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Seeing big things: Overestimation of heights is greater for real objects than for objects in pictures

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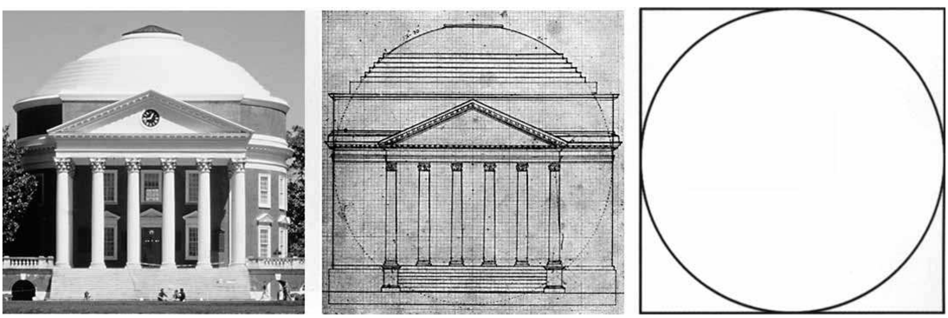
Abstract. In six experiments we demonstrate that the vertical – horizontal illusion that is evoked when viewing photographs and line drawings is relatively small, whereas the magnitude of this illusion when large objects are viewed is at least twice as great. Furthermore, we show that the illusion is due more to vertical overestimation than horizontal underestimation. The lack of a difference in vertical overestimation between pictures and line drawings suggests that vertical overestimation in pictures depends solely on the *perceived physical size* of the projection on the picture surface, rather than on what is apparent about an object's represented size. The vertical – horizontal illusion is influenced by perceived physical size. It is greater when viewing large objects than small pictures of these same objects, even when visual angles are equated.

1 Introduction

Thomas Jefferson's elevation drawing of the Rotunda at the University of Virginia illustrates how the vertical – horizontal proportions of this building are based on a circle embedded within a square (see figure 1). An attentive visitor to the real building notices, however, that the building appears elongated vertically when compared to the illustration showing how the building's horizontal and vertical dimensions are physically equal. The real building also looks elongated vertically when compared to a photograph of the building.

These observations illustrate the two perceptual phenomena documented in this paper. First, the observation that the height of the Rotunda looks greater than its width illustrates what has been called the vertical – horizontal illusion. In the traditional demonstrations of the illusion, the vertical extent of lines or geometric figures on paper appear slightly longer than horizontal extents of the same physical length. Second, the difference in perceived proportions between the real Rotunda and a photograph or a line



(a) (b) (c)

Figure 1. The importance of proportions in large-scale form. The Rotunda at the University of Virginia (a) and an original drawing by Jefferson (b) illustrate how the elevation of the building is based on a circle embedded within a square (c). [See http://www.perceptionweb.com/perc0499/yang.html for color versions of the photographs in this article as well as some additional color images.]

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drawing of the building illustrates that vertical overestimation is greater with large, real objects, such as buildings, than with small photographs and line drawings.

A critical difference between viewing real objects and depictions of them is that pictures evoke a *dual awareness* (Gibson 1971; Pirenne 1970). When viewing a picture of a scene, (i) people are aware that it is a two-dimensional treated surface, while at the same time (ii) they are aware of the three-dimensional scene that is being depicted. This duality is not present, of course, when viewing the scene itself. One aspect of the dual awareness evoked by pictures is that there exists a dissociation between perceived physical and perceived representational size. *Perceived physical size* refers to how large something appears to be, without taking into account that it is a depiction of something having a different size. For example, a picture of an elephant may be only five inches high. Five inches would be its perceived physical size. *Perceived representational size* refers to how large something appears to be in the real three-dimensional scene and, of course, in this regard the elephant is perceived to be huge.

When viewing a scene in the environment, perceived physical size corresponds to whatever size an object appears to be. Available size information is used, such as the horizon ratio. Thus, in the case of looking at a real elephant, perceived physical size might be around two eye heights tall. There is no representational size because the elephant is not a projection on a surface, and therefore, is not a representation.

With respect to the *vertical – horizontal illusion*, we propose that the magnitude of vertical overestimation increases with the perceived physical size, not the perceived representational size, of objects. This explains why large objects viewed in the world appear vertically elongated relative to how they appear in pictures. This proposal is supported by six experiments reported herein. Before describing these studies, we briefly review the relevant literature on this illusion. Most studies have employed pictorial materials; however, there have been a few studies conducted out of doors with real objects.

1.1 *The vertical – horizontal illusion in pictures*

Vertical overestimation in the traditional vertical – horizontal illusion is highly reliable, but quite small in magnitude. Traditionally, the illusion has been studied with small lines and figures drawn on paper. The two main variations of this illusion use the 'L' figure and the upside-down 'T'. In the 'L' figure, which demonstrates the pure effect of the illusion, a vertical line generally looks about 2% to 6% longer than a horizontal line of the same physical extent (eg Avery and Day 1969; Begelman and Steinfeld 1967; Finger and Spelt 1947; Schiffman and Thompson 1975; Thompson and Schiffman 1974; Von Collani 1985b). The upside-down 'T' figure yields a greater vertical overestimation, about 9% (Finger and Spelt 1947; Künnapas 1955), but some researchers have argued that the enhanced vertical overestimation results from the bisection of the horizontal line which makes it appear shorter. The effect of bisection is greater than the pure vertical – horizontal illusion: when one rotates the upside-down 'T' figure 90°, the bisected line, now vertical, still appears shorter (Coren and Girgus 1978; Finger and Spelt 1947).

Although the vertical – horizontal illusion has been thoroughly investigated with an 'L' figure presented in simple line drawings on paper, the magnitude of the illusion in line drawings has not been systematically compared with pictures of real scenes. We made this comparison in our experiments and found no difference in vertical overestimation between photographs and line drawings.

1.2 *Vertical overestimation in large, real objects*

In contrast to the size of vertical – horizontal illusion observed in line drawings, the few studies conducted out of doors have found greater vertical overestimations. Most notably, Chapanis and Mankin (1967) had observers match a frontal (as opposed to oriented in depth) horizontal distance to the heights of objects of varying size. The viewing distances were set so that the visual angle subtended by all target objects was approximately 22 deg.

Vertical overestimation was greater for the five largest objects than for the five smallest objects and as great as 24% for one of the largest objects (a 17.7 m building). Although viewing distance was necessarily increased with object size to keep angular subtense constant, this study suggests that the magnitude of the illusion might increase with the physical size of the object.

Higashiyama (1996) also found a substantial overestimation of vertical extents compared to horizontal extents. Observers adjusted their distance from a building to produce extents in depth to match both vertical and frontal-horizontal target extents. As reflected in the in-depth extents produced by observers, vertical extents were overestimated by 57%, while frontal-horizontal extents were overestimated by 14%. From the functions relating vertical and frontal-horizontal extents, we can compute that vertical extents looked about 38% greater than frontal-horizontal extents.

The relative overestimation of the vertical in the Higashiyama (1996) study is considerably greater than in the Chapanis and Mankin (1967) study. This greater overestimation may have resulted from at least two aspects of the study. First, the visual angles subtended by the target extents changed when observers moved towards or away from the target to produce their estimate. Furthermore, the segmentation of the vertical dimension of the building by rows of windows could have caused vertical extents to appear even longer; whereas a single bisection of a line makes it appear shorter, segmentation into several parts makes it seem longer. This effect is referred to as the Oppel – Kundt Illusion (Coren and Girgus 1978).

In an experiment by Higashiyama and Ueyama (1988), observers stood at the base of a building and regarded five target marks on the building facade: 3.0, 6.8, 10.6, 14.4, 18.7 m from the ground. Observers matched these heights to distances on the ground by telling an experimenter to move out from the base of the building so that the extent between the experimenter and the base of the building equaled the height of the target mark. Observers overestimated vertical extents by about 16%.

In another condition, observers moved away from the building to make their distance to the building equal to the height of the targets. In this condition, observers overestimated heights by 67% relative to in-depth extents on the ground. In these studies by Higashiyama (1996) and Higashiyama and Ueyama (1988), the substantially greater overestimation that results from comparing heights to in-depth rather than frontal-horizontal extents is consistent with previous research which has documented that people underestimate extents in-depth relative to frontal extents (eg Toye 1986; Wagner 1985).

The two categories of studies we have reviewed suggest that vertical overestimation may be greater with large, real objects than what has typically been found with small figures on paper. We report six experiments to directly compare the relative perception of horizontal and vertical extents in real environments and pictorial displays. In all but experiment 4, observers indicated this perception by producing a frontal-horizontal extent that appeared equal to the height of a target object. In experiment 1, we replicated the finding of greater overestimation with real objects in naturalistic settings. In experiment 2, we experimentally manipulate object height to show that vertical overestimation increases with object height and that vertical overestimation is greater with real objects than with pictures or line drawings matched for visual angle. In experiment 3, we demonstrate that the reduced overestimation in pictures is not due to the cropping and framing of the visual scene by the edges of the picture. In experiment 4, verbal estimates of horizontal and vertical extents provide a converging measure of vertical overestimation. In experiment 5, we demonstrate that an immersive, virtual-reality head-mounted display system evokes the same greater vertical overestimation as found outdoors. In experiment 6, we show conclusively that the magnitude of vertical overestimation is influenced by whether the scene is perceived as being a full-scale environment or a small projection.

2 Experiment 1: Exploratory study demonstrating enhanced vertical overestimation with real objects in naturalistic environments

In this exploratory study, we replicated previous findings that suggest that the magnitude of vertical overestimation with large, real objects is greater than has been found in the traditional vertical–horizontal illusion on paper.

2.1 *Method*

2.1.1 *Participants.* Two hundred and thirty undergraduate and graduate students from the University of Virginia participated as volunteers. All had normal or corrected-to-normal vision.

2.1.2 *Design.* A 4 (Target Object) × 11 (Viewing Distance category) between-subjects design was used.

2.2 *Stimuli and apparatus*

Observers viewed four target objects around the grounds of the University of Virginia: a door on the outside of the chemistry building (2.18 m tall), a light pole (4.50 m tall), an edge on the chemistry building (13.6 m tall), and an edge on the psychology building (13.6 m tall). We chose these objects for their varying heights and because the objects were located in flat open areas, with enough space to vary the viewing distance of the observer and with enough lateral space for an experimenter, holding a marker pole (a white PVC pole, 1.5 m tall, 2.2 cm diameter), to walk out laterally to produce a horizontal extent as instructed by the observer.

We did not use the same set of viewing distances for each object. For each object, we chose specific viewing distances for the observers' convenience and to avoid physical barriers. For the door, these distances were as follows: 0.91, 2.39, 3.87, 5.35, 6.82, 8.29, 9.79, 14.2, 15.7, 17.1, 18.6, 20.1, and 21.6 m. For the light pole, the viewing distances were: 0.19, 2.46, 4.83, 7.16, 9.50, 11.8, 14.2, 16.5, 18.8, and 21.8 m. For the edge of the psychology building, the viewing distances were: 0.23, 1.70, 3.17, 4.65, 6.13, 7.61, 9.08, 10.5, 12.0, and 13.5 m. For the edge of the chemistry building, the viewing distances were: 0.38, 1.85, 3.34, 4.81, 6.29, 7.76, 9.26, 10.7, 12.2, 13.6, 15.1, 16.6, 18.1, 19.5, and 21.0 m.

2.3 *Procedure*

Each observer looked at one target object from one of the distances listed above and produced a frontal extent on the ground to match the height of the target. They regarded the scene with both eyes.

To ensure that target heights and frontal extents on the ground were not differentially foreshortened, we positioned each observer so that the lateral position of each observer's viewpoint was displaced one observer eye height away from the edge of the target object, in the direction of the experimenter's walk (see figure 2). We used this method of lateral positioning for all of the outdoors studies and for the virtual-reality study (experiment 5).

An experimenter, holding a marker pole upright, walked out from the object laterally. The observer produced a frontal distance on the ground to match the height of the target object by instructing the experimenter to stop walking when the distance on the ground between the target object and the marker pole appeared equal to the height of the target. Observers could adjust their initial estimate by instructing the experimenter to move out from or in towards the target object. Observers were given as much time as needed to make their estimates.

All of the experiments except the verbal-estimates study (experiment 4) followed this basic procedure. The marker pole always started next to the target object and was moved outwards. In earlier pilot experiments, we had tried having observers make their judgments by moving the marker pole in from a distant point, but this manipulation did not produce appreciably different results. Thus, for all the experiments we report, observers moved the marker pole outward from the target object.

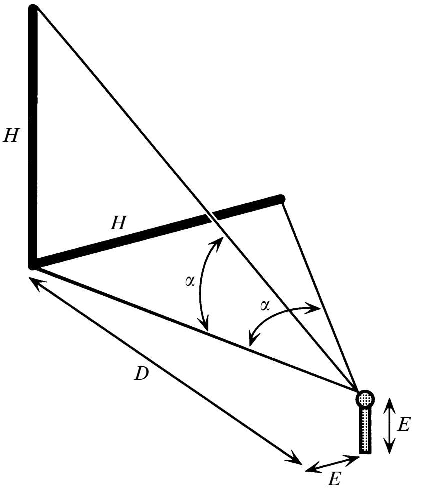

Figure 2. Diagram illustrating where observers stood relative to the target object in the outdoors conditions (outdoors, frame, verbal estimates) and in the virtual-reality condition. At any given viewing distance in depth, *D*, positioning the observer one eye height, *E*, laterally to the side of a vertical target object of a given height, *H*, ensures that this extent and a frontal extent on the ground of the same physical length, *H*, both subtend the same visual angle α.

2.4 *Results and discussion*

The larger the object, the more observers overestimated its height relative to horizontal extents (see figure 3). Viewing distance did not systematically affect estimates. As an index of the relative perception of vertical and horizontal extents, we calculated proportional overestimation of vertical, which is equal to produced horizontal length divided by actual height of target. If observers overestimate vertical extents relative to horizontal ones, they should produce a physically longer horizontal distance to match the height of the target object. A proportional overestimation greater than 1.0 would indicate a relative overestimation of vertical extents. A proportional overestimation of 1.0 would indicate that physically equal horizontal and vertical extents are perceived as equal. A value of less than 1.0 would indicate that observers underestimate vertical extents relative to horizontal extents. This index was our primary dependent measure for all the experiments.

We analyzed proportional overestimation as a function of the physical height of the objects and viewing distance. Because the viewing distances did not match up exactly for the four objects, we compared the effect of viewing distance in an ANOVA by grouping viewing distances into a set of 11 ordered categories of 2 m increments.

The mean proportional overestimation of height for the four objects was as follows: door, 0.99; light pole, 1.06; chemistry building, 1.13; psychology building, 1.18. A multiple linear regression with the physical height of the target objects and viewing distance

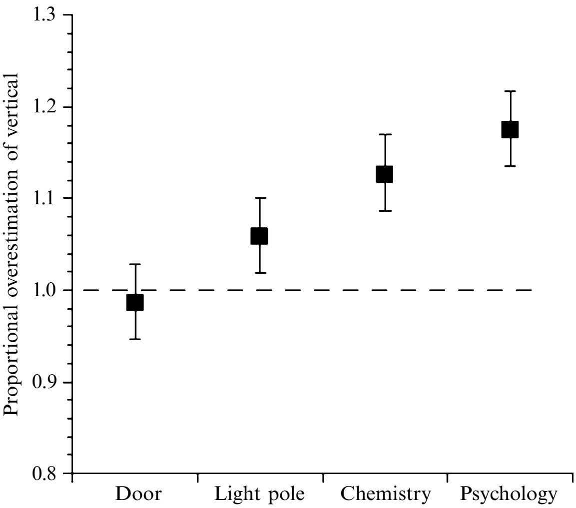

Figure 3. Data from experiment 1. Proportional overestimation of vertical (produced horizontal extent divided by actual height) increases with the physical size of the objects.

categories as fixed continuous predictors and gender as a fixed discrete predictor showed that proportional overestimation of height increased reliably with the physical size of the target ($F_{1,226} = 7.51$, $p = 0.007$), but did not systematically increase or decrease with viewing distance ($F_{1,226} = 0.91$, $p = 0.340$).

The objects that we selected for this study also varied in other factors such as mass, segmentation, and surrounding context, which may have influenced the results. For instance, vertical overestimation of the psychology building is a bit greater than that of the chemistry building, perhaps because the psychology building has more decorative elements that segment the form of the building. In experiment 2, we examine the relative perception of heights and frontal distances on the ground more systematically by experimentally manipulating object height.

3 Experiment 2: Comparing the vertical – horizontal illusion outdoors and in pictures

In this study, we demonstrate that (i) vertical overestimation is greater when viewing real objects outdoors than when viewing photographs or line drawings of the objects, and that (ii) the magnitude of this overestimation increases with the physical size of both real and pictured objects. One group of observers viewed ten poles of varying heights in a field (outdoors condition). Another group viewed photographs of the ten poles presented on a computer monitor (pictures condition). A third group viewed vertical lines on a computer monitor (lines condition). We refer to the latter two conditions as desktop-display conditions.

3.1 *Method*

3.1.1 *Participants.* Seventy-two undergraduate and graduate students at the University of Virginia participated in this study either for course credit, payment, or in exchange for candy or soda. All observers had normal or corrected-to-normal vision. There were twenty-four observers in each of the three conditions. None had participated in experiment 1.

3.1.2 *Design.* A 3 (Viewing Condition) × 10 (Pole Length) design was used, where Viewing Condition (outdoors, pictures, lines) was a between-subjects variable and Pole Length was a within-subjects variable.

3.2 *Stimuli and apparatus*

3.2.1 *Outdoors condition.* The target poles were ten white PVC poles, 4.8 cm in diameter, with the following heights: 0.61, 1.22, 1.83, 2.44, 3.04, 3.54, 4.15, 4.76, 5.37, and 5.97 m. We constructed each of the five tallest poles by mounting one of the five smallest poles to a 2.93 m long extension pole. The extension pole had a 10 cm long metal shaft upon which each of the five smallest poles could be attached. The metal shaft fit inside the hollow of both poles and was not visible. The seam between the two poles was not noticeable from a distance. Another PVC pole (1.50 m long, 2.2 cm in diameter) served as a marker pole. A tripod with a square wooden platform (33 cm × 33 cm) attached at the top served as a chin-rest, which stabilized the observer's viewing position.

3.2.2 *Desktop-display conditions.* For the pictures condition, we took pictures of the scene from the position of an observer in the outdoors condition and presented these pictures to observers on a computer with the drawing program Canvas 3.54. Using a Nikon 6006 SLR camera with a 35 – 70 mm zoom lens set at 35 mm,[(1)] we created ten

[(1)] The zoom lens was set at 35 mm for a number of reasons. First, we photographed the scene from the vantage point of the observer in the outdoors condition, and having the zoom lens set at 35 mm allowed us to just fit the largest pole into the image and thus have maximal discriminability in length between the different poles. Second, this enframement of the scene also provided ample room for observers to produce a horizontal extent for the task. Third, taking the pictures with the 35 mm lens created pictures which, when presented on the monitor for the pictures condition, had a center of projection (appropriate viewing distance) which was not too close to the screen to be uncomfortable.

photographic slides of one of the authors as the experimenter holding each of the ten poles (see figure 4). The camera was mounted on a tripod set at the eye height of one of the other authors (1.58 m) and positioned 13.65 m in depth and 1.58 m to the right of the target poles. The scene was framed with the experimenter and target pole to the left of the image so observers would have plenty of lateral space to the right to produce a horizontal extent during the task.

Figure 4. Photograph of the scene used in the outdoors condition of experiment 2 with an experimenter holding the tallest pole.

Using a Nikon Cool-Scan slide scanner, we scanned these slides into digital images at 72 pixels inch^{-1}, and presented these images to observers on a Macintosh computer with a Sony Trinitron Multi-scan HG 17 inch monitor. As measured on the monitor screen, each picture was 20.3 cm tall $\times$ 31.2 cm wide. The length of the poles, as measured on the monitor screen were: 1.31, 2.60, 3.92, 5.29, 6.63, 7.69, 9.07, 10.37, 11.75, and 12.77 cm. When viewed from the center of projection, at 30.6 cm from the monitor screen, the angular subtense of each of the pictured poles matched the angular subtense of the corresponding real poles in the outdoors condition.

A white vertical marker line (3.4 cm tall) was superimposed onto the digitized pictures by means of the drawing program. The marker line served the same function as the marker pole in the outdoors condition. It was drawn with its base at the same height in the picture plane as the target poles, to simulate the marker pole at the distance in depth that was used in the outdoors condition. The marker line subtended the same visual angle as the marker pole in the outdoors condition.

For the lines condition, observers viewed white vertical lines on a uniform black background. We created these images by using Canvas to trace a white vertical line over the poles in the digital images used in the pictures condition. We replaced the rest of the image with a black background. Measured on the screen, these lines were the same lengths as the pole images used in the pictures condition.

In both conditions, a tripod with the square wooden platform served as a chin-rest to fix the observer's viewing position.

3.3 *Procedure*

3.3.1 *Outdoors condition.* As with experiment 1, observers produced a frontal extent on the ground to match the height of this target object. The outdoors condition was conducted in a large, flat, grassy field on the grounds of the University of Virginia. Observers stood on a marker and, for each trial, viewed a target pole held upright by an experimenter (see figure 4) at 13.65 m in depth. Relative to the target pole, the observer's viewpoint was displaced to the right by one observer eye height (see figure 2) to ensure that physically equal heights and frontal extents on the ground would subtend the same visual angle from the observer's viewpoint. To stabilize the observer's viewing position, the observer rested his or her chin on a square wooden platform, which was mounted on a tripod and raised to the chin height of the standing observer.

A second experimenter, holding the marker pole, walked out laterally to the right from the target pole at the steady pace of a slow walk. Using hand signals, the observer instructed the second experimenter to stop when the distance on the ground between the target pole and the marker pole appeared equal to the height of the target pole. The observers took as much time as needed to make their decisions and could change their initial response by signaling to the second experimenter with their hands. Observers gave right and left signals by moving their thumbs right and left, respectively. The observers gave a pause signal by showing a flat open hand. When the observers were satisfied with their responses, they gave a 'thumbs up' signal to the experimenter.

After each pole judgment, the observers turned to face the opposite direction while the experimenters measured the produced distance and prepared the next pole. These steps were carried out for each of the ten poles. The presentation order of the ten poles was randomized. Each session lasted approximately 30 min.

3.3.2 *Desktop-display conditions.* Observers in the pictures condition viewed digitized images of the outdoors scene on a computer monitor (see figure 5). At the beginning of each trial, the marker line was positioned just to the right of the pictured target pole. The observer adjusted the horizontal position of the marker line to make the horizontal distance on the screen between the pictured target pole and the marker line to equal the height of the target pole on the computer screen.

Figure 5. Photograph of an observer in the pictures condition of experiment 2 viewing a picture of the outdoors scene (figure 4).

The observer performed this task while resting his or her chin on a chin-rest in front of a computer monitor. Before each trial, an experimenter used a measuring stick to adjust the observer's viewing position (distance) to be as close as possible to the center of projection of the photographs at 30.6 cm from the screen. Because desktop monitor displays are viewed binocularly in normal use, we chose to have our observers view the scene binocularly, with their eyes straddling the center of projection to either side.

After positioning the observer's viewing position, the experimenter placed the observer's fingers on keys on the keyboard which controlled the horizontal position of the marker line. The experimenter placed the observer's left forefinger over the option key and the observer's right forefinger and second finger on the left and right arrow keys, respectively.

Holding down the option key while pressing the left or right arrow keys moved the marker line in increments of about 1.75 cm, while pressing the arrow keys alone moved the marker line in fine increments of about 0.5 mm.

Observers had as much time as needed to make their decisions and could adjust their initial response until they were satisfied. After each judgment, observers turned and faced the opposite direction while the experimenter measured the produced distance using a measurement tool in the drawing program and prepared the next stimulus screen. These steps were repeated for each of the ten pictures. The presentation order of the ten pictures was randomized. Each session lasted approximately 30 min. The lines condition followed the same procedure as the pictures condition, except that white lines on a black background were used in place of digitized photographs.

3.4 *Results and discussion*

Figure 6 illustrates the two main findings: (i) vertical overestimation was greater for the outdoors condition than for the pictures and lines conditions; (ii) vertical overestimation increased with the size of the real or pictorially represented object.

Collapsed across pole length, the mean proportional overestimations for the outdoors, pictures, and lines conditions, were, respectively, 1.12, 1.02, and 1.03. A repeated-measures multiple linear regression, with Pole Length as a continuous predictor and Viewing Condition as a discrete predictor, revealed a reliable difference between the means for Viewing Condition ($F_{2,647} = 7.19$, $p = 0.002$). Bonferroni a posteriori tests showed that outdoors was reliably different from pictures ($t_{46} = 3.46$, $p = 0.003$), and reliably different from lines ($t_{46} = 3.08$, $p = 0.009$); pictures did not differ reliably from lines ($t_{46} = 0.37$, $p = 0.975$).

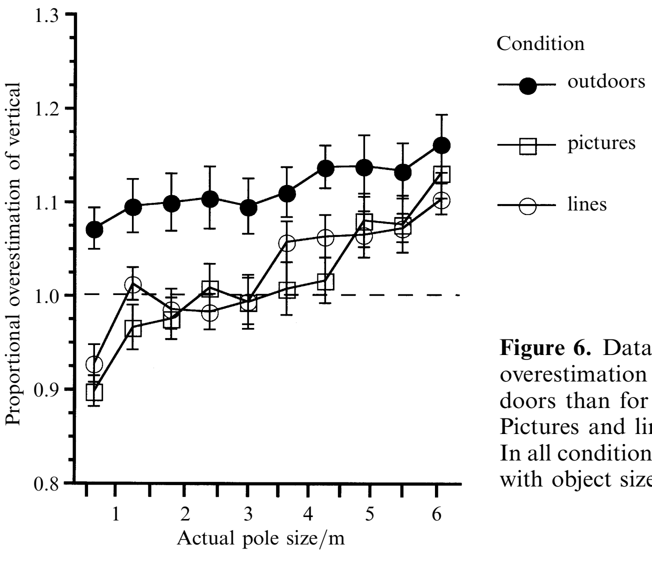

Figure 6. Data from experiment 2. Proportional overestimation of vertical is greater for the outdoors than for the pictures and lines conditions. Pictures and lines data are not reliably different. In all conditions, vertical overestimation increases with object size.

The mean proportional overestimation for individual pole lengths ranged from 1.07 to 1.16 (outdoors), 0.90 to 1.13 (pictures), and 0.93 to 1.10 (lines). For the smallest poles viewed in the pictures and lines conditions, observers actually underestimated the height.

For all conditions, proportional overestimation increased with the height of the real or represented object ($F_{1,647} = 211.21$, $p < 0.0001$). The slopes (proportional overestimation divided by object height in meters) of the linear regression lines were reliably positive: outdoors slope = 0.014 ($t_1 = 2.69$, $p = 0.008$); pictures slope = 0.035 ($t_1 = 7.35$, $p < 0.0001$); lines slope = 0.027 ($t_1 = 7.17$, $p < 0.0001$).

The relation between produced length versus object height is described very well by power functions. The log–log transformations of these data show linear trends with excellent fits: outdoors $R^2 = 97.1\%$; pictures $R^2 = 97.5\%$; lines $R^2 = 98.1\%$. Estimates of the exponents of the power function were slightly greater than 1 for all conditions: outdoors exponent = 1.03; pictures exponent = 1.08; lines exponent = 1.07.

In sum, experiment 2 confirms the finding of experiment 1 that vertical overestimation is greater with relatively large, real objects than with the traditional vertical–horizontal illusion. Vertical overestimation is greater with real objects than for the same objects depicted in pictures, even when people view the pictures from the center of projection so that the pictured object would subtend the same visual angle as the real object would.

Von Collani (1985a) reported results suggesting that the magnitude of vertical overestimation might be greater in photographs than with lines; however, in our study these two conditions were directly compared, with angular subtense and experimental method equated, and no difference was found. We interpret this lack of difference in our study to mean that with photographs the relative perception of horizontal and vertical extents depends on the small perceived physical size of the projected image on the picture surface and not on the large represented size of the objects in the pictorial space. In addition, note that even though the *physical size* of the largest pole viewed on the desktop is much smaller than that of the smallest pole viewed outdoors, the visual angle of the latter is much greater than that of the former. Clearly, visual angle is also an important determinant of the size of the illusion.

4 Experiment 3: Framing the visual field does not decrease overestimation outdoors

In experiment 3, we demonstrate that the reduced vertical overestimation with pictures and lines does not result solely from the cropping or framing of the scene. This experiment was conducted exactly like the outdoors condition of experiment 2, except that observers viewed the scene through a frame (frame condition) which cropped the scene to the same extent as in the pictures condition.

4.1 *Method*

4.1.1 *Participants.* Twenty-four undergraduate students at the University of Virginia participated in this study for course credit or as volunteers. All had normal or corrected-to-normal vision. None had participated in the previous experiments.

4.1.2 *Design.* For the analyses, we combined the frame condition data from this experiment with the data from experiment 2 to create a 4 (Viewing Condition) × 10 (Pole Length) design. Viewing Condition (outdoors, pictures, lines, frame) was a between-subjects variable and Pole Length was a within-subjects variable. There were twenty-four observers in each of the four Viewing Conditions.

4.2 *Stimuli and apparatus*

The stimuli and apparatus were the same as for the outdoors condition of experiment 2 except for the addition of a foam-core viewing box, through which observers viewed the outdoors scene (see figure 6). The viewing box was mounted onto the square chin-rest platform on top of the tripod.

The dimensions of the viewing box were 42 cm (wide) × 32.3 cm (tall) × 30 cm (deep). The side of the viewing box into which observers placed their heads was open. The opposite side had a rectangular aperture, 20.3 cm (tall) × 31.2 cm (wide), the same dimensions as the photographs presented on the monitor in the pictures condition of experiment 2. The open side had an upside-down T-shaped bar against which observers rested their foreheads. This bar helped observers center the lateral position of their heads and fixed their viewing distance at about 30.6 cm to the rectangular cropping aperture. At this distance, the viewing box cropped and framed the outdoors scene to the same extent as the photographs of the scene presented in the pictures condition of experiment 2.

4.3 *Procedure*
The procedure was the same as that of the outdoors condition of experiment 1, except that observers in the frame condition viewed each of the ten poles through the foam-core viewing box (figure 7).

Figure 7. Photograph of an observer in the frame condition of experiment 3. The viewing box cropped the outdoors scene to the same extent as the computer monitor cropped the photographs used in the pictures condition of experiment 2.

4.4 *Results and discussion*
Framing the outdoors scene did not reduce vertical overestimation to the same amount found in the pictures and lines conditions (see figure 8). Collapsed across pole length, the mean proportional overestimation in the frame condition was 1.14 compared to 1.12 for the outdoors condition. We combined the frame condition data with the data from the three conditions of experiment 2 in a repeated-measures multiple linear regression, with Pole Length as a continuous predictor and Viewing Condition as a discrete predictor. This analysis showed that the four conditions differed reliably overall ($F_{3,863} = 8.35$, $p < 0.0001$). Proportional overestimation in the frame condition did not differ from the outdoors condition ($t_{46} = 0.70$, $p = 0.9809$), but was reliably greater than in the pictures condition ($t_{46} = 4.02$, $p = 0.0231$), and reliably greater than in the lines condition ($t_{46} = 3.66$, $p = 0.0025$).

We conclude that the reduced relative overestimation of height in the pictures and lines conditions did not result simply from the cropping or framing of the visual scene. The fact that cropping did not reduce overestimation is consistent with previous research which has shown that surrounding the vertical–horizontal figure with a frame which has a longer horizontal dimension actually increases slightly the relative overestimation of the vertical (Houck et al 1972; Künnapas 1957a, 1957b, 1959; Prinzmetal and Gettleman 1993). We suggest that the magnitude of vertical overestimation was not reduced when observers viewed the outdoors scene through a frame because observers still perceived these objects to be large objects in a real environment rather than small projections on a flat, picture surface.

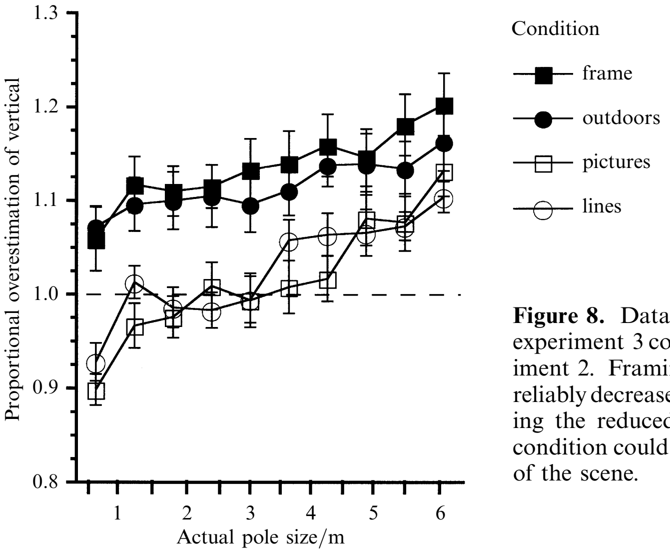

Figure 8. Data from the frame condition of experiment 3 combined with the data from experiment 2. Framing the outdoors scene did not reliably decrease vertical overestimation, suggesting the reduced overestimation in the pictures condition could not be attributed to the cropping of the scene.

5 Experiment 4: Verbal estimates as converging measure of relative height overestimation

The use of multiple, converging measures to study a psychological phenomenon allows one to disentangle the effects of the phenomenon of interest from the specific effects associated with any particular measure (Wagner 1985). In this experiment, verbal estimates of vertical and horizontal poles viewed outdoors confirm that people overestimate heights relative to frontal-horizontal extents and show that our findings from the previous experiments were not simply due to the specific production task that we employed.

5.1 *Method*

5.1.1 *Participants.* Twenty-five undergraduate students at the University of Virginia participated in this study for course credit or as volunteers. All had normal or corrected-to-normal vision. None had participated in the previous experiments.

5.1.2 *Design.* A 2 (Horizontal Poles versus Vertical Poles) × 10 (Pole Length) within-subjects experimental design was used.

5.2 *Procedure*

Observers made verbal estimates of the lengths of poles held upright and lying on the ground. We conducted this study in the same setting as the outdoors condition of experiment 2. The positioning of the observer relative to the poles was the same as in the outdoors study. An experimenter told observers that they would be estimating the lengths of poles either held upright or lying on the ground. The experimenter gave the observer a metal 1 foot ruler to hold and use as a reference, to give them a sense of how long a foot was. The experimenter told the observer to make length judgments either in feet and inches or fractions of a foot or in meters and centimeters. This experimenter also recorded observers' verbal estimates for all of the trials.

A second experimenter presented the poles to the observer. Observers viewed each of the ten poles twice, once horizontally, once vertically, for a total of 20 different stimuli. The order of pole presentation was randomized, with horizontal and vertical poles randomly intermixed. When a pole was presented vertically, the experimenter held the pole as in experiment 2. When a pole was presented horizontally, it was positioned on the ground frontally relative to the observer, with one end of the pole at the experimenter's toes. The experimenter stood next to the horizontal poles to make the scenes with the horizontal poles as comparable as possible to scenes with the vertical poles.

5.3 *Results and discussion*

The verbal estimates also showed that people perceive lengths oriented vertically as substantially longer than the same lengths oriented horizontally. Vertical overestimation in our previous experiments was not due solely to the production measure that we used. Furthermore, this effect held when the same poles were shown both horizontally and vertically to the same observers.

To measure relative vertical overestimation within subjects, we divided each observer's verbal estimate of a pole shown vertically by their estimate of the same pole shown horizontally (see figure 9). Collapsed across pole length, this measure was reliably greater than 1 ($t_{248} = 9.640$, $p < 0.0001$). A repeated-measures linear regression showed that this relative overestimation of the vertical increased reliably with Pole Length ($F_{1,223} = 29.906$, $p < 0.0001$).

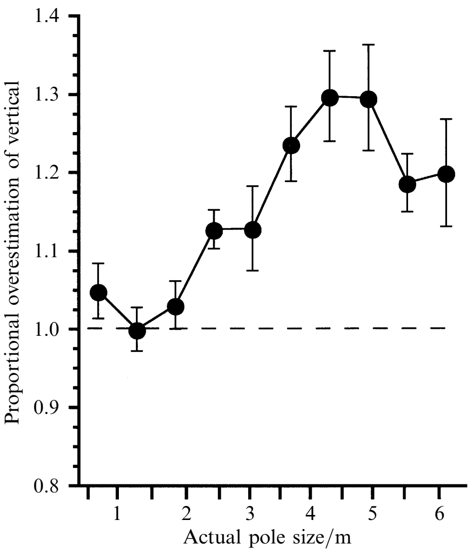

Figure 9. Data from experiment 4. The *y*-axis represents the value of each observer's verbal estimate for a given pole oriented vertically divided by the observer's verbal estimate of the length of the same pole oriented horizontally.

Furthermore, the proportional overestimation (estimate of length divided by actual length) measure revealed that while observers reliably overestimated the length of Vertical Poles (mean = 1.08) ($t_{249} = 5.92$, $p = 0.0001$), they also slightly underestimated the length of Horizontal Poles (mean = 0.96) ($t_{249} = -2.80$, $p = 0.003$). The mean proportions for the Vertical and Horizontal Poles suggest that a vertical overestimation influences the vertical – horizontal illusion twice as much as a horizontal underestimation.

A repeated-measures multiple linear regression, with Horizontal Poles versus Vertical Poles as a fixed discrete factor and Pole Length as a continuous factor, showed a reliable difference between the slopes of the proportional overestimations for Horizontal Poles and Vertical Poles ($F_{1,473} = 58.91$, $p < 0.0001$), as well as an overall reliable increase in proportional overestimation with Pole Length ($F_{1,473} = 22.22$, $p < 0.0001$).

However, regressing vertical estimates and horizontal estimates separately on Pole Length showed that while the proportional overestimation for vertical extents increases as a function of Pole Length (see figure 10) ($t_{248} = 5.71$, $p < 0.0001$), the proportional underestimation for horizontal extents remains constant across Pole Length ($t_{248} = 0.224$, $p = 0.823$). This further supports the idea that vertical extents are perceived differently than horizontal extents of the same length.

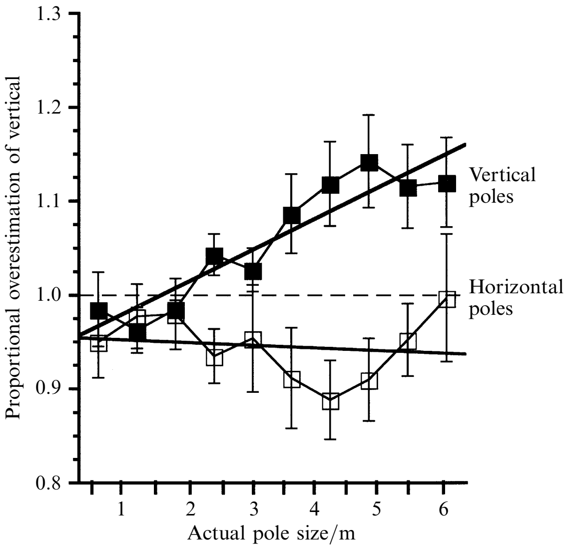

Figure 10. Data from experiment 4 separated by vertical poles and horizontal poles. The *y*-axis represents each observer's verbal estimate divided by the actual height of the pole. Regression lines fit to both sets of data show that proportional overestimation of vertical increases with actual pole size for the vertical poles, but not for the horizontal poles.

6 Experiment 5: Vertical overestimation is preserved for objects in a virtual-reality head-mounted display system

In experiment 5, we examined the relative perceptions of horizontal and vertical extents in virtual reality (VR). A VR system simulates an interactive environment that an observer views through a head-mounted display (HMD). The observer views a computer-generated scene through two small color LCDs inside the HMD. A tracker and computer system continuously records position and orientation information of the user's head and uses this information to simulate a stable environmental layout by updating the images on the display screens to appropriately correspond to the user's viewpoint and gaze. Whereas observers looking at a traditional computer monitor feel as if they are looking at a display, observers in VR generally perceive themselves to be immersed in the simulated environment.

We demonstrate that virtual reality (VR condition) preserves the magnitude of vertical overestimation found in the outdoors condition. However, if a snapshot of the same computer graphics scene is presented on a traditional desktop monitor (VR pictures condition), the magnitude of vertical overestimation diminishes and becomes similar to that of the pictures and lines conditions.

6.1 *Method*

6.1.1 *Participants.* Forty-eight undergraduate students at the University of Virginia participated in this study for course credit or for pay. None had participated in the previous experiments. All had normal vision or vision corrected to normal by contact lenses. Participants who wore glasses were not permitted in the study because glasses cannot be worn with the HMD.

6.1.2 *Design.* For the analysis, we combined the VR and VR pictures data from this experiment with the outdoors and pictures conditions of experiment 2 to create a 4 (Viewing Condition) $\times$ 10 (Pole Length) experimental design. Viewing Condition (outdoors, pictures, VR, VR pictures) was a between-subjects variable and Pole Length was a within-subjects variable. There were twenty-four observers in each of the four viewing conditions.

6.2 *Stimuli and apparatus*

Observers viewed a computer graphics rendering of the outdoors scene, either through an HMD (VR condition) or as a snapshot presented on a computer monitor (VR pictures condition). This virtual environment was designed and created with the use of Alice version 0.9.711 (beta version), a 3-D computer graphics authoring software.[2] The execution of the program as well as rendering and tracking were handled by a Gateway 2000 computer with a 233-MHz Intel Pentium processor, the Microsoft Windows 95 operating system, 256 MB RAM, and a Monster 3-D PCI Video Multimedia Device graphics card. Observers viewed the virtual environment through a Virtuality Visette Pro HMD with two active-matrix color LCDs operating in a pseudo VGA video format. The resolution of each display screen was 640 pixels (horizontal) $\times$ 480 pixels (vertical), per color pixel. The field of view per eye was 60 deg (horizontal) $\times$ 46.8 deg (vertical).

This HMD presented a bi-ocular display, meaning that the two display screens present the same image to each eye, rather than the two different images of a stereoscopic (or binocular) pair. These images are viewed through collimating lenses that allow the observer's eyes to focus at optical infinity. The screen refreshed at a rate of 60 Hz. The computer registered six degrees of freedom of the position and orientation of the HMD through an Ascension Space Pad magnetic tracker. The computer used this position and orientation information to update the scene appropriately. The end-to-end latency of the VR system, which was calculated with the pendulum method described by Liang et al (1991), was approximately 100 ms. The end-to-end latency is the length of time it takes the tracking system to sense the HMD position and orientation changes caused by an observer's head movements and then update the scene in the HMD.

6.2.1 *VR condition.* A 360° virtual scene was rendered to approximate the setting in which the outdoors condition of experiment 1 was conducted. Observers viewed this scene through an HMD. The scene contained a textured, green ground plane, trees, sky and clouds, and a virtual experimenter, all arrayed appropriately in three dimensions. The virtual experimenter, in three different postures to hold poles of different heights, was created by cropping digital images of the experimenter from the pictures condition study, scaling the images to the correct virtual size and texture-mapping them onto a transparent graphical object. The scene also contained a white vertical marker pole, but did not contain a second virtual experimenter.

6.2.2 *VR pictures condition.* The stimuli for the VR pictures condition were analogous to the pictures of the outdoors condition. The stimuli were ten static snapshots of the VR scene with the virtual experimenter holding each of the ten poles. The snapshot was created with the field-of-view parameter set to replicate a real outdoors scene photographed with a 35-mm lens. These pictures were presented on a Gateway Vivitron 21 monitor with the size of the picture on the screen set to 20.3 cm (tall) $\times$ 31.2 cm (wide), the same size as the desktop displays used in experiment 1. The sizes of the poles as measured on the screen surface were the same size as in the pictures condition of experiment 2. Viewed from the center of projection, at 30.6 cm from the monitor screen, the angular subtense of each of these pictured poles matched the angular subtense of the corresponding poles in the outdoors and VR conditions. A tripod with a square wooden platform served as a chin-rest to fix the observer's viewing position.

6.3 *Procedure*

6.3.1 *VR condition.* Each observer put on the HMD, tightened it until comfortable, and adjusted the focus and interocular settings until the image was clear. Observers viewed a scene in VR, which simulated the task, the distances, and sizes used in the outdoors condition of experiment 2. In the scene, a virtual experimenter held the virtual target poles 13.65 virtual meters away and displaced one observer eye height to the left to prevent differential foreshortening of horizontal and vertical extents. The visual angles

[2] Alice was created by the Stage 3 Research Group in the Computer Science Department at Carnegie Mellon University and is available free at http://alice.cs.cmu.edu.

subtended by the virtual poles thus matched the visual angles subtended by the real poles in the outdoors study. Observers could look around the scene before starting the experiment and were encouraged to do so.

At the beginning of each trial, a virtual marker pole (1.5 virtual meters tall) was positioned next to the target pole. Unlike the outdoors study, there was no second experimenter in the virtual scene to hold the marker pole. As with the other experiments, the experimenter explained to the observer that the task was to instruct the experimenter to move out a target pole to make the horizontal distance between the marker pole and the target pole equal to the height of the target pole.

When the observer was ready to start, the experimenter moved the virtual marker away from the target pole to the right, using the keyboard. The experimenter moved the marker pole out at a steady pace until the participant verbally instructed the experimenter to stop. The observers used as much time as needed to make their adjustment and could change their initial response by asking the experimenter to move the marker pole left or right.

6.3.2 *VR pictures condition.* The set up and procedure of this condition resembled that of the desktop-display conditions in experiment 2 (see figure 5). On a desktop monitor, observers viewed a static snapshot of the graphics scene used in the VR condition. Each observer sat and rested his or her chin on a chin-rest in front of the monitor. With a measuring stick, the experimenter adjusted the observer's viewing position (distance) to be as close as possible to the center of projection of the images, at 30.6 cm from the monitor screen. Viewed from the center of projection, the ten poles subtended the same visual angle as the corresponding poles viewed through the HMD in the VR condition and the same visual angle as the real poles in the outdoors condition. Observers viewed the scene binocularly, with their eyes straddling the center of projection of either side.

The observer instructed the experimenter to move a pictured marker pole away laterally from the target pole to create a distance between the two poles that appeared equal to the height of the target pole. Observers used as much time as needed to make their decisions and could change their initial response by moving the marker pole left or right. After each judgment, observers turned and faced the opposite direction while the experimenter measured on the screen the horizontal distance produced(3) and prepared the next stimulus screen. These steps were repeated for each of the ten poles. Each session lasted approximately 30 min.

6.4 *Results and discussion*

Vertical overestimation was greater in the VR than in the VR pictures condition. Vertical overestimation in the VR condition was comparable to that of the outdoors condition, and vertical overestimation in the VR pictures condition was comparable to that of the pictures condition (see figure 11).

We combined the VR and VR pictures data from this experiment with the outdoors and pictures data from experiment 2 and analyzed differences in proportion overestimation between the four conditions in a repeated-measures multiple linear regression. Pole Length was a fixed, continuous variable, and Viewing Condition (VR versus VR pictures versus outdoors versus pictures) was a fixed discrete variable.

These data contained eight extreme outliers that were defined as values greater than three standard deviations above or below the mean. Seven of these outliers were in the VR condition and one was in the VR pictures condition. Two of these outliers came from one observer and three came from another observer. The other three outliers each came from the first experimental trial of three other observers. Since our experiments contained no practice trials, we suspect that these three extreme values may have resulted

(3) The method used for siting the produced horizontal distance was unaffected by the curvature of the screen.

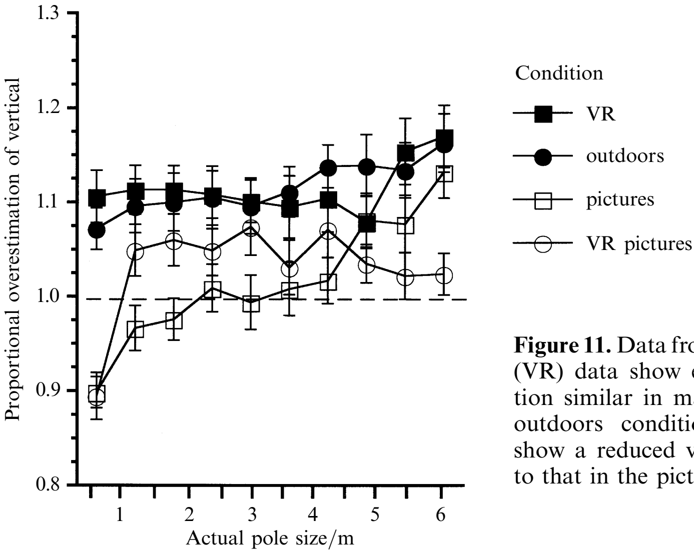

Figure 11. Data from experiment 5. Virtual-reality (VR) data show enhanced vertical overestimation similar in magnitude to that found in the outdoors condition while VR pictures data show a reduced vertical overestimation similar to that in the pictures condition.

from observers' lack of familiarity with the procedure and most likely with VR. We report analyses first with outliers removed, then with outliers included.

With extreme outliers removed, the means for the outdoors, VR, pictures, and VR pictures conditions were as follows: 1.12, 1.12, 1.02, and 1.03. Outdoors and VR were both reliably different from pictures and VR pictures. Outdoors and VR were not reliably different, and VR and VR pictures were not reliably different. The overall difference between Viewing Conditions was reliable ($F_{3,92} = 6.26$, $p = 0.0006$). Vertical overestimation in the outdoors condition was reliably greater than in both pictures ($t_{46} = 3.32$, $p = 0.0098$) and VR pictures conditions ($t_{46} = 2.72$, $p = 0.0462$). Likewise, vertical overestimation in the VR condition was reliably greater than in both pictures ($t_{46} = 3.36$, $p = 0.0068$) and VR pictures conditions ($t_{46} = 2.84$, $p = 0.033$). Outdoors and VR data were not reliably different ($t_{46} = 0.15$, $p = 1.000$), and pictures and VR pictures data were not reliably different ($t_{46} = 0.52$, $p = 0.996$). We note that the graphical representation of the pictures and the VR pictures data by pole length (see figure 11) seems to show that overestimation is greater for VR pictures for some of the shorter poles but greater for pictures for the taller poles. Although this effect was unexpected, the overall results between the two conditions were not reliably different from each other.

With extreme outliers included, the means for the four individual viewing conditions were as follows: outdoors = 1.12, VR = 1.12, pictures = 1.02, and VR pictures = 1.04. The overall difference between Viewing Conditions was reliable ($F_{3,92} = 5.24$, $p = 0.0022$). Vertical overestimation in the outdoors condition was reliably greater than in the pictures condition ($t_{46} = 2.93$, $p = 0.025$), but not reliably greater than in the VR pictures condition ($t_{46} = 2.35$, $p = 0.118$). Vertical overestimation in the VR condition was reliably greater than in the pictures condition ($t_{46} = 3.18$, $p = 0.012$), but not reliably different than in the VR pictures condition ($t_{46} = 2.60$, $p = 0.063$). Outdoors and VR data were not reliably different ($t_{46} = 0.25$, $p = 1.000$), and pictures and VR pictures data were not reliably different ($t_{46} = 0.58$, $p = 0.993$).

Even when the angular subtenses of objects in the outdoors, VR, and pictures conditions are equated, VR works better than pictures in simulating the enhanced vertical overestimation found with real objects outdoors. The lack of reliable differences between outdoors and VR data and between pictures and VR pictures data suggests that whether observers viewed the real scene or the computer-graphics-rendered scene did not make a difference. With regard to the relative perceptions of horizontal and vertical extents, a VR environment experienced through an HMD is interpreted in a similar way to a real outdoors scene, whereas a snapshot of the same scene presented on a desktop monitor is interpreted as a picture.

7 Experiment 6: Vertical overestimation in virtual reality results from perceptual interpretation, not from the optics of the head-mounted display

This study was designed to demonstrate that the increased vertical overestimation found outdoors and in VR results from the perceptual interpretation of the scene and not from the optics or other specific characteristics of the desktop or VR display system. Observers donned the HMD and viewed a virtual laboratory designed to resemble our real laboratory. In the simulated laboratory was a virtual desktop monitor displaying a snapshot of the computer-generated outdoors scene that was used in the VR pictures condition. Observers moved their heads to the center of projection of this virtual picture so that the visual angles of objects in the scene would correspond to that of both the VR condition and the VR pictures condition of experiment 5.

7.1 *Method*

7.1.1 *Participants.* Twenty-four undergraduate students at the University of Virginia participated in this study for course credit or for pay. None had participated in the previous experiments. All had normal vision or vision corrected to normal by contact lenses.

7.1.2 *Design.* For the analysis, we combined the virtual monitor data from this experiment with the VR and VR pictures conditions of experiment 5 to create a 3 (Viewing Condition) $\times$ 10 (Pole Length) experimental design. Viewing Condition (VR, VR pictures, and virtual monitor) was a between-subjects variable and Pole Length was a within-subjects variable. There were twenty-four observers in each of the three viewing conditions.

7.2 *Stimuli and apparatus*

The apparatus was the same as that used in experiment 5. The virtual environment was a 360° scene rendered to resemble the main features of our laboratory. The three-dimensional coordinates and dimensions of the real laboratory and its furnishings (eg the counters, cupboards, the chin-rest, and the computer monitor) were measured and programmed into the virtual environment. As viewed in the HMD, the locations of objects in the virtual world corresponded to the locations of objects in the real world. The tracking of the position and orientation of the observer's head allowed the VR system to compute and render and continuously update the perspective projection which would be appropriate for the observer's viewpoint relative to objects in the virtual world.

7.3 *Procedure*

Observers in the virtual monitor condition performed a task similar to that of the VR pictures condition of experiment 5, except that the observers performed the task viewing a virtual monitor in a virtual laboratory seen through an HMD. Before putting on the HMD, each observer sat down in a chair in front of the monitor, which had a chin-rest in front of it. The observer then put on the HMD to view a virtual environment that simulated the laboratory room and its furnishings. Wearing the HMD was like entering a computer graphics version of the real laboratory. In the virtual room there was, among other objects, a virtual monitor on which the snapshot of the VR scene was displayed. There was also a virtual chin-rest in front of the virtual monitor.

To enhance the believability of the virtual environment, a magnetic tracker was attached to the back of the real chair in which the observer sat. When the observer moved the real chair, the virtual chair viewed through the HMD moved in correspondence with the real chair. In addition, the experimenter encouraged the observer to reach out and touch the virtual monitor and the virtual chin-rest. Because the position and size of these virtual objects were simulated to correspond to their real counterparts in the real laboratory, when the observer reached out to where he or she perceived the virtual monitor and virtual chin-rest to be, the observer's hand touched the real monitor and chin-rest in the real laboratory.

The procedure for this study was similar to the procedure for the VR pictures condition. Observers moved their heads towards the virtual monitor and positioned their heads on the chin-rest. In the virtual laboratory, a cross-hair with a vertical line drawn to the chin-rest marked the position of the center of projection and helped observers position themselves at the center of projection of the virtual picture. Observers moved towards the cross-hair until they just passed through it, at which point the cross-hair disappeared.

As with the VR pictures condition, observers instructed the experimenter to move a pictured marker pole away laterally from the target pole to create a distance between the two poles that appeared equal to the height of the target pole. Observers used as much time as needed to make their decisions and could change their initial response by moving the marker pole left or right. The computer recorded the horizontal distance produced by observers in virtual centimeters. After each judgment, observers turned and faced the opposite direction while the experimenter prepared the next stimulus screen. These steps were repeated for each of the ten poles. Each experimental session lasted approximately 30 min.

7.4 *Results and discussion*

The magnitude of vertical overestimation in the virtual monitor condition was similar to that found with pictures (see figure 12). We combined the virtual monitor data with the VR and VR pictures data from experiment 5 and analyzed differences in proportional overestimation in a repeated-measures multiple linear regression. Pole Length was a fixed, continuous variable and Condition was a fixed, discrete variable. Again, we report the results first with extreme outliers from the VR and VR pictures conditions removed, then with these outliers included. Extreme outliers were defined as those data points that were greater than three standard deviations above or below the mean.

With extreme outliers removed, the mean proportional overestimation for the VR, VR pictures, and virtual monitor conditions was as follows: 1.12, 1.04, and 1.03. The overall difference between the three groups was reliable ($F_{2,69} = 5.51$, $p = 0.006$). Bonferroni a posteriori comparisons showed that vertical overestimation in the VR condition was reliably greater than that of the VR pictures condition ($t_{46} = 2.664$, $p = 0.010$), and reliably greater than that of the virtual monitor condition ($t_{46} = 2.48$, $p = 0.025$).

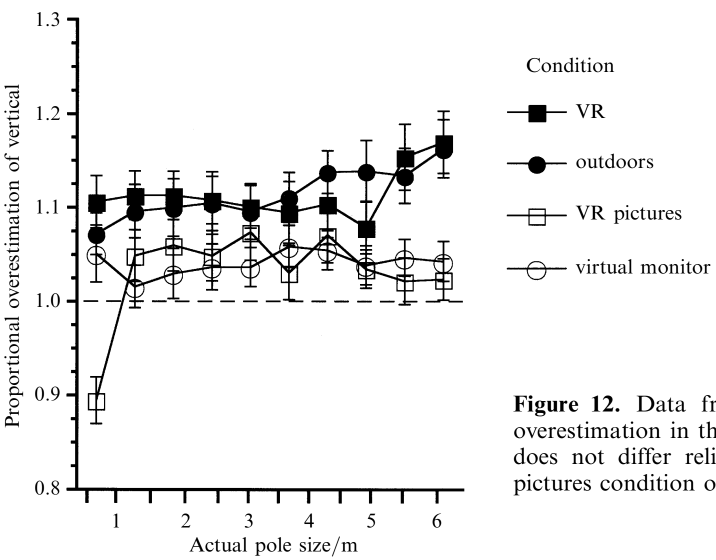

Figure 12. Data from experiment 6. Vertical overestimation in the virtual monitor condition does not differ reliably from that of the VR pictures condition of experiment 5.

There was no reliable difference between the VR pictures condition and the virtual monitor condition ($t_{46} = 0.18$, $p = 0.983$).

Analyses with the outliers included showed the same pattern of results. The mean proportional overestimation for the VR, VR pictures, and virtual monitor conditions was as follows: 1.12, 1.04, and 1.04. The overall difference between the three groups was reliable ($F_{2,69} = 4.43$, $p = 0.016$). Bonferroni a posteriori comparisons showed that vertical overestimation in the VR condition was reliably greater than that of the VR pictures condition ($t_{46} = 3.029$, $p = 0.029$), and reliably greater than that of the virtual monitor condition ($t_{46} = 2.71$, $p = 0.046$). The same a posteriori comparison between the VR and VR pictures data with outliers included was statistically significant in this analysis, but not in experiment 5 ($p = 0.063$) presumably because the Bonferroni correction was more stringent in experiment 5 because of the greater number of comparisons. There was no reliable difference between the VR pictures condition and the virtual monitor condition ($t_{46} = 0.33$, $p = 0.998$).

Because visual angles of objects in the virtual picture matched those of previous conditions, these results suggest that the increased overestimation found outdoors and in VR does not result from the optics or display characteristics of the desktop monitors or HMD. The critical variable is whether or not the scene is perceived to be a small projection.

8 General discussion

The present studies have demonstrated several important findings with regard to the vertical–horizontal illusion: (i) The magnitude of the vertical overestimation for objects viewed in (real and virtual) desktop displays of photographs and line drawings is relatively small and approximates that of the traditional illusion. (ii) The magnitude of the vertical overestimation for objects viewed in real and immersive virtual scenes is at least twice as great as that found in desktop displays matched for visual angle. (iii) Under all viewing conditions, the magnitude of the illusion increases with object height. (iv) The illusion is driven by the *perceived physical size*, not the *represented size*, of the objects.

In experiment 2, the lack of difference in vertical overestimation between the pictures and lines conditions suggests that vertical overestimation in pictures depends on the perceived physical size of the projection on the picture surface. Likewise, the lack of a difference between the VR and outdoors conditions suggests that vertical overestimation in VR depends on the perceived size of the object in the immersive environment. Finally, these differences in perceived proportions exist even when visual angles are equated between conditions, suggesting again that perceived proportions depends on our perceptual interpretation of the physical size of an object.

Unlike scenes in the real world or in VR, pictorial representations evoke a dual awareness of the size of an object. For small projections, the viewer perceives objects as physically small projections on a flat surface, despite a simultaneous awareness of the representational content (familiar size and pictorial depth information), which suggests larger objects in the pictorial space. This perception of the small projection causes vertical overestimation in desktop displays to be smaller and to approximate that of the traditional vertical–horizontal illusion. Perceived proportions are thus different between desktop displays and the real world or VR because the visual system is influenced by the perceived physical size of the projection. We believe that the reduced overestimation in desktop displays does not result from their flat, projective nature per se, but from the small size of the projection on the picture surface. Thus, we propose that vertical overestimation would increase if a picture were magnified, for instance, by projecting it onto a large movie screen.

With regard to the vertical–horizontal illusion, which has been studied for at least 140 years, its cause has yet to be explained. Three main types of theories have been proposed to explain the illusion: physiological, visual field, and gravitational [see Higashiyama (1996) for an empirical comparison of these theories]. Two examples of physiological variables that have been postulated to explain the illusion are corneal astigmatism (Pearce and Matin 1969) and effortful eye movements (Wundt 1858, cited in Boring 1942). Corneal astigmatism is described as greater curvature along the vertical meridian relative to the horizontal meridian, as the cornea approaches the sclera. Pearce and Matin (1969) proposed that the greater curvature of the vertical meridian influences the refraction of light and causes images to become distorted in the vertical direction. Thus, the greater the curvature of the vertical meridian, the more distortion and the greater the illusion. Another physiological variable that was suggested to account for the illusion is the differential effort involved in the production of vertical and horizontal eye movements. Wundt (1858, cited in Boring 1942) proposed that because vertical eye movements require more muscular effort than horizontal ones, vertical extents are perceived to be longer than horizontal extents of equal length. Because these physiological explanations apply to orientation and angles, but not to the differences between viewing pictures and real objects, they cannot account for the increased size of the illusion that occurs when viewing large objects.

The second type of theory that has been proposed to explain the vertical–horizontal illusion involves the shape of the visual field. Because the visual field is thought to be a horizontal ellipse, vertical extents approach the vertical perimeter of the visual field more quickly than horizontal extents approach the horizontal perimeter. The difference in distance to the perimeter of the visual field may result in a vertical extent being overestimated relative to a horizontal extent of equal length. In support of the visual field theory, Künnapas (1957b, 1958) showed that while the illusion occurred in conditions of full light, it was diminished in conditions of darkness and it was reversed when the head was tilted 90°. On the other hand, Avery and Day (1969) also reported a reversed illusion when the head was tilted 90°; however, they found an increased illusion in conditions of darkness relative to conditions of full light. As with physiological explanations, those that appeal to the shape of the visual field cannot account for the difference between viewing pictures and real objects. In fact, if anything, our results are contrary to what this explanation would predict: although the scene in the pictures condition is cropped by the landscape frame of the picture boundaries, overestimation in the pictures compared to the outdoors condition is less rather than more.

Finally, a gravitational theory has been proposed to explain the illusion, although little attention has been devoted to developing it further (Howard and Templeton 1966). This theory emphasizes that increased effort is associated with locomotion in the vertical plane, for example, when climbing hills. If increased effort is translated into increased distance, then vertical extents should be overestimated relative to horizontal extents of equal length. It follows from this theory that the illusion should increase as the *perceived physical size* of a vertical extent increases. Given that the perception of the slant of hills is affected by effort—for example, hills appear steeper when a heavy backpack is worn (Bhalla and Proffitt 1999)—it seems to us that the vertical–horizontal illusion may also be subject to considerations of effort, especially when very large objects are observed.

The difference in perceived proportions between a full-scale environment, VR, and pictures relates to the general problem of how we perceive large-scale environments as compared to their small-scale model representations. The awareness of the physical smallness of model representations relative to the size of our bodies has been referred to as the 'Gulliver Gap' (Anderson 1970, 1972; Porter 1979). Our perceptual awareness of the smallness of the projection on a picture surface suggests that the 'Gulliver Gap' applies to pictorial representations as well. Our experiments suggest that the difference in perceived scale also causes a difference in perceived proportions.

One suggestion for how to bridge the Gulliver Gap in traditional pictures has been to render pictures from standing eye-height perspective or even to move a miniature camera through a small-scale model from the perspective of a miniature person. Such a technique presumably makes a viewer feel as if he or she were part of the scene (Ching 1996). Although such an eye-level rendering as well as the presence of familiar-sized objects in a traditional picture might diminish the perceptual difference between a real environment and a picture, our findings on the difference in perceived proportions between pictures and real environments suggest that this bridging is incomplete.

VR, however, appears to bridge this gap better by eliminating the observer's perception of the flat projection surface and by causing them to spontaneously scale the scene to their standing eye height, and thus, perceive it as full-scale. In VR, observers are known to spontaneously employ eye-height scaling of size (Dixon et al, in press). Our experiments show that VR effectively evokes both the impression of physical largeness and the perceived proportions of large-scale objects.

At this point it is not clear to us what perceptual mechanism might cause vertical overestimation to increase with perceived size or whether such a phenomenon has adaptive significance. However, this phenomenon is a large robust effect that is meaningful in real contexts, in our appreciation of the proportions of large-scale architectural forms, and in simulating these perceived proportions in various types of spatial representations. Specifically, we might institute optical corrections to the physical proportions of buildings (as with the Greek Parthenon) to create desired perceived proportions. Likewise, in envisioning these large-scale forms, we might alter the physical proportions of traditional small-scale drawings and models to better represent how the real buildings might appear once they are built.

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