface near the edges of the screen. And this allows the viewer to better compensate for his or her oblique viewpoint. To fully realize this advantage, the projection of images onto the screen should take into account the compensation that the viewer is likely to do. One can use Equation (12) as a guide. One could accomplish this by curving the projection plane used to create the images to match screen curvature. But this is impractical because television broadcasts are intended for wide distribution and most screens are flat, which means that content will presumably continue to be based on planar projection. There is, however, another way to achieve the same result. One could vary pixel size on curved screens depending on the horizontal eccentricity of the pixel: narrower pixels at greater eccentricities. This along with appropriate choice of focal length in the projection could greatly minimize the wide-angle distortions depicted in Figure 9.

The calculations and behavioral data presented in this article should be extendable to smaller consumer screens, such as smartphones and tablets. However, viewing habits for such handheld devices are typically more constrained (viewed straight ahead from arms length) and therefore less prone to perceptual distortions caused by eccentric viewing. Our calculations and data should also be extendable to head-mounted displays used for virtual and augmented reality.

7 CONCLUSION

We showed that curved television screens have some perceptual benefits relative to flat screens. They increase the field of view slightly, possibly leading to greater immersion. Curved screens significantly reduce the likelihood of seeing reflections off the screen from environmental light sources, but reflections that are seen are generally larger than those from flat screens. Curved screens also reduce perceptual distortions of shape that can occur with large screens and incorrect viewing positions, but the reduction depends on the location of the object on the television screen.

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