1-1-2000

Mapping the Zone of Eye-Height Utility for Seated and Standing Observers

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Perception, 2000, volume 29, pages 1361 – 1383

DOI:10.1068/p2837

Mapping the zone of eye-height utility for seated and standing observers

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Received 27 July 1998, in revised form 19 June 2000

Abstract. In a series of experiments, we delimited a region within the vertical axis of space in which eye height (EH) information is used maximally to scale object heights, referred to as the "zone of eye height utility" (Wraga, 1999b *Journal of Experimental Psychology, Human Perception and Performance* **25** 518 – 530). To test the lower limit of the zone, linear perspective (on the floor) was varied via introduction of a false perspective (FP) gradient while all sources of EH information except linear perspective were held constant. For seated (experiment 1a) observers, the FP gradient produced overestimations of height for rectangular objects up to 0.15 EH tall. This value was taken to be just outside the lower limit of the zone. This finding was replicated in a virtual environment, for both seated (experiment 1b) and standing (experiment 2) observers. For the upper limit of the zone, EH information itself was manipulated by lowering observers' center of projection in a virtual scene. Lowering the effective EH of standing (experiment 3) and seated (experiment 4) observers produced corresponding overestimations of height for objects up to about 2.5 EH. This zone of approximately 0.20 – 2.5 EH suggests that the human visual system weights size information differentially, depending on its efficacy.

1 Introduction

Recent studies have shown that eye height (EH), the altitude of one's line of gaze parallel to the ground, is a useful metric not only for perceiving affordances (Mark 1987; Warren and Whang 1987) but also for determining the absolute heights of objects (Stoper 1990; Stoper and Bautista 1992; Wraga 1999a; Dixon et al 2000). The latter holds true for both standing and seated observers (Wraga 1999b). Most of these studies have tested observer's performance with object heights in the range of 1 EH. However, it is reasonable to suppose that the effectiveness of EH-scaling might vary as a function of object height. For example, would we use EH information to scale a small object such as a flower pot, whose height is about one-tenth of EH? Conversely, would we use it to scale a building ten times the EH value?

In fact, several experiments suggest that the human visual system weights EH and other sources of size information differentially, on the basis of their relative efficacy (Wraga 1999a, 1999b). Wraga (1999b) has proposed the "zone of eye height utility" to delimit the usefulness of EH information along the vertical axis of space. According to this notion, objects whose heights correspond to 1 EH are scaled maximally to observer EH. As object heights fall progressively above or below 1 EH, the body-scaling metric becomes less efficient, until at some point reliance on EH information is superseded by a more expedient source of size information.

The goal of the current experiments was to determine the viability of the zone of EH utility by providing a preliminary quantification of its upper and lower limits. We conducted five experiments in which seated and standing observers judged the heights of a range of rectangular targets. To determine the lower limit of the zone, we varied a source of size information that was presumably highly salient for small objects: linear perspective from the floor. At the same time, all sources of EH information except perspective information were held constant. The upper limit was determined by manipulating EH

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information itself to find the largest target value for which this manipulation had an impact. We found that a bounded region within the vertical axis of space indeed exists, in which observers use EH information most effectively to scale object heights.

1.1 *The geometry of EH-scaling*

The notion of EH-scaling[(1)] was introduced by Gibson (1979) and his students. Sedgwick (1973) provided an early formalization of the relationship between EH and perceived size, in connection with the 'horizon ratio relation'. When an observer stands on flat ground, her/his horizontal line of gaze is always level with the visible horizon. An object resting on the ground will thus be intersected by the observer's line of gaze at the horizon line. The implication of this correspondence is that the object's vertical extent is available as a ratio of effective eye height (EEH). In the absence of an explicit horizon line, such as in any indoor setting, the horizon (and hence EEH) is specified implicitly via several oculomotor and environmental sources (see Wraga 1999a).

Figure 1a shows the geometry of the EH model for an object taller than observer EH. The actual ratio of total object height (Y) to the portion of the object below EEH (E) is equal to the corresponding ratio in the projection at the eye. Expressed in terms of visual angle,

$$Y/E = 1 + \tan(y - e)/\tan e\,,$$

where $y - e$ is the visual angle subtended by the portion of the object above the point of EEH intersection, and e is the visual angle of the object from EEH intersection to the object's base.

For an object smaller than observer EH (see figure 1b),

$$Y/E = 1 - \tan(e - y)/\tan e\,,$$

where $e - y$ is the visual angle subtended by the region between the point of EEH intersection and the top of the object (Sedgwick 1973). Thus, the relationship between an object's height and observer's EEH is specified by a retinal ratio. If observer EH is a known value, the actual height of the object is determinable. Moreover, the retinal ratio is invariant over distance: Regardless of how far away the object is from the observer, the relative proportion of EH it subtends will remain constant.

1.2 *EH-scaling of object heights at or near 1 EH*

A reliable method of studying EH-scaling is to put observers in a situation in which EEH is manipulated, and then record how this manipulation affects judgments of perceived size. Researchers have used a variety of EH manipulation techniques. However, as previously mentioned, the majority of these studies have assessed observers' performance with object heights in the range of 1 EH. For example, Stoper (1990; Stoper and Bautista 1992) had participants judge the heights of triangular targets (approximately 0.45 – 0.96 EH tall), presented in a large pitch box. In line with the EH model, Stoper found that upward shifts of the pitch box produced systematic underestimations of the targets, whereas downward shifts of the pitch box produced overestimations. Wraga and Neisser (1995) found a similar albeit reduced effect on size judgments of rectangles (0.87 – 1.00 EH tall) using a periscope that shifted effective EH up and down.

Bertamini et al (1998) tested the effectiveness of EH information on relative-size judgments. Seated and standing participants viewed two poles at different distances from each other in a hallway, and judged which of the pair was taller. There were two height categories of the pole pairs: tall (values corresponding to standing EH) and short

[(1)] As in previous work, the concept of eye height will be used in two ways throughout this paper (Wraga 1999a, 1999b). 'Eye height' (EH) refers to the actual altitude of an observer's line of gaze with respect to level ground. 'Effective eye height' (EEH) refers to the projection of the observer's eye height into the environment, which is used to scale object heights.

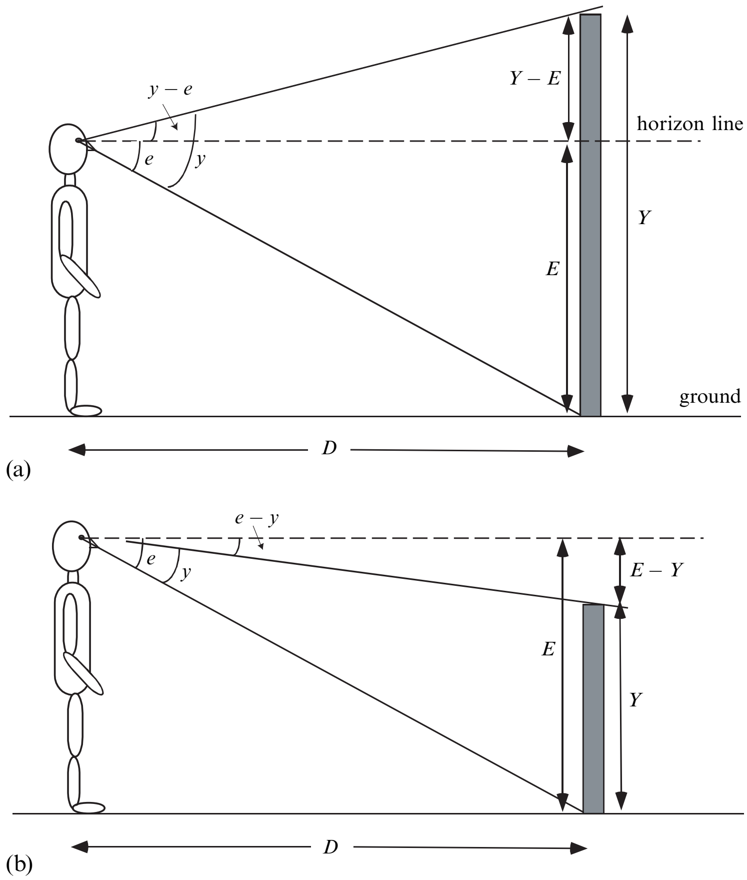

Figure 1. The geometry of the EH model for perceived height of (a) an object taller than observer EH, and (b) an object smaller than observer EH.

(values corresponding to seated EH). Bertamini et al found that participants were most accurate at discriminating relative heights when the size of the poles corresponded to the participants' current EH value: tall poles were best discriminated by standing observers, and short poles were best discriminated by seated observers. These results provided the first evidence that the efficacy of EH-scaling may be a function of object size.

Wraga (1999a) found robust evidence of EH-scaling for absolute-size judgments of object height. In this study, EEH was manipulated via Warren and Whang's (1987) false-floor technique. Rectangular targets were surreptitiously placed on a platform raised 17 cm off the ground on which observers stood, which effectively lowered observer EH by the same amount. The false-floor manipulation produced systematic overestimations of height, corresponding to 49% of the bias predicted by the EH model. An identical effect was found for seated observers, by the same false-floor method (Wraga 1999b).

Finally, Dixon et al (2000) have recently demonstrated EH-scaling in a virtual reality environment. They presented simulated cubes of heights 0.3 – 1.0 EH in a reduced-cue virtual environment, which contained only a ground plane and sky. Observers viewed the scene through a head-mounted display. For half of the trials, observers' simulated EH was projected 30% below their actual EH in the scene. This EH manipulation produced overestimations of height that were 77% of the bias predicted by the EH model. The greater magnitude of this effect in virtual reality versus the physical world was possibly due to the fact that virtual displays allow a greater degree of control over the presence of additional sources of layout information in the scene, which might conflict with EH information.

Interestingly, when participants viewed the same scenes 'pictorially' on a television monitor, the effect of the EH manipulation was negligible. Dixon et al concluded that EH-scaling did not occur in the monitor condition because the altitude of the horizon in a pictorial display is inherently ambiguous. A related possibility is that, in such a display, the depicted sizes of the objects themselves are ambiguous (Proffitt and Kaiser 1986). Objects appearing on a TV screen have a physical size of a certain number of units, in addition to the size they are supposed to represent. If participants in Dixon et al's TV-monitor condition were influenced by the physical sizes of the objects, the absence of EH-scaling could have been due to the fact that these values (about 0.05 EH) were below the lower limits of the EH zone.

1.3 *EH-scaling of object-heights greater than 1 EH*

Only a few studies have looked at the role of EH in size judgments of large objects. Bingham (1993) examined effects of EEH manipulations on the perceived size of trees. Participants were shown depictions of trees in which the horizon line was projected both at normal EH, and at an altitude 42% higher than normal EH. The raised EH produced significant underestimations of tree size, but not to the full effect predicted by the EH model. Bingham concluded that participants had used EH information in a limited manner, to scale portions of trunks extending from the ground to the horizon (ie for sizes of 1 EH); for the remaining height, tree form properties were used. These results make sense in the context of an upper region of EH utility within the vertical axis of space: Bingham's simulated tree heights ranged from 2.7 to 16 EH.

In a study of the role of EH-scaling across multiple postures, Wraga (1999b) found selective usage based on information utility. Participants viewed targets of heights around one seated-EH (1 EH_{seated}) from standing, seated, and prone (lying on the floor) postures. From the perspective of the prone observers, target heights were on average 4.4 times greater than their EH in that position. Wraga found a dissociation of perceived size between prone observers and standing/seated observers, which was not attributable to some aspect of the prone posture itself. Separate experiments revealed that the dissociation was due to reliance on different sources of size information in the respective postures. Using the false-floor technique to manipulate EEH, Wraga found that seated observers based judgments on EH information in a manner identical to standing observers. However, prone observers had relied on another source: linear perspective from the floor. Linear perspective serves as a source of size information in two ways: It can be used to scale an object's base and height as units of texture, or its vanishing point can be used to specify EEH. Wraga showed that prone participants use the former version of linear perspective by having participants in seated and prone postures view targets (of heights around 1 EH_{seated}) that appeared on a perspective gradient consisting of seemingly parallel lines with respect to the line of sight. Unbeknown to participants, two perspective gradients were actually used: In one, the lines were truly parallel to each other. In the other, the lines converged slightly to create a false-perspective (FP) gradient. The FP gradient was created in such a way as to have multiple vanishing points, which would thus provide ambiguous information for EEH. Judgments in the FP condition were found to be overestimated relative to the true-perspective (TP) condition, for observers in the prone position only. When the same targets were viewed by the same participants from a seated posture, there was no effect of the perspective manipulation. Wraga (1999b) concluded that seated observers had utilized EEH information to scale 1 EH_{seated}-tall targets; from such a vantage point, linear perspective from the floor was not as effective. In contrast, prone viewers, for whom EH-scaling was not a viable option, relied on highly salient linear perspective for their judgments.

These findings suggest that the human visual system weights size information according to its effectiveness. In the case of EH-scaling, effectiveness may be dependent on the height of the object to be scaled. Wraga proposed the "zone of EH utility" to delimit the region within the vertical axis of space in which EH information is most effective as a size scalar. According to this view, object heights corresponding to a given EH value are maximally scaled relative to it, and the informativeness of EH diminishes as objects get progressively smaller or larger than this value (see figure 2).

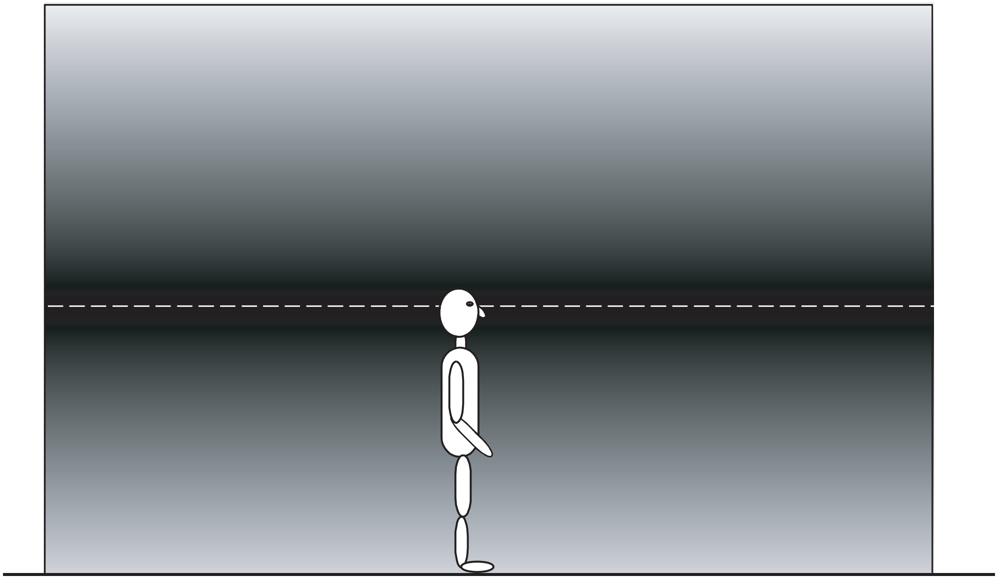

Figure 2. The zone of eye-height utility for a standing observer. The darkest area, around 1 EH, corresponds to the region in which EH-scaling occurs maximally. Medium-dark areas correspond to intermediary regions, where EH information is less effective and may be mitigated by other sources of size information. Object heights falling within the lightest regions are outside the zone, where EH information is superseded by other sources.

1.4 *Overview to the experiments*

In the present study, we conducted a series of experiments to establish the upper and lower limits of the zone of EH utility across two EH values: those of seated and standing observers. We did not expect to delimit precise, intractable values for the upper and lower limits, but rather approximations that might generalize across a range of environmental contexts. In every experiment, participants made absolute-size estimations of a range of rectangular targets. To determine the lower limits of the zone, we utilized the paradigm of Wraga (1999b). Another source of size information—linear perspective from the floor—was manipulated via introduction of an FP gradient while all sources of EH information except linear perspective were held constant. We hypothesized that targets falling outside the lower limits of the EH zone would be affected by the perspective manipulation, whereas those within the zone would not. In experiment 1a, the FP gradient produced overestimations of height for seated observers' judgments of targets up to 0.15 EH, but not 0.50 – 1.0 EH targets. Experiment 1b essentially replicated this result in a virtual reality environment. Experiment 2 yielded similar results for standing observers' judgments in a virtual reality environment.

The upper limits of the zone for standing and seated observers were examined in experiments 3 and 4, respectively. In these experiments, EH information itself was manipulated by varying the center of projection of observers' line of sight within the virtual scene. For standing observers, the EH manipulation affected target heights up to 2.0 $EH_{standing}$. For seated observers, the EH manipulation produced overestimations of target heights through values of 3.0 EH_{seated}.

2 Experiment 1a: Lower limits of the seated-observers' EH zone, real environment

The first experiment utilized Wraga's (1999b) perspective-gradient technique to map the lower limit of the EH zone for seated observers. Participants made height judgments of a range of rectangular targets. In choosing this range, we took into account previous demonstrations of EH-scaling. For example, Dixon et al (2000) found that observers used EH information to scale object heights as small as 0.30 EH. Thus, our smallest targets were set somewhat below that ($M = 0.15$ EH). The entire range was 0.09 – 1.10 EH_{seated}. For half the trials, the targets appeared on a TP gradient, whose orthogonals were parallel to each other (see figure 3a). For the other half, an FP gradient was surreptitiously introduced (see figure 3b). The FP gradient contained multiple sets of orthogonal pairs, each of which converged by 4° regardless of its distance from the FP midline. The resulting effect of multiple vanishing points was designed to minimize participants' reliance on the FP gradient as a source of EEH. If used as a texture scale, the FP gradient should produce height overestimations of 17% compared to judgments in the TP condition (number of units subtending object base, TP/number of units subtending object base, FP). However, we predicted that the FP gradient would only affect small targets, for which linear perspective from the floor would be a more efficient scaling metric. In contrast, on the basis of Wraga's (1999b) findings, judgments of targets at around 1 EH_{seated} would be unaffected, owing to reliance on EEH-scaling rather than linear perspective. The target height at which the FP gradient produced a significant bias was taken to be just outside the lower limit of the zone of EH utility.

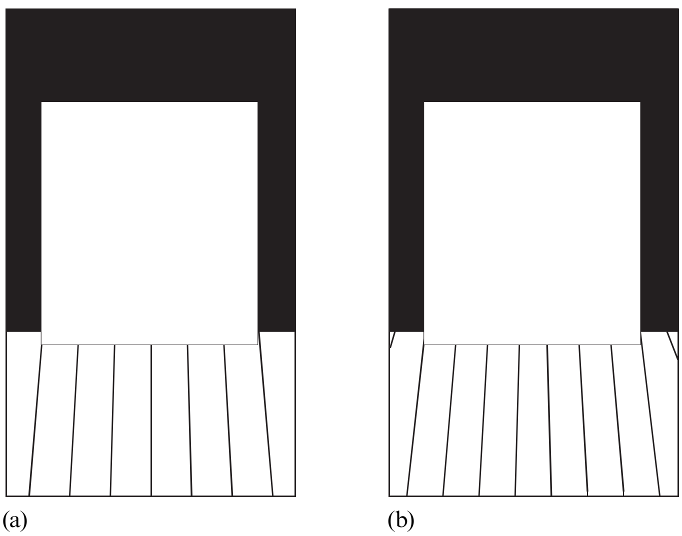

Figure 3. Conceptual drawing of perspective conditions in experiments 1a, 1b, and 2: (a) true perspective gradient, (b) false perspective gradient.

2.1 *Method*

2.1.1 *Participants.* Sixteen University of Virginia undergraduates (twelve females, four males) participated in the experiment as part of a research credit requirement. None knew the hypothesis being tested.

2.1.2 *Equipment.* The experiment was conducted in a 6 m × 2.2 m × 2.7 m (length × width × height) room (see figure 4). At the far end of the room, targets appeared before a seamless backdrop, which was created by suspending a 1 m × 2.5 m piece of black cloth

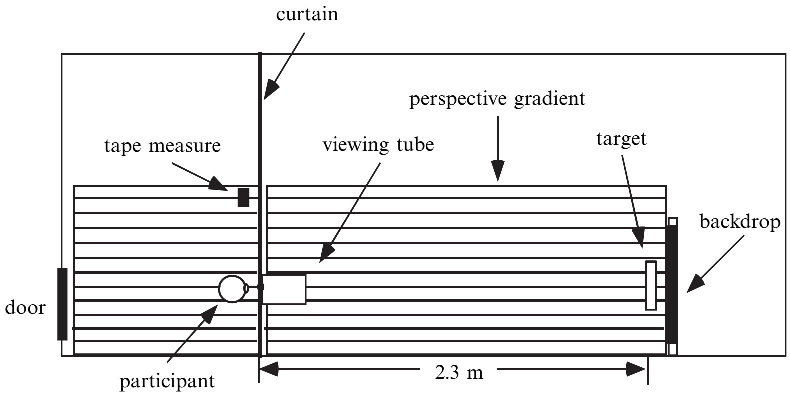

Figure 4. Overhead view of the experimental setup, experiment 1a. The participant is making judgments in the true perspective condition.

from the ceiling by wires. The cloth was pulled taut and fastened over two 2 cm diameter, 1 m wide PVC poles, one of which rested on the floor and the other of which was near the ceiling, out of participants' view. At the front end of the room, a 2.2 m × 2.5 m black curtain was hung across the entire room width to prevent participants from obtaining information about the length of the room. The distance from the curtain to the far end of the room was 3.4 m. A 4 cm diameter hole was cut out of the curtain, 50 cm to the left of the right wall, and 109 cm off the floor. Participants viewed targets monocularly through a 22 cm × 7 cm × 19 cm (length × width × height) rectangular viewing tube, whose 2.5 cm diameter peephole was aligned with the hole in the curtain. This was achieved by affixing the viewing tube to a 1 m tall metal camera tripod, raised so that the viewing tube was fixed at the correct altitude (109 cm) off the floor.

The field of view of the viewing tube (18 deg × 46 deg visual angle) allowed participants to see the target, part of the black curtain behind it, and about 0.5 m of the floor in front of the target. The sides of the back curtain, as well as the sides and ceiling of the room, were not visible.

2.1.3 *Perspective gradients.* The same simple linear perspective gradient of Wraga (1999b) was used. The TP gradient consisted of a 2.4 m × 1.2 m white fiberglass sheet containing thin black lines perpendicular to the midfrontal plane (orthogonals), spaced 10 cm apart. A shorter (1.5 m × 1.2 m) version of the TP gradient (viewer gradient) was positioned in front of the curtain so as to appear continuous with the floor viewed through the peephole. The FP gradient was identical in size to the TP gradient. However, its orthogonal pairs converged 4° at its far viewing end (see figures 2a and 2b). At its near end, the FP orthogonals were aligned with the viewer gradient.

2.1.4 *Stimulus materials.* Targets were nine foam-core rectangles, all 30 cm wide, with three height categories: small (10, 15, 20 cm); medium (50, 55, 60 cm), and large (110, 115, 120 cm), presented 2.3 m from the participant. In order to make the targets freestanding, a 5 cm deep triangular foam-core 'fin' was attached to the back of each one. The fin heights were a few centimeters shorter than their corresponding target heights and thus were not visible from a front view.

2.1.5 *Size judgments.* A tape measure was fastened to the floor, 78 cm to the left of the participant, with its numbered side facing away. Participants sat in an adjustable chair, positioned so that seated-observers' EH was aligned with the viewing-tube peephole. To make height judgments, participants watched as the experimenter (standing 70 cm in front of the tape) adjusted the tape, and then indicated when the height of the tape matched the perceived height of the target seen through the viewing tube.

The tape was either raised from its base on the floor (ascending presentation) or lowered from a height of 200 cm (descending presentation). Participants were allowed to look freely between the target and the moving tape, and were given as much time as necessary to complete each judgment.

2.2 *Procedure*

Each participant ran in two sessions, usually two days apart. In one session, all targets appeared on the TP gradient; in the other, targets appeared on the FP gradient. Stimuli were changed by an assistant, who remained behind the main curtain, out of participants' view, for the duration of the experiment. For each trial, participants were instructed to close one eye and move their heads as closely as possible to the viewing aperture. Between trials, participants looked down at their feet so that they could not see the stimuli being changed. In debriefing, all participants were asked whether they had noticed anything different (ie the FP gradient) in the FP session.

2.3 *Design*

The orders of the two gradient conditions (TP, FP) and two tape presentations (ascending, descending) were counterbalanced across participants. Targets were presented in random order. Participants made 2 judgments of each target in each gradient condition, 36 overall.

2.4 *Results*

No participants reported noticing the FP gradient. The principal finding was that the FP gradient produced size overestimations of targets in the small-target group, but not in the medium-target or large-target group.

In order to perform a general analysis of the nine target heights, we created mean scores based on the small ($M = 0.15$ EH), medium ($M = 0.50$ EH), and large ($M = 1.05$ EH) target categories. A 2 (gradient order) × 2 (tape order) × 3 (size) × 2 (gradient) mixed-design ANOVA performed on the mean category scores yielded a main effect of size ($F_{2,24} = 1891.4$, $p < 0.0001$), and no effects of gradient order, tape order, or gradient. However, the predicted size × gradient interaction was significant ($F_{2,24} = 2021.7$, $p < 0.0001$). Simple comparisons revealed a significant difference between FP and TP judgments for small targets ($p < 0.05$), but not medium or large targets (ps > 0.05). Two triple interactions were also significant: floor order × size × gradient ($F_{2,24} = 6.12$, $p < 0.01$), and tape order × size × gradient ($F_{2,24} = 3.79$, $p < 0.05$).

2.4.1 *Effect of false perspective.* To assess the magnitude of the FP effect for the three size categories, 'perspective ratios' were created by dividing FP judgments by TP judgments. A score of 1.0 reflected no bias; values greater than 1.0 reflected a positive bias (ie overestimation) due to the FP gradient; and values less than 1.0 reflected a negative bias (ie underestimation) due to the FP gradient. The predicted value based on the geometry of the FP gradient was 1.17 (ie 17% positive bias). Figure 5 shows the perspective ratios and standard errors as a function of the three size categories. The FP gradient produced a +5.6% bias for small targets on average, whereas medium (0%) and tall targets (−1%) showed negligible biases. The +5.6% bias in small targets was 33% of the effect predicted by the FP geometry. This effect is similar in magnitude to that found by Wraga (1999b) with prone observers (37%).

2.4.2 *Accuracy.* To assess the accuracy of participants' judgments in the TP condition, TP judgments were compared to actual target values. Small and medium targets were considerably overestimated (small: $M = 41\%$, SE = 0.05; medium: $M = 22\%$, SE = 0.03), whereas overestimations of large targets were more moderate ($M = 12\%$, SE = 0.02). Overestimation percentages in each group were all significantly different from each other (ps < 0.01).

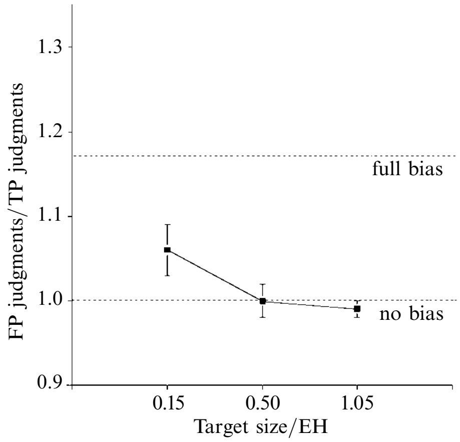

Figure 5. Mean perspective ratios and standard errors, experiment 1a.

2.5 *Discussion*

As predicted, the FP gradient produced significant overestimations of small targets, but not of medium or large targets. Linear perspective from the floor was thus an effective source of size information for scaling target heights of about 0.15 EH_{seated}, but it was not effective for target heights between 0.50 – 1.0 EH_{seated}. This finding is consistent with Wraga (1999b), who found no effect of the FP manipulation on seated participants' judgments of targets around 1 EH_{seated}. She proposed that the absence of an FP gradient effect for targets in this size range was caused by participants' reliance on another source of size information: EH. We extend this claim by proposing that the lower limit of EH-scaleability for seated observers corresponds to the target value beyond that at which linear perspective had an effect (0.15 EH) and below that at which Dixon et al (2000) demonstrated an EH effect (0.30 EH). The lower limit is thus approximately 0.20 – 0.25 EH_{seated}.

An alternative interpretation of these results is that they are due not to discrete changes in participants' reliance on one source of size information over the other, but rather on a general inability to use EH information. This argument is based on the assumption that participants' major source of EH information in the setup was the perspective gradient, whose orthogonals (in the FP condition) rendered EH information ambiguous. However, reliable EH information was available from other sources, including oculomotor signals specifying the position of the eye with respect to the head and vestibular signals signifying the position of the head with respect to the body (Matin and Fox 1989; Matin and Li 1995). It is reasonable to assume that participants relied on these sources, given that the results bear out the predictions of the study. If EH information had generally been rendered unreliable, then one would expect the FP gradient to produce shifts in size overestimations across target heights. This was not found. Instead, the FP gradient influenced perceived size only for those sizes that fell below 0.50 – 1.0 $EH_{seated.}$

For the most part, judgment accuracy was consistent with previous findings. Overestimations of large targets (12%) were similar to those found for targets 1 EH tall (Wraga 1999b). Medium-target overestimations (22%) were somewhat higher. However, the small-target overestimation of 41% is not in agreement with Wraga's previous finding that judgments based on linear perspective information tended to be less overestimated compared to those made with EEH.[2] The present study differs from Wraga's

[2] This finding was not due to inherent inaccuracies of EH-scaling versus reliance on linear perspective. Rather, it was due to the necessary use of certain cue-reduction equipment, such as a viewing tube similar to the one used in the present study. The mechanics of the tube inadvertently caused underestimations of perceived EH (and thus overestimations of perceived height). For further discussion, see Wraga (1999a, 1999b).

in that participants' utilization of both sources of information occurred within one given session, which entailed judgments of a large range of object heights. Thus, a factor present in the current study but not in Wraga (1999b) was that of 'high-contrast' relative size. The presence of objects 1 EH tall within the same testing session may have inflated judgments of objects 0.1 EH tall. If this explanation is correct, then we would expect overestimations of small targets appearing as part of a larger range to be a persistent finding.

3 Experiment 1b: Lower limits of the seated-observers' EH zone, virtual environment

Having established that the FP manipulation was an effective method of determining the lower limits of the EH zone, we next wanted to see whether linear perspective would be used similarly in a virtual world. Experiment 1b was essentially a replication of experiment 1a, in a virtual reality environment instead of a real one. Although virtual reality displays have a somewhat cartoon-like quality, they provide an immersive environment by surrounding observers with a three-dimensional scene that updates with observer movement, via head-tracking. The advantage of using virtual reality is that a larger range of stimuli can be sampled more easily than in the physical environment. The experimenter also potentially has more control over extraneous variables in virtual reality.

A recent study by Dixon et al (2000) demonstrated that observers were able to utilize EH information to scale the heights of objects in a virtual scene. We hoped that observers also would be sensitive to manipulations of virtual linear perspective. In this experiment, participants viewed virtual targets of heights identical to those in experiment 1a, presented in a virtual room whose floor could be switched from a TP gradient to an FP gradient. We predicted that, as in experiment 1a, small targets would be affected by the FP manipulation, but that medium and large targets would not.

3.1 *Method*

3.1.1 *Participants.* Twelve University of Virginia undergraduates (six females, six males) participated in the experiment as part of a research credit requirement. All participants were tested individually; none was aware of the hypothesis being tested.

3.1.2 *Equipment and stimuli.* The virtual stimuli were created with Alice, a 3-D graphics authoring software run on a Pentium 200 MHz PC, via a 64 MB Diamond Stealth Multimedia graphics card. Stimuli were transmitted to a Virtuality Visette full-color, biocular head-mounted display, with field of view of 47 deg × 60 deg visual angle, and resolution of 640 × 480 pixels. Stimuli were tracked with an Ascension Spacepad tracking system with 12 ms latency, run on a Gateway 2000 486, 66 MHz PC. Viewing was biocular. The system consisted of trackers with 6 degrees of freedom, which continuously recorded and updated the x, y, and z coordinates, as well as the pitch, roll, and yaw movements of the head-mounted display.

The virtual scene consisted of two adjacent rooms sharing a mutual doorway (see figure 6). The 2 m × 3 m × 2.5 m (length × width × height) front room (antechamber), in which the participant stood, contained blue textureless walls. The room was empty, except for a 1.7 m tall black halogen lamp standing in the back right corner. The floor contained a pattern of 10 cm wide alternating black and white stripes, perpendicular to the frontal plane. These stripes continued through to the floor of the second room (chamber) via a 2 m × 0.6 m doorway with 5 cm deep door frame centered on the width of the two rooms. The chamber was identical in size to the antechamber, and it also contained similar walls. In it appeared the targets, which were presented one at a time against the far wall of the chamber, centered on the door frame. Targets were rectangular in shape and colored brown. All were 30.5 cm wide and 15 cm deep. The three height categories were, as fractions of virtual EH: 0.1, 0.15, and 0.20 (small); 0.50, 0.55, and 0.60 (medium); and 0.95, 1.0, and 1.05 (large).

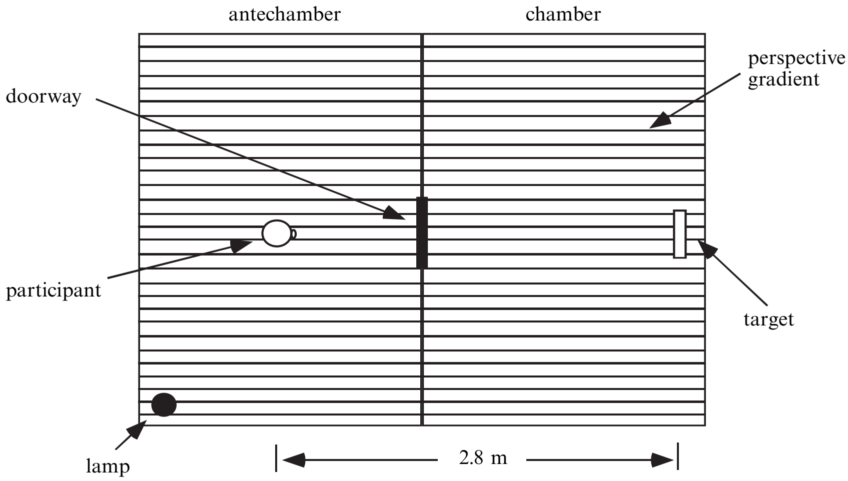

Figure 6. Overhead view of the experimental setup, experiment 1b. The participant is making judgments in the true perspective condition.

The floor in the chamber could be switched from the pattern identical to that of the antechamber (TP gradient) to one in which the stripe pairs converged 4° (FP gradient). In both gradient conditions, the stripes at the near end of the chamber were aligned with those of the antechamber.

3.1.3 *Size judgments.* To shorten the duration of time in which participants were in the head-mounted display, the tape-matching procedure from experiment 1a was abandoned in lieu of a simpler method. Participants made verbal estimates of the targets, in whatever units they felt comfortable using. These values were converted to centimeters for data analysis.

3.2 *Procedure*

Each participant ran in two sessions, usually two days apart. In one session, all targets appeared on the TP gradient; in the other, targets appeared on the FP gradient. Participants were seated in a chair that was positioned directly below the Spacepad tracker. Their EH ($M = 118.75$ cm) was measured with a measuring stick and entered into the computer program that generated the virtual room. Before participants put on the head-mounted display, the experimenter gave a general description of the two-room layout. Once the head-mounted display was on, participants found themselves in the center of the antechamber. They explored the antechamber by turning in place and looking up and down the walls. Once they were acclimatized to the virtual space, participants were permitted to move in the chair toward the door. They could peer around each side of the doorway into the chamber but could not move into the chamber. They then moved back to the center of the antechamber, from which position they made size judgments of the targets. Between trials, they looked down at the floor where their feet would be, so that they could not see the stimuli changing.

In debriefing, all participants were asked whether they had noticed anything different (ie the FP gradient) in the FP session.

3.3 *Design*

The order of the two gradient conditions (TP, FP) was counterbalanced across participants. Targets were presented in random order. Participants made two judgments of each target in each gradient condition, 36 overall.

3.4 *Results*

No participants reported noticing the FP gradient. The principal finding was again that the FP manipulation produced size overestimations of targets in the small-target group, but not in the medium-target or large-target group.

In order to perform a general analysis of the nine target heights, mean scores based on the small, medium, and large target categories were again created. A 2 (gradient order) × 3 (size) × 2 (gradient) mixed-design ANOVA performed on the mean category scores yielded a main effect of size ($F_{2,20} = 87.8$, $p < 0.0001$), and no effects of gradient order or gradient. However, a significant size × gradient interaction was found ($F_{2,20} = 112.9$, $p < 0.0001$). Simple comparisons revealed a significant difference between FP and TP judgments for small targets ($p < 0.01$), but not for medium or large targets (ps > 0.05). No other interactions were significant.

3.4.1 *Effect of false perspective.* To assess the magnitude of the FP effect for the three size categories, perspective ratios were created by dividing FP judgments by TP judgments. As in experiment 1a, a value of 1.0 reflected no bias; values greater than 1.0 reflected a positive bias due to the FP gradient; and values less than 1.0 reflected a negative bias due to the FP gradient. The predicted value based on the geometry of the FP gradient was 1.17 (ie 17% positive bias). Figure 7 shows the perspective ratios and standard errors as a function of the three size categories. The FP gradient produced a +21% bias in small targets on average, which is much greater than the effect found for small targets in experiment 1a (+5.6%). This +21% bias was 123% of the effect predicted by the FP geometry. In contrast, medium (−3%) and tall (+5%) targets showed negligible biases, similar to those of experiment 1a (medium: 0%; tall: −1%).

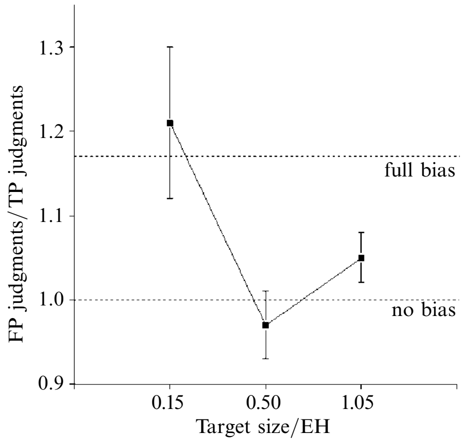

Figure 7. Mean perspective ratios and standard errors, experiment 1b.

3.4.2 *Accuracy.* To assess the accuracy of participants' judgments in the TP condition, TP judgments were compared to actual target values. Small targets were moderately overestimated ($M = 17\%$, SE = 0.11), and medium and tall targets were closer to actual target values (medium: $M = -2\%$, SE = 0.11; tall: $M = +9\%$, SE = 0.11). The magnitude of overestimation of small targets was significantly greater than the measures for medium and large targets (ps < 0.05); values for medium and large targets were not significantly different from each other ($p > 0.05$).

3.5 *Discussion*

The virtual FP gradient produced significant overestimations of small targets, but had a negligible effect on medium and large targets. This finding is identical to that of experiment 1a, carried out in the physical environment. Participants used linear perspective from the floor to scale target heights of about 0.15 EH_{seated}. In contrast, perspective information appears not to have been used for target heights between 0.50 and 1.0 EH_{seated}. These results lend support to our proposal that the lower limit of the range of EH-scaleability for seated observers falls at about 0.20 – 0.25 EH_{seated}.

One major difference of this virtual reality replication is that the FP manipulation had a greater impact on small-target judgments (123% of the predicted effect), compared to experiment 1 (32%). Dixon et al (2000) have reported comparable elevated effects for virtual reality manipulations of EEH [eg a 77% effect in virtual reality, versus 49% effect of using false floor (Wraga 1999a, 1999b)]. This phenomenon is most likely attributable to the fact that greater experimental control can be exerted over the layout information present in virtual versus real environments.

We again found greater overestimations of small targets, compared to medium and large ones, which indicates that relative-size contrasts might have been in effect. However, judgments were generally more accurate than in the previous experiment. The biggest improvement was found for the small-target overestimations, which dropped from 41% (experiment 1a) to 17% (experiment 1b). It is not clear whether the virtual setup per se, or some unrelated factor such as subject variability, contributed to this result.

We took the general correspondence between experiments 1a and 1b to suggest that virtual reality is a viable tool for mapping the EH zone. Therefore, the remaining experiments were conducted in virtual reality.

4 Experiment 2: Lower limits of the standing-observers' EH zone

Experiment 2 was designed to test whether the FP gradient would affect standing participants' judgments of target size similarly to those of seated participants. Wraga (1999b) has shown that EH information for size is accessible from both seated and standing postures. It is thus reasonable to assume that the zone of EH utility would be in evidence for more than one EH value. In this experiment, participants viewed virtual targets of heights similar to experiment 1b, presented in the same virtual space whose floor could be changed from TP to FP gradient. We again predicted that small targets ($M = 0.10$ EH) would be affected by the FP manipulation, but that medium targets ($M = 0.50$ EH) and large targets ($M = 1.0$ EH) would not. As in experiments with seated observers, the target height at which the FP gradient produced significant overestimations was taken to be just outside the lower limit of the zone of EH utility.

4.1 *Method*

4.1.1 *Participants.* Twelve University of Virginia undergraduates (nine females, three males) participated in the experiment as part of a research credit requirement. All participants were tested individually; none was aware of the hypothesis being tested.

4.1.2 *Equipment and stimuli.* The hardware and software described in experiment 1b were also used in experiment 2.

The virtual scene of two adjoining rooms was identical to that of experiment 1b, except that the floor was a checkerboard rather than a striped pattern. That is, 10 cm deep transversals (lines parallel to the frontal plane) were added to the orthogonals of the floor gradient. This change was made after a pilot study revealed that, when viewed in the head-mounted display, the striped floor was less visible from a standing position than from a seated one. The transversals did not become more dense in the FP condition: as in experiment 1a, only the orthogonals varied. The range of target heights used was also slightly different. The three height categories were, as fractions of virtual EH: 0.5, 0.10, and 0.15 (small); 0.50, 0.55, and 0.60 (medium); and 0.95, 1.0, and 1.05 (large). To reduce participants' reliance on relative-size judgments, targets were also colored in different primary and secondary solid colors.

4.1.3 *Size judgments.* Size judgments were identical to those in experiment 1b.

4.2 *Procedure*

Each participant ran in two sessions, within the same day. In one session, all targets appeared on the TP gradient; in the other, targets appeared on the FP gradient. Participants stood directly below the Spacepad tracker. Their EH ($M = 158.33$ cm) was measured with a measuring stick and entered into the computer program that generated the virtual room. As in experiment 1b, they received a general description of the room before putting on the head-mounted display, and explored the virtual space similarly once in it. Between trials, they looked down at the floor where their feet would be, so that they could not see the stimuli changing. Between sessions, they remained in the head-mounted display and looked around the antechamber again. During this interlude, the experimenter changed the perspective gradient to the next condition as soon as the floor was not in participants' field of view.

In debriefing, all participants were asked whether they had noticed anything different (ie the FP gradient) in the FP session.

4.3 *Design*

The design was the same as that of experiment 1b, except that target color was also randomized within and between experimental sessions.

4.4 *Results*

No participants reported noticing the FP gradient. The main finding was that the FP manipulation affected standing observers' judgments of targets in the small-target group, but not in the medium-target or large-target group.

Mean scores based on the small-, medium-, and large-target categories were created for a general analysis. A 2 (gradient order) × 3 (size) × 2 (gradient) mixed-design ANOVA performed on the mean category scores yielded a main effect of size ($F_{2,20} = 475.73$, $p < 0.0001$) and no effects of gradient order or gradient. However, a significant size × gradient interaction was found ($F_{2,20} = 713.58$, $p < 0.0001$). Simple comparisons revealed a significant difference between FP and TP judgments for small targets ($p < 0.01$), but not for medium or large targets (ps > 0.05). No other interactions were significant.

4.4.1 *Effect of false perspective.* To assess the magnitude of the FP effect for the three size categories, perspective ratios were created by dividing FP judgments by TP judgments. Figure 8 shows the perspective ratios and standard errors as a function of the three size categories. Small targets yielded a +21% bias on average, which is identical to the effect found in the previous experiment for seated participants' judgments of

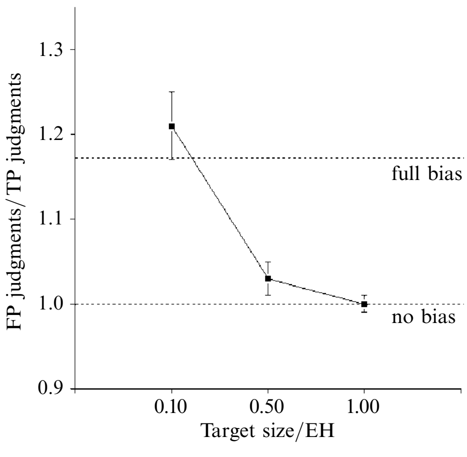

Figure 8. Mean perspective ratios and standard errors, experiment 2.

small targets in virtual reality. The bias for standing participants was again 123% of the effect predicted by the FP geometry. In contrast, medium targets (+3%) and tall targets (0%) showed negligible biases.

4.4.2 *Accuracy.* To assess the accuracy of participants' judgments in the TP condition, TP judgments were compared to actual target values. Small targets were greatly overestimated ($M = 72\%$, $SE = 0.05$). Judgments of medium and large targets revealed somewhat less but still considerable overestimations (medium: $M = 33\%$, $SE = 0.02$; large: $M = 27\%$, $SE = 0.01$). Overestimations of small targets were significantly greater than those of medium and large targets ($p\text{s} < 0.05$); overestimations of medium and large targets were not significantly different from each other ($p > 0.05$).

4.5 *Discussion*

Once again, the virtual FP gradient produced significant overestimations of small targets, but had a negligible effect on medium and large targets. Standing participants used linear perspective from the floor to scale target heights of up to about 0.10 $EH_{standing}$, but did not use it to scale heights between 0.50 and 1.0 $EH_{standing}$. This finding is similar to those of experiments 1a and 1b, for seated observers. The lower limit of the range of EH-scaleability for standing observers falls at about 0.15 – 0.20 $EH_{standing}$.

As in the previous virtual reality experiment, we found a full effect of the FP manipulation (123%) on small targets, which indicated that participants had relied heavily on linear-perspective information for those height values. However, we also found much larger overestimations of virtual size, for all three target categories. Overestimations of small targets (72%) were particularly high. Overestimations of medium (33%) and large (27%) targets were inconsistent with previous studies (Dixon et al 2000), which have demonstrated near-perfect accuracy for standing observers' judgments of similar-sized objects in a virtual scene. Further empirical investigation is necessary to determine the source of this inconsistency.

To summarize the first group of experiments, the lower region of the vertical axis of space can be segmented according to the efficacy of EH-scaling, for both seated and standing observers. Object heights falling below the boundary are scaled to linear perspective from the floor; object heights falling above the boundary are scaled to EH. We tentatively place this boundary at about 0.20 EH. The last two experiments sought to establish the upper limits of the EH zone.

5 Experiment 3: Upper limit of standing-observers' EH zone

The upper limit of the EH zone necessarily involves large-scale object heights. However, to the best of our knowledge, few researchers have examined the perceived size of large-scale objects, let alone developed a general theory on what information observers use to scale them. For example, in a study on the perceived size of trees, Bingham (1993) found that observers based judgments on information about the relative sizes and densities of tree limbs. Unfortunately, such biological-form information has limited generalizability. Other researchers have examined size perception of large objects indirectly, in the context of the horizontal – vertical illusion (eg Chapanis and Mankin 1967; Higashiyama 1996; Higashiyama and Ueyama 1988). In the absence of a general theory for size-scaling of large objects, we took a different approach to establishing the upper limits of the EH zone than we did for the lower limits. Large-scale targets were presented in a scene in which EEH information itself was manipulated. We reasoned that, if there were an upper height limit to EH-scaling, at some point the EEH manipulation would produce no effect.

Experiment 3 utilized the EEH manipulation method of Dixon et al (2000), which has produced strong effects on standing observers' judgments of absolute size. For this reason, our first attempt at mapping the upper limits of the EH zone tested observers in a standing posture. In experiment 3, standing participants viewed a virtual reality display of rectangular targets appearing on a randomly textured ground.[(3)] The targets were of three size categories: 1.0, 2.0, and 3.0 $EH_{seated.}$ For half of the trials, the virtual center of projection (ie the horizon) in the scene corresponded to the participants' actual EH; for the other half, the center of projection was lowered by 30%. If used exclusively, the EEH manipulation would produce height overestimations of 43%. However, we predicted that it would only affect target heights within the lower range.

5.1 *Method*

5.1.1 *Participants.* Fourteen University of Virginia undergraduates (ten females, four males) participated in the experiment as part of a research credit requirement. All participants were tested individually; none knew of the hypothesis being tested.

5.1.2 *Equipment and stimuli.* The hardware and software described in experiment 1b were also used in experiment 3.

The virtual scene consisted of a blue sky, a yellowish ground plane, and grey cube-like targets (see figure 9). The ground plane projected to infinity. It consisted of random-sized oval shapes, each with a unique aspect ratio, placed at random locations and

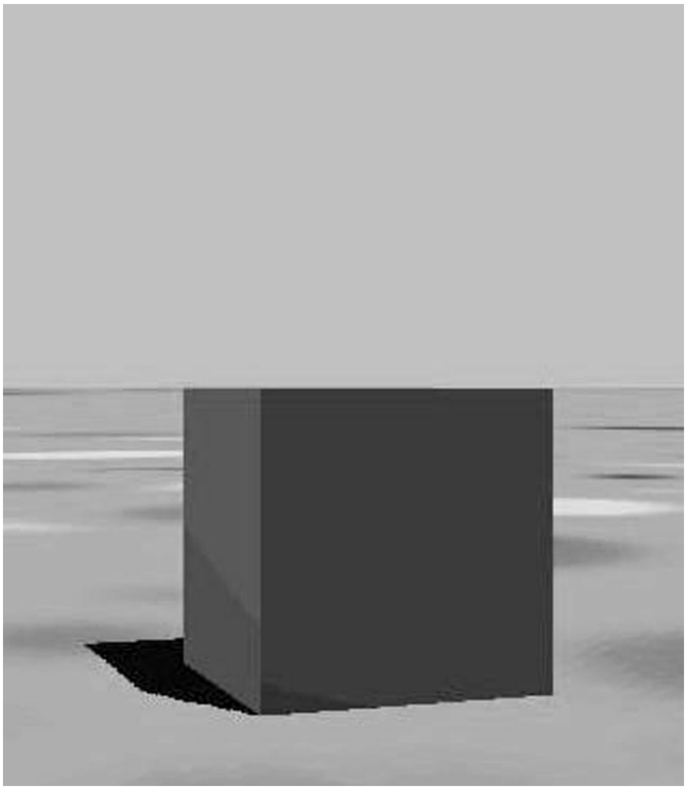

Figure 9. Depiction of the virtual scene, experiments 3 and 4. This is a target of size 0.95 EH, presented at level (ie 1.0 EH) center of projection, and a distance of 7 m.

(3) Wraga (1999b) found that a linear perspective gradient had no effect on height judgments of targets at around 1 EH. Because in the current study target heights of 1 EH and greater were used we replaced the LP gradient of experiments 1 and 2b with one that had previously proved successful in testing EEH manipulations (Dixon et al 2000). Although theoretically possible, we speculate that this change would have had minimal effects on participants' ability to use EH information.

orientations. These measures ensured that perspective information from the ground was minimized but not rendered misleading. The three target height categories were, as fractions of virtual EH: 0.95 and 1.05 (1.0); 1.95 and 2.05 (2.0); and 2.95 and 3.05 (3.0). Targets appeared individually, at two distances: 7 m and 10 m from the participant. This distance manipulation ensured that the EEH manipulation could not be detected by participants simply noticing height in the visual plane. Target location with respect to the participant was randomized.

5.1.3 *Size judgments.* Size judgments were identical to those of experiment 1b.

5.2 *Procedure*

The experiment was run in one session. Participants stood directly beneath the tracker. To specify the placement of the virtual horizon for each participant, their EH was first measured and then entered into the computer. The computer program set the center of projection at true EH in the level condition. To achieve the effect of reducing EH (lowered condition), the scene was actually raised 30% with respect to the true EH center-of-projection value. This method ensured that the horizon line remained at true eye level in each EEH condition. After putting on the head-mounted display, participants briefly explored the virtual space by turning in place. They then completed six practice size trials, which utilized two targets (0.25 EH and 5.0 EH) appearing at two distances (1 m and 7 m, respectively). None of the practice cubes appeared in the testing phase of the experiment. For each trial, participants searched the scene for a target by turning around in place. Upon finding the target, they made a size judgment. No feedback was given for judgments, in either practice or test trials.

5.3 *Design*

Each of the six target heights appeared in each EEH condition (level, lowered), at each distance (7 m, 10 m). The resulting combinations appeared randomly. Participants viewed each combination two times, for a total of 48 trials.

5.4 *Results*

The principal finding was that the EEH manipulation affected targets of 1 EH and 2 EH, but not 3 EH heights.

Mean scores based on the small, medium, and large target categories were created for general analysis. A 3 (size) × 2 (EH) × 2 (distance) repeated-measures ANOVA performed on the mean category scores yielded main effects of size ($F_{2,26} = 129.69$, $p < 0.0001$) and distance ($F_{1,13} = 45.72$, $p < 0.0001$), but no effect of EH. However, the predicted size × EH interaction was significant ($F_{2,26} = 10.06$, $p < 0.001$). Simple comparisons revealed a significant difference between virtual EH conditions for 1 EH and 2 EH targets (ps < 0.01), but not for 3 EH targets ($p > 0.05$). A significant size × distance interaction was also found ($F_{2,26} = 31.14$, $p < 0.0001$). The main distance effect was that observers tended to judge targets viewed at 7 m as significantly larger ($M = 3.86$ m) than those viewed at 10 m ($M = 3.46$ m). Simple comparisons revealed that this difference was more pronounced for 1 EH targets than 2 EH and 3 EH targets (ps < 0.05). One triple interaction was also significant: size × EH × distance ($F_{2,26} = 4.9$, $p < 0.05$).

5.4.1 *Effect of EH.* To assess the magnitude of the EH effect for the three target-size categories, EH ratios were created by dividing judgments in the lowered condition by judgments in the level condition. Figure 10 shows the EH ratios and standard errors as a function of the three target-size categories. Biases were greatest for 1 EH targets on average (+22%), reduced for 2 EH targets (+6%), and negligible for 3 EH targets (−1%). The magnitude of the bias for 1 EH targets was 52% of the effect predicted by the EH model. A 3 (size) × 2 (distance) repeated-measures ANOVA performed on the

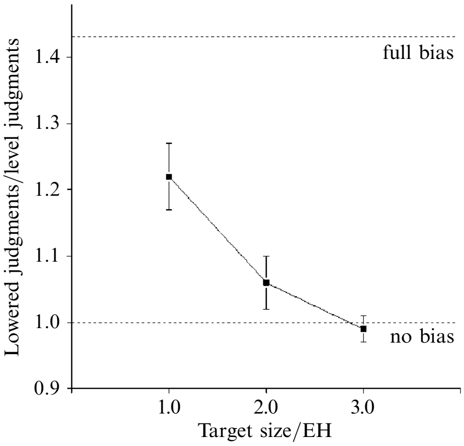

Figure 10. Mean EH ratios and standard errors, experiment 3.

EH ratios revealed a main effect of size ($F_{2,26} = 10.16$, $p < 0.001$), but no effect of distance and no interactions.

5.4.2 *Accuracy.* To assess the accuracy of participants' judgments in the level condition, judgments in the level condition were compared to virtual target values. All targets were judged fairly accurately. 1 EH targets were slight underestimations of virtual height ($M = -3\%$; SE = 0.22) whereas 2 EH and 3 EH targets were slight overestimations (2 EH: $M = 5\%$, SE = 0.30; 3 EH: $M = 8\%$, SE = 0.35). Accuracy of 1 EH targets was significantly better than those of 2 EH and 3 EH targets ($p < 0.05$). Accuracy of 2 EH and 3 EH targets did not differ significantly ($p > 0.05$).

5.5 *Discussion*

As predicted, the virtual EEH manipulation affected perceived target height differentially. Lowering observers' center of projection in the scene produced significant size biases in standing observers' judgments of 1 EH and 2 EH targets, but had no effect on 3 EH targets. This finding suggests that the upper limit of the zone of $EH_{standing}$ utility is between 2.0 – 2.5 $EH_{standing}$.

The fact that the virtual EEH manipulation caused significant overestimations of some targets lends support to Dixon et al's (2000) findings that observers use EH information in virtual scenes. However, the strongest effect of the EEH manipulation in the present study (for 1 EH targets) was only 52% of what the EH model predicted. This is less than EEH effect in virtual reality (77%) reported by Dixon et al, who utilized the same virtual scene but a smaller range of object heights. However, consistent with Dixon et al, judgments were highly accurate, particularly for targets at 1 EH, which were slight underestimates of virtual height (−3%) on average.

6 Experiment 4: Upper limit of seated-observers' EH zone

In the final experiment we examined whether the EEH manipulation would affect seated observers' judgments of large targets. Seated participants viewed a virtual reality display depicting rectangular targets of three size categories: 1.0, 2.0, and 3.0 EH_{seated}. These values were the same EH proportions of experiment 3; however, when multiplied by EH_{seated} rather than $EH_{standing}$, they produced smaller absolute height values. As in experiment 3, the virtual center of projection in the scene corresponded to the participants' actual EH for half of the trials, and was lowered by 30% for the other half. We predicted that this manipulation would only affect smaller targets. The greatest target height at which the EEH manipulation produced significant overestimations was taken to approximate the upper limit of the zone of EH utility.

6.1 *Method*

6.1.1 *Participants.* Eleven University of Virginia undergraduates (five females, six males) participated in the experiment as part of a research credit requirement. The data of one additional participant were removed owing to experimenter error. All participants were tested individually; none knew of the hypothesis being tested.

6.1.2 *Equipment and stimuli.* The hardware and software described in experiment 1b were used in experiment 4. The virtual scene of experiment 3 was also used. The three target-height categories were all proportions of participants' EH_{seated}: 0.95 and 1.05 virtual EH (1.0); 1.95 and 2.05 virtual EH (2.0); and 2.95 and 3.05 virtual EH (3.0). Targets appeared at the same distances (7 m and 10 m) as in experiment 3.

6.1.3 *Size judgments.* Size judgments were identical to those of experiment 3.

6.2 *Procedure*

The procedure was identical to that in experiment 3, except that participants sat in a chair that turned 360°. To search for a target, participants turned in place in the chair, which was positioned directly beneath the tracker.

6.3 *Design*

The design was identical to that of experiment 3.

6.4 *Results*

The principal finding was that the EEH manipulation affected targets of all height categories.

Mean scores based on the 1 EH, 2 EH, and 3 EH categories were created for general analysis. A 3 (size) × 2 (EH) × 2 (distance) repeated-measures ANOVA performed on the mean category scores yielded main effects of size ($F_{2,20} = 314.59$, $p < 0.0001$), and EH ($F_{1,10} = 117.52$, $p < 0.0001$). In addition, a significant size × distance interaction was found ($F_{2,20} = 7.09$, $p < 0.01$). Simple comparisons revealed that 3 EH targets appearing at 7 m ($M = 111$ cm) tended to be judged taller than the same objects appearing at 10 m ($M = 95$ cm), whereas 1 EH and 2 EH targets did not (ps > 0.05).

6.4.1 *Effect of EH.* To assess the magnitude of the EH effect for the three size categories, EH ratios were created by dividing judgments in the lowered condition by judgments in the level condition. Figure 11 shows the EH ratios and standard errors as a function of the three size categories. Biases due to the EEH manipulation decreased as target size increased. The bias for 1 EH targets ($M = +25\%$) was 57% of the effect predicted by the EH model. The biases for 2 EH and 3 EH targets were somewhat reduced, but still present (2 EH: $M = +9\%$; 3 EH: $M = +8\%$).

A power function fitted to the data revealed that the x-axis was intercepted at 3.4 EH_{seated}. The function accounted for about 90% of the variance ($r^2 = 0.903$).

6.4.2 *Accuracy.* To assess the accuracy of participants' judgments in the level condition, judgments in the level condition were compared to virtual target values. 1 EH targets ($M = 95\%$, SE = 0.25), 2 EH targets ($M = 75\%$, SE = 0.21), and 3 EH targets ($M = 81\%$; SE = 0.20) were all greatly overestimated. Overestimations of 1 EH targets were significantly greater than those of 2 EH targets ($p < 0.05$), but not 3 EH targets ($p > 0.05$). 2 EH and 3 EH overestimations were not significantly different from each other ($p > 0.05$).

6.5 *Discussion*

Although the effect diminished with increasing object size, the virtual EH manipulation produced significant size biases in seated-observers' judgments of targets up to 3 EH in height. This finding suggests that the upper limits of the zone of EH_{seated} utility extends beyond 3 EH_{seated}. The power function we fit to the data places the upper limit

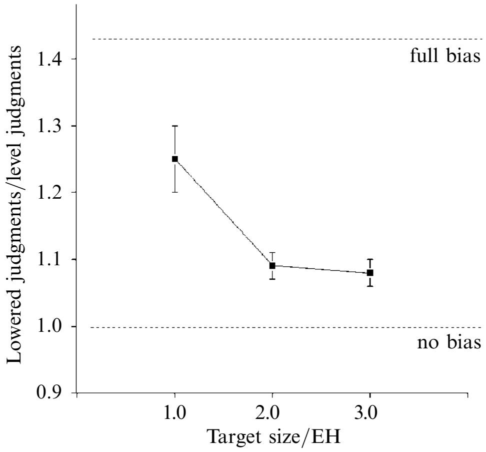

Figure 11. Mean EH ratios and standard errors, experiment 4.

at a value of approximately 3.4 EH_{seated}. The absolute value of this proportion is equivalent to that of 2.5 $EH_{standing}$.

The strongest effect of the EEH manipulation, for 1 EH targets, was about 57% of what the EH model predicted. This is similar to what we found for standing observers (52%) in experiment 3. However, we also found enormous overestimations of virtual size, particularly for targets at 1 EH, which were judged to be nearly twice virtual size. This result was not consistent with either Dixon et al's (2000) findings or the results of experiment 3, which showed high accuracy for standing-participants' judgments of large-scale targets.

7 General discussion

Our goal was to approximate the upper and lower limits of the region within the vertical axis of space in which EH information is used maximally to scale object heights: what Wraga (1999b) has termed the "zone of eye height utility". We conducted five experiments to test this hypothesis. The results of these studies suggest that the EH zone is indeed a viable construct.

Experiment 1a sought to explicate the lower limits of the EH zone for seated observers. We hypothesized that target heights falling below the lower limit would be scaled to sources of size information other than EH, such as linear perspective from the floor. To this end, we varied linear perspective by introducing true perspective (TP) and false perspective (FP) gradients into the field of view while holding constant all sources of EH information except linear perspective. The FP gradient produced systematic biases of targets up to about 0.15 EH; greater heights were not affected. We tentatively placed the lower limit of the zone to be somewhere around 0.20 – 0.25 EH. Further support was found in two replications in a virtual reality environment. Experiment 1b repeated the 0.20 – 0.25 EH findings for seated observers. In experiment 2 we tested the lower limits of the EH zone for standing observers, and found it to be around 0.20 EH. From these results we proposed that the lower limits for standing and seated observers are about 0.20 EH.

In experiments 3 and 4 we tested the upper limits of the EH zone, for standing and seated observers, respectively. Height judgments of a range of targets were made within an EEH-shifting paradigm that consisted of lowering the center of projection of participants' line of gaze within a virtual scene. In experiment 3, the lowered center of projection produced corresponding positive size biases for target heights up to 2.0 $EH_{standing}$. In experiment 4, the lowered center of projection affected all targets observed by seated viewers (heights up to 3.0 EH_{seated}). The extrapolated upper limit for seated viewers was found to be 3.4 EH_{seated}, the value of which corresponds roughly to 2.5 $EH_{standing}$. We thus place the upper limits of EH-scaleability for standing and seated observers at a value of about 2.5 $EH_{standing}$.

To summarize these findings, we tentatively map the zone of EH utility for seated and standing observers as follows: The region at which EH information is used maximally corresponds to an altitude of 1 EH off the ground. As object heights become progressively smaller than 1 EH, EH-scaling becomes a less efficient strategy. Object heights smaller than 0.20 EH may not scaled to EH at all; at that point, EH-scaling may be superseded by more efficient strategies. Correspondingly, object heights extending above 1.0 EH become progressively less EH-scaleable. Beyond heights of 2.5 $EH_{standing}$, EH information may no longer be used.

Although the EH zone appears to be fairly constant across standing and seated postures, as well as real and virtual environments, it remains an open question as to whether its region as we have mapped it generalizes to all situations. For example, if linear-perspective information for texture-scaling were made less salient in the scene by elimination of the perspective gradient, we might expect the lower limit of the EH zone to move down further. The implication of this possibility is that linear perspective is also mapped along the vertical axis of space. Thus, the region of utility for a given source of size information may be a function of its interaction with other size sources.

Another question stemming from these findings is what information participants used to gauge the heights of targets falling outside the upper limit of the zone. Because this was not the main focus of the study, we can only conjecture about possible sources based on our experimental setup. Apart from EH information in the form of the projected horizon line, the virtual scene itself contained little other size information. Ground texture was deliberately set to provide no consistent information about size or depth, and the targets themselves were textureless. The displays were viewed biocularly, so depth via binocular disparity was not available. Some motion-parallax information was present; however, participants did not move side-to-side very much. One possible cue was vestibular and proprioceptive information of the head–neck system for the angle of participants' heads with respect to their bodies. In order to see the tops of the 3 EH targets, participants had to tilt their heads at a steeper angle than for the 1 and 2 EH targets, which would have produced a corresponding stronger signal for head position. Degree of head pitch is also related in part to the visual angle subtended by the portion of the target above observer line of gaze ($y - e$; see figure 1a). For the 3 EH targets, lowering EEH increases $y - e$ by a relatively small amount, compared to the change produced in $y - e$ when EEH is lowered with respect to target heights near 1 EH. Thus, for 3 EH targets, the combination of head tilt to the same position across level and lowered EEH conditions and strong vestibular and proprioceptive feedback specifying such position may have enabled participants' to rely solely on head tilt, while ignoring the portion of the target below the line of sight (e), which is necessary for EH-scaling. This issue warrants further empirical investigation.

In the two experiments (3 and 4) in which EEH was varied, effects of this manipulation were less (experiment 3: 52%; experiment 4: 57%) than previous findings in a similar controlled virtual environment (Dixon et al 2000: 77%). Apart from the participants themselves, the major difference between Dixon et al's study and the present ones was the range of target heights used. Dixon et al's range spanned 0.70 EH; ours spanned 3.0 EH. Our unusually large range was intended to capture target heights beyond the upper limits of the EH zone. Because this manipulation was done within one testing session, judgments of targets less affected by the EEH manipulation (ie taller ones) may have influenced judgments of targets to which EH information is usually more informative. The high relative-size contrast between small and large targets in the range may have also caused unusually inflated absolute judgments of smaller targets that we found consistently.

The main theoretical implication of these findings is that the human visual system does not process size information uniformly. As evidenced by the zone of eye-height utility, individual sources may instead be weighted according to their relative efficacy. This idea is consistent with a recent analysis by Cutting and Vishton (1995), who examined multiple sources of layout information along the horizontal plane. They found that the horizontal plane can be segmented into at least three regions, based on the efficacy of different sources of layout information associated with each. Personal space corresponds to a 1 m radius area surrounding the observer in which such close-range sources as accommodation and retinal disparity are effective. Action space, corresponding to an area approximately 30 m beyond personal space, is subserved by sources advantageous to the moving, acting observer, such as binocular disparity and motion perspective. Sources effective in vista space, the area beyond 30 m, include traditional pictorial cues such as aerial perspective, which are useful for viewing distant objects and scenes.

Our results indicate that the vertical axis of space also can be segmented on the basis of the efficacy of at least two sources of size information: eye height and linear perspective. Objects smaller than 0.20 EH appear to be scaled most effectively to linear perspective from the floor. For object heights between 0.20 and 2.50 EH, EH-scaling is a more efficient strategy. Further research is necessary to determine whether other sources of size information can be similarly apportioned along the vertical axis of space.

Acknowledgements. This research was supported by NIMH grant MH11462 to the first author; and NIMH grant MH52640, NASA grant NCC 2-1093, and CMU/DARPA grant 539689-52273 to the second author. We wish to thank Tyrone Yang, Fred Mast, Hal Sedgwick and one anonymous reviewer for comments on an earlier draft of this paper. We also thank Melissa Russano, Eugene Yun, Wendy Farmer, and Lynn Metzger for assistance in data collection.

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